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MODULATING CYTOKININ LEVELS FOR EFFICIENT *IN VITRO* CLONAL PROPAGATION OF POTATO (*SOLANUM TUBEROSUM* L.) CULTIVARS

Md. Iqbal Hossen[1], Gm Maruf[1], Talha Zubair Masror[2], Md. Jamal Hossain[2], Fahim Reza Jhelom[2], S. M. Abdullah Al Mamun[1*] and Md. Monirul Islam[1]

ABSTRACT: *In vitro* micropropagation has emerged as an efficient strategy for producing disease-free and genetically uniform potato (*Solanum tuberosum* L.) planting materials. The present study was conducted to evaluate the varietal response of two potato cultivars, BARI Alu-41 and BARI Alu-72, to *in vitro* regeneration under different concentrations of 6-benzylaminopurine (BAP). Shoot tip explants were cultured on Murashige and Skoog (MS) medium supplemented with varying BAP concentrations to assess their effects on shoot multiplication, node formation, leaf number, shoot length, and root traits. Significant differences were observed between the two varieties for most regeneration traits. BARI Alu-72 exhibited superior performance, producing a higher number of nodes (11.05), leaves (10.60), longer shoots (71.56 mm), and longer roots (26.07 mm) compared to BARI Alu-41. In contrast, shoot number and root number did not differ significantly between the varieties. BARI Alu-41 performed slightly better in *ex vitro* conditions than BARI Alu-72, reflecting genotypic differences in acclimatization. These findings indicate that BAP plays a critical role in stimulating shoot proliferation and plantlet growth. The differential varietal responses highlight that *in vitro* regeneration efficiency in potato is genotype-dependent, and thus, optimization of hormone combinations is essential for each cultivar. This study provides a reliable framework for variety-specific micropropagation, enabling rapid multiplication of disease-free seed potatoes to enhance productivity and ensure a sustainable seed supply in regions where viral and other systemic infections pose a major threat to crop production.

KEYWORDS: Potato, shoot tip culture, cytokinin BAP, *in vitro* regeneration, genotype-specific response.

INTRODUCTION

Potato (*Solanum tuberosum* L.), a tetraploid (2n = 4x = 48) herbaceous dicotyledon belonging to the Solanaceae family, is a vegetatively propagated crop that originated from the Peru-Bolivian Andes and southern Chile (Swamy, 2023). Globally recognized as the fourth most important food crop, it serves as a staple in more than 40 countries and contributes nearly 45% of the total world production of tuber crops (Chandrasekara and Kumar, 2016, Hu *et al*., 2025). It thrives best in cool climates, with tuber production optimal at around 20°C but severely hampered when temperatures rise above 30°C (Nasif *et al*., 2018; Liu *et al*., 2025).

In Bangladesh, potatoes are primarily cultivated as a winter crop and rank third in terms of total cultivated area after rice and wheat, while being the leading vegetable crop in both area and production (Rahim *et al*., 2023). Among the improved cultivars

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developed by the Bangladesh Agricultural Research Institute (BARI), BARI Alu-41 and BARI Alu-72 are notable for their yield potential. BARI Alu-41 is more suited to northern regions, while BARI Alu-72 performs well in saline-prone coastal areas (Rahman et al., 2021). Despite their promising agronomic traits, both cultivars are vulnerable to a wide range of pathogens, especially viruses such as PVX, PVY, PVA, PVS, PVM, and PLRV (Kenzhebekova *et al*., 2025), which can reduce yields by up to 80-90% (Masum *et al*., 2011). A major factor contributing to disease prevalence in Bangladesh is the widespread use of infected tubers due to the unavailability of clean planting material. Using disease-free seed tubers can boost potato yield by 20-30% (Karim *et al*., 2011; Yayeh *et al*., 2025). However, diagnosing and treating pathogen-infected tubers is costly and often ineffective, highlighting the urgent need for a reliable alternative propagation method.

In vitro tissue culture techniques, particularly shoot tip or meristem culture, offer a sustainable solution by enabling large-scale production of disease-free planting materials. Meristem culture is proven to eliminate systemic pathogens, including viruses, and is more practical and cost-effective compared to other tissue culture methods. Cytokinins, especially BAP (6-benzylaminopurine), play a central role in shoot initiation and proliferation *in vitro* (Adu Donyina *et al*., 2025). While BAP promotes cell division and axillary bud development, it may also inhibit root formation (Dilshad *et al*., 2021; Vaičiukynė *et al*., 2025). Therefore, precise modulation of cytokinin levels is critical for optimizing micropropagation protocols.

Although a few attempts have been made in Bangladesh to produce virus-free potato plants through tissue culture (Nasif *et al*., 2018; Azad *et al*., 2020; Rahman *et al*., 2021), there is a noticeable research gap regarding the *in vitro* propagation of specific high-yielding cultivars like BARI Alu-41 and BARI Alu-72. These cultivars are yet to be extensively studied for their responses to cytokinin-mediated shoot tip culture, which is essential for establishing a reliable and genotype-specific propagation protocol. Considering the aforementioned context, the present study was undertaken with the following specific objectives:

1. To assess the effect of different concentrations of cytokinin (BAP) on the shoot proliferation of potatoes.
2. To explore the potentialities of two potato cultivars responding to *in vitro* shoot tip culture.

MATERIALS AND METHODS

Experimental site and duration

The study was carried out at the Plant Breeding and Biotechnology Laboratory, Agrotechnology Discipline, Khulna University, Khulna, Bangladesh, from February to November 2024.

Plant materials

Two potato cultivars, BARI Alu-41 and BARI Alu-72, were used in the experiment. These were collected from the Bangladesh Agricultural Research Institute (BARI), Gazipur. Shoot tips of the sprouts, developed under laboratory conditions, were used as the source material for *in vitro* culture.

Culture media and hormonal treatments

All *in vitro* cultures were initiated and maintained on Murashige and Skoog (MS) medium (Murashige and Skoog, 1962), supplemented with 30 g L^{-1} sucrose and solidified with 8 g L^{-1} agar. The media were fortified with different concentrations of BAP

(0.0, 1.5, 2.0, 2.5, and 3.0 mg L^{-1}), each in combination with 0.2 mg L^{-1} NAA. The pH of the medium was adjusted to 5.6 before autoclaving at 121°C and 1.5 kg cm^{-2} pressure for 20 minutes. The prepared medium was poured into test tubes, each containing 10 ml media.

Sterilization procedures

All glassware were sterilized by autoclaving at 121°C for 30 minutes at 1.5 kg cm^{-2} pressure. Metal instruments were sterilized through dry heat and by dipping in 100% ethanol followed by flaming prior to use. The culture room and laminar airflow cabinet were disinfected with 70% ethanol and formaldehyde prior to use.

Surface sterilization of explants

Sprouts were first rinsed with tap water, then surface sterilized in 70% ethanol for 30 seconds, followed by treatment in 0.1% $HgCl_2$ for 10 minutes. They were then rinsed three times with sterile distilled water and dried on autoclaved tissue paper in the laminar airflow cabinet.

Inoculation of explants and incubation

Using aseptic techniques, 2 cm shoot tips were excised and inoculated individually onto the prepared media in test tubes. The tubes were incubated at 25±1°C with a 16-hour photoperiod, light intensity of ~3000 lux, and relative humidity of approximately 65%. Shoot proliferation was first observed after 15 days of culture and further sub-culturing was done for two times to facilitate shoot multiplication and plantlet development each after 4 weeks interval.

Experimental design

The experiment was laid out in a two-factor factorial completely randomized design (CRD) with three replications. Factor A was variety (BARI Alu-41 and BARI Alu-72) and factor B was BAP concentrations (0.0, 1.5, 2.0, 2.5, and 3.0 mg L^{-1}). Each replication consisted of seven test tubes, with one explant cultured per tube.

Data collection

Quantitative data were recorded at three different intervals (30, 60, and 90 days after culture) on the following parameters:

- Shoot length (cm)
- Number of shoots $explant^{-1}$
- Number of nodes $plantlet^{-1}$
- Number of leaves $plantlet^{-1}$
- Number of roots $plantlet^{-1}$
- Root length (cm)
- *Ex vitro* survivability (%)

Statistical analysis

Collected data were analyzed using Analysis of Variance (ANOVA) in the R programming environment (R Core team, 2024). Mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a 5% significance level.

RESULTS

Effect of BAP concentration on *in vitro* multiplication efficiency of potato

BAP concentration significantly influenced shoot number, node number, leaf number, and shoot length, while root number and root length remained unaffected (Table 1). The highest number of shoots (2.98), nodes (11.39), and leaves (9.40) $plantlet^{-1}$ was recorded at 2.0 mg L^{-1} BAP, which was significantly superior to the lowest values observed at control as well as 3.0 mg L^{-1} for shoots and nodes, and at 2.5 mg L^{-1} for leaves. Shoot length was also highest at 1.5 mg L^{-1} (68.96 mm) and 2.0 mg L^{-1} (66.46 mm), which were significantly greater than the shortest length in control

Table 1. Effect of BAP concentration on *in vitro* multiplication efficiency of potato

BAP (mg L^{-1})	Shoots $plant^{-1}$	Nodes $plant^{-1}$	Leaves $plant^{-1}$	Roots $plant^{-1}$	Shoot length (mm)	Root length (mm)
0	1.35^{c}	5.42^{c}	3.15^{c}	14.25	39.62^{c}	18.73
1.5	2.55^{ab}	8.87^{ab}	7.46^{ab}	15.73	68.96^{a}	20.84
2.0	2.98^{a}	11.39^{a}	9.4^{a}	16.60	66.46^{a}	22.54
2.5	2.97^{a}	8.37^{ab}	5.47^{b}	11.17	43.77^{b}	22.52
3.0	2.2^{b}	7.93^{b}	7.6^{ab}	16.60	57.44^{ab}	26.41
LS	*	*	*	NS	*	NS

followed by 43.77 mm shoot length at BAP 2.5 mg L^{-1}. Root number and root length did not differ significantly among treatments, although slightly longer roots were observed at 3.0 mg L^{-1} (26.41 mm).

Varietal effect on *in vitro* regeneration of potato

The two potato varieties exhibited notable differences in several regeneration parameters under *in vitro* conditions (Fig. 1). BARI Alu-72 significantly outperformed BARI Alu-41 in terms of number of nodes (11.05 vs. 7.23) and number of leaves $plantlet^{-1}$ (10.60 vs. 4.37), both at the 1% level of significance. Similarly, BARI Alu-72 produced significantly longer shoots (71.56 mm) and roots (26.07 mm)

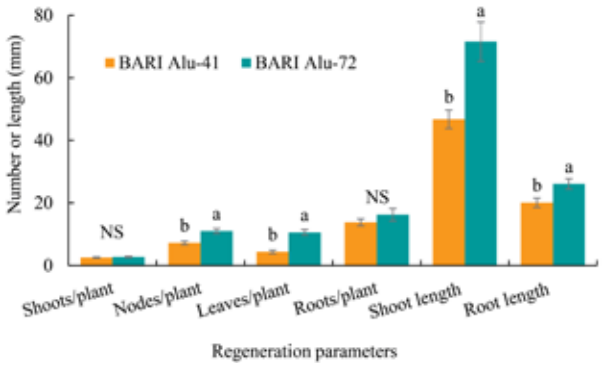


Fig. 1. Regeneration efficiency of two potato varieties in in vitro conditions

compared to BARI Alu-41 (46.76 mm and 20.08 mm, respectively), with shoot length differing at the 1% level and root length at the 5% level of significance. However, no significant varietal differences were observed in the number of shoots $plantlet^{-1}$ and number of roots $plantlet^{-1}$.

Interaction effect of variety and BAP concentration on *in vitro* multiplication efficiency of potato

The interaction between variety and BAP concentration had significant effects on all evaluated parameters except shoot number, which was significant at the 5% level (Table 2). The highest number of shoots

Table 2. Interaction of variety and BAP concentration on *in vitro* multiplication efficiency of potato

Variety	BAP (mg L^{-1})	Shoots $plant^{-1}$	Nodes $plant^{-1}$	Leaves $plant^{-1}$	Roots $plant^{-1}$	Shoot length (mm)	Root length (mm)
BARI Alu- 41	0	1.22^{c}	4.35^{c}	2.10^{d}	7.05^{bc}	32.84^{d}	15.21^{b}
	1.5	2.64^{ab}	6.12^{b}	2.51^{d}	9.79^{bc}	44.80^{cd}	16.40^{b}
	2.0	3.32^{a}	10.03^{ab}	6.71^{c}	13.72^{abc}	54.18^{cd}	23.81^{ab}
	2.5	2.45^{ab}	6.67^{b}	3.80^{cd}	13.89^{abc}	37.40^{d}	17.39^{b}
	3.0	1.91^{b}	6.08^{b}	4.47^{cd}	17.78^{ab}	50.68^{cd}	22.73^{ab}
BARI Alu- 72	0	1.48^{c}	6.27^{bc}	3.56^{cd}	12.84^{bc}	40.15^{d}	18.64^{b}
	1.5	2.46^{ab}	11.62^{a}	12.42^{a}	21.66^{a}	93.12^{a}	25.28^{ab}
	2.0	2.64^{ab}	12.74^{a}	12.11^{a}	19.48^{a}	78.74^{ab}	21.26^{ab}
	2.5	3.50^{a}	10.06^{ab}	7.14^{bc}	8.45^{c}	50.15^{cd}	27.66^{a}
	3.0	2.50^{ab}	9.78^{ab}	10.74^{ab}	15.42^{abc}	64.21^{bc}	30.08^{a}
Level of significance		*	*	**	**	**	*

** = Significant at 1% level of significance; * = Significant at 5% level of significance

plantlet^{-1} (3.50) was recorded in BARI Alu-72 at 2.5 mg L^{-1} BAP, followed closely by BARI Alu-41 at 2.0 mg L^{-1} (3.32). Node number was significantly higher in BARI Alu-72 at both 2.0 mg L^{-1} (12.74) and 1.5 mg L^{-1} (11.62) BAP, while the lowest was in BARI Alu-41 at control (4.35).

Leaf number varied significantly across treatments. The maximum was observed in BARI Alu-72 at 1.5 mg L^{-1} (12.42), statistically similar to 2.0 mg L^{-1} (12.11), while the lowest was in BARI Alu-41 at control (2.10) followed by BAP 1.5 mg L^{-1} (2.51). Root number also showed significant interaction effects, with the highest value in BARI Alu-72 at 1.5 mg L^{-1} (21.66), and the lowest in variety BARI Alu-41 at control (7.05) followed by BAP 2.5 mg L^{-1} (8.45) in BARI Alu-72. Shoot length differed markedly across combinations, with the longest shoots produced by BARI Alu-72 at 1.5 mg L^{-1} (93.12 mm), while the shortest was observed in BARI Alu-41 at control (32.84 mm). Root length was also significantly affected, with BARI Alu-72 at 3.0 mg L^{-1} showing the highest value (30.08 mm), and the lowest being recorded in BARI Alu-41 at control followed by BAP 1.5 mg L^{-1} (16.40 mm).

Relationships between BAP concentrations and shoot production efficiency of potato varieties

The regression analysis showed that shoot production efficiency in BARI Alu-41 increased slightly with rising BAP concentration, following the equation y = 0.3192x + 1.7321 with a coefficient of determination of R^2= 0.1896. This indicates that 18.96% of the variation in shoot production was explained by BAP concentration.

For BARI Alu-72, shoot production exhibited a stronger positive linear relationship with BAP concentration, described by the equation y = 0.4857x + 1.6417 with R^2 = 0.3797. In this case, 37.97% of the variation in shoot production was explained by BAP concentration (Fig. 2).

Ex vitro hardening

Ex vitro hardening of regenerated potato plantlets revealed notable differences between the tested substrates for both varieties (Table 3). In BARI Alu-41, the highest survival rate (94.2%) was obtained in cocopeat + vermicompost, followed by 87.5% in soil +

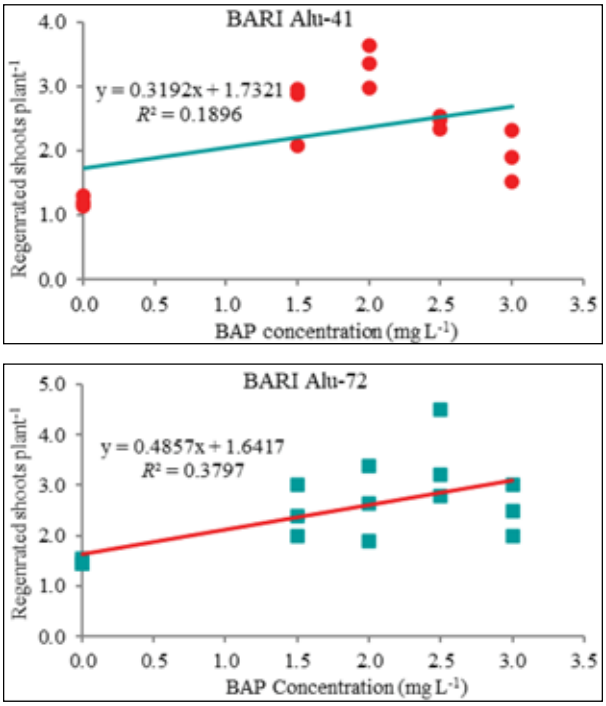


Fig. 2. Comparative regression analysis of BAP concentration and shoot multiplication efficiency in potato varieties.

Table 3. *Ex vitro* hardening of regenerated potato plantlets in different substrates

Variety	Hardening media	Survival rate (%)
BARI Alu-41	Cocopeat + Vermicompost	94.2 ± 0.85^{a}
	Soil + Sand + Compost (1:1:1)	87.5 ± 1.10^{b}
	Sand + Soil + Cow dung (1:1:1)	79.1 ± 1.24^{c}
	Garden Soil	71.0 ± 1.32^{d}
BARI Alu-72	Cocopeat + Vermicompost	92.8 ± 0.92^{a}
	Soil + Sand + Compost (1:1:1)	85.0 ± 1.18^{b}
	Sand + Soil + Cow dung (1:1:1)	78.3 ± 1.27^{c}
	Garden Soil	69.6 ± 1.40^{d}

sand + compost (1:1:1). Survival decreased further in sand + soil + cow dung (79.1%) and was the lowest (71.0%) in garden soil.

Similarly, in BARI Alu-72, cocopeat + vermicompost also supported the highest survival (92.8%), while soil + sand + compost (85.0%) and sand + soil + cow dung (78.3%) performed moderately. The lowest survival (69.6%) was observed in garden soil. Between the two varieties, BARI Alu-41 exhibited slightly higher survival percentages in all substrates compared to BARI Alu-72. However, the trend of survival across substrates was consistent in both varieties, with cocopeat + vermicompost performing the best and garden soil the least effective.

DISCUSSION

In vitro regeneration of potato plantlets has become an important strategy for producing disease-free and high-quality planting materials, especially given the susceptibility of potatoes to viral and bacterial pathogens. The present study evaluated the interaction effect of variety and BAP concentration on *in vitro* shoot multiplication efficiency in two potato varieties, BARI Alu-41 and BARI Alu-72, using shoot tip explants (Fig. 3). The results (Table 2) revealed that shoot proliferation parameters, including shoot number, node number, leaf number, root traits, and plant length, were significantly influenced by both genotype and BAP concentration, indicating a genotype × hormone interaction effect.

Influence of BAP on shoot and node multiplication

Cytokinins, particularly BAP, are well known for their role in inducing axillary

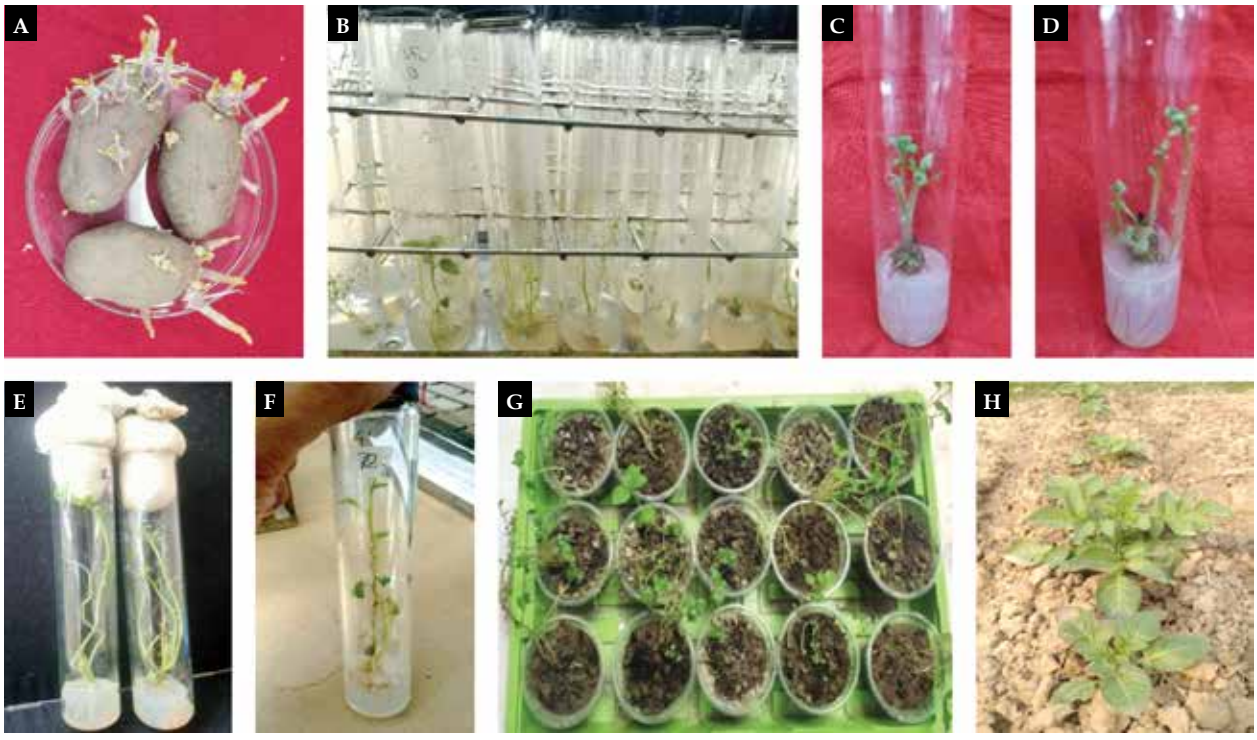


Fig. 3. Sequential steps of clonal micropropagation of potato: A. Potato sprouts used as a source of explant, B. In vitro incubation of culture, C-D. In vitro shoot multiplication and root growth of BARI Alu-41, E-F. In vitro shoot multiplication and root growth of BARI Alu-72, G. Ex vitro hardening of plantlets, H. Established micropropagated potato plants in the field.

shoot proliferation through cell division and apical dominance release (Lyndon, 1990; Müller and Leyser, 2011). In this study, both varieties showed increased shoot and node multiplication with increasing BAP concentration up to an optimum range, beyond which performance either plateaued or declined. For BARI Alu-41, the highest shoot number (3.32) and node number (10.03) were recorded at 2.0 mg L^{-1} BAP, whereas higher concentrations (2.5-3.0 mg L^{-1}) reduced efficiency. In contrast, BARI Alu-72 responded better to 2.5 mg L^{-1} BAP with the highest shoot number (3.50), suggesting that genotypic differences strongly influence cytokinin sensitivity. These results align with previous reports where optimal shoot multiplication was observed within the range of 1.5-3.0 mg L^{-1} BAP in potato varieties (Motallebi-Azar et al., 2011). Similar varietal variation in BAP requirement was reported by Hajare et al. (2021), where variety Gudiene responded best at 1.5 mg L^{-1} BAP + 3.0 mg L^{-1} NAA, whereas variety Belete performed better at 1.0 mg L^{-1} BAP + 0.2 mg L^{-1} NAA. Such findings emphasize that no unique BAP concentration ensures maximum shoot induction across varieties.

Effect on leaf number and shoot length

Leaf development was also significantly influenced by BAP concentration and variety interaction. BARI Alu-72 consistently produced more leaves, with the maximum leaves plantlet^{-1} (12.42) observed at 1.5 mg L^{-1} BAP, whereas BARI Alu-41 lagged behind with fewer leaves under all concentrations. This suggests a stronger morphogenic capacity of BARI Alu-72 under cytokinin influence. Cytokinins are reported to stimulate foliar development and enhance photosynthetic tissue formation in potato shoot tip cultures (Dilshad *et al*., 2021), which could partly explain the superior response of BARI Alu-72. Shoot length exhibited a similar trend, with the highest elongation (93.12 mm) in BARI Alu-72 at 1.5 mg L^{-1} BAP. Comparatively, BARI Alu-41 recorded only moderate elongation, even at optimal concentrations. Comparable findings were reported by Dhaka and Nailwal (2015), and Masekesa *et al*. (2016), who observed significant enhancement of shoot length with BAP in combination with GA_3. Our results corroborate that moderate BAP concentrations not only induce axillary shoot multiplication but also support elongation, although varietal background remains a decisive factor.

Root development under BAP influence

BAP affected root induction variably across varieties. BARI Alu-72 produced the highest number of roots (21.66 plant^{-1}) at 1.5 mg L^{-1} BAP, while BARI Alu-41 attained the maximum (17.78 plant^{-1}) at 3.0 mg L^{-1} BAP. However, root length was less responsive to BAP in BARI Alu-41 compared to BARI Alu-72. This partially contradicts earlier findings suggesting that BAP tends to inhibit root formation in potato meristem culture (Aprilia *et al*., 2022). It is possible that varietal genetic makeup modulates the balance between cytokinin-induced shoot proliferation and root formation. In this context, supplementary auxins *viz*., NAA or IBA are generally recommended to achieve balanced rooting (Rout *et al*., 2001), which was also observed in several earlier studies (Hajare *et al*., 2021).

Varietal differences in regeneration potential

The comparative performance of BARI Alu-41 and BARI Alu-72 demonstrates that varietal differences play a significant role in tissue culture responsiveness. BARI Alu-72 consistently outperformed BARI Alu-41 in most traits, particularly in shoot length,

leaf number, and rooting ability, indicating a higher regeneration potential. Such genotypic variability in micropropagation efficiency has been reported earlier (Rohela *et al*., 2018), suggesting that tissue culture success is inherently genotype-dependent.

Ex vitro hardening

Ex vitro hardening success varied with substrate and genotype (Sharma *et al*., 2023). Cocopeat + vermicompost gave the highest survival in both varieties due to its superior aeration, moisture retention, and nutrient availability. Intermediate survival in soil + sand + compost and sand + soil + cow dung indicates partial suitability, while the lowest survival in garden soil reflects poor porosity and nutrient balance. Between varieties, BARI Alu-41 showed slightly higher survival than BARI Alu-72, suggesting genotypic differences in adaptability.

The regression analysis further substantiates the ANOVA-based findings presented in Tables 1 and 2, where BAP concentration exerted a significant influence on shoot production efficiency in both varieties. For BARI Alu-41, the regression indicated only a weak positive relationship (R^2 = 0.1896), suggesting that shoot proliferation was less responsive to increasing BAP levels. This aligns with the ANOVA results, where BARI Alu-41 showed relatively lower shoot numbers compared to BARI Alu-72. In contrast, BARI Alu-72 displayed a stronger positive response to BAP concentration, as reflected in a higher regression coefficient and R^2 value (0.3797). This trend is consistent with the ANOVA-based interaction effects, which revealed that higher BAP concentrations, particularly 2.5 mg L^{-1}, markedly enhanced shoot multiplication in BARI Alu-72. Together, these results confirm that varietal differences strongly modulate the response to BAP (Hossain *et al*., 2019), with BARI Alu-72 showing greater efficiency and predictability in shoot induction compared to BARI Alu-41.

BAP alone can successfully induce shoot multiplication in potato (Motallebi-Azar *et al*., 2011; Dilshad *et al*., 2021); however, Salem and Hassanein (2017) and Buckseth (2023) suggested that MS medium devoid of growth regulators is sufficient for potato single-node cultivation. Our findings clearly demonstrated that exogenous cytokinin supplementation is essential for efficient regeneration in the tested potato varieties. This discrepancy may arise from differences in explant type, physiological state, or inherent varietal traits. The ANOVA results indicated significant varietal and BAP concentration effects, with BARI Alu-72 exhibiting superior shoot multiplication compared to BARI Alu-41. Regression analysis further supported this observation, revealing a stronger positive relationship between BAP concentration and shoot induction efficiency in BARI Alu-72 (R^2 = 0.3797) than in BARI Alu-41 (R^2 = 0.1896). These findings suggest that while both varieties respond to BAP, the degree of responsiveness is cultivar-specific. Moreover, the results corroborate earlier reports by Kazemiani *et al*. (2018), who concluded that the most favorable shoot induction occurs with BAP concentrations ranging between 1.5–3.0 mg L^{-1}. The present study strengthens this conclusion, emphasizing that the optimal concentration lies within this range but differs according to varietal background.

CONCLUSION

The present study demonstrated that *in vitro* multiplication efficiency of potato is significantly influenced by the interaction between genotype and BAP concentration. Both BARI Alu-41 and BARI Alu-72 exhibited differential responses to varying BAP levels, highlighting the necessity of genotype-

specific optimization. Among the tested combinations, MS medium supplemented with 2.0 mg L^{-1} BAP supported superior shoot multiplication in BARI Alu-41, while 2.5 mg L^{-1} BAP favored higher shoot proliferation in BARI Alu-72. Furthermore, BAP concentrations strongly influenced shoot number, node production, leaf development, and shoot length; whereas root traits were less responsive, suggesting that additional auxin supplementation may be required for optimal root induction. The genotype-specific variation observed in this study reinforces that no universal protocol exists for potato regeneration. Standardization of hormone regimes for individual varieties is therefore crucial for efficient micropropagation and for the large-scale production of disease-free, quality seed potatoes.

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CONFLICT OF INTEREST

The authors declare no conflict of interest for the article.

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals.

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EFFECT OF TILLAGE METHODS ON GROWTH AND YIELD OF POTATO (*SOLANUM TUBEROSUM* L.) VARIETIES IN JHAPA, NEPAL

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ABSTRACT: An experiment was conducted on the year 2025 to evaluate the effects of varieties (Kufri Jyoti, Khumal Ujjwal, and IPY-8) and tillage methods (zero tillage, minimum tillage, and conventional tillage) on the growth and yield performance of potato in Jhapa, Nepal. Parameters including sprout number, plant height, leaf number, canopy spread, tuber yield, individual tuber weight, tuber diameter, total tuber number, and number of green tubers were recorded. Among the tested varieties, Khumal Ujjwal performed significantly better, recording the highest plant height (73.4 cm), canopy spread (72.97 cm), tuber yield (15.4 t ha^{-1}), individual tuber weight (74.6 g), and tuber diameter (5.26 cm). Although Kufri Jyoti produced the highest number of tubers, a greater proportion of them were green and therefore less marketable. Tillage methods had no significant effect on the most of the growth and yield parameters, implying tedious and cost consuming process of tillage can be skipped for potato cultivation, if the the number of green tubers could be controlled. Similarly, the interaction between variety and tillage method showed no significant influence on plant height, canopy spread, sprout number, tuber yield, tuber weight, and tuber diameter. These findings indicated that varietal selection even on non-tilled lands plays an important role in determining potato productivity under the agro ecological conditions of Jhapa, with Khumal Ujjwal emerging as the most promising variety for cultivation.

KEYWORDS: Growth; Potato; Tillage; Variety; Yield

INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the most important food crops in Nepal, contributing significantly to food security, income generation and agricultural sustainability (Bhattarai, 2025). It is widely consumed throughout the country in various forms, including as a staple food, vegetable, pickle and snack. In Nepal, the crop occupies approximately 197,037 ha of cultivated area, with a total production of 2,586,287 metric tons and an average productivity of 13.13 metric tons ha^{-1} (Chauhan *et al.*, 2022).

Owing to its adaptability, high productivity, and market demand, potato is a priority crop for Nepalese farmers (Sapkota and Bajracharya, 2018). Among the factors influencing potato production variety and tillage practices play crucial roles in determining growth, yield and tuber quality. Tillage enhances crop productivity by modifying soil physical conditions, reducing compaction, improving infiltration and aeration, and suppressing weeds, thereby creating a more favorable soil environment for crop growth (Verma *et al.*, 2023).

The selection of suitable high-yielding varieties adapted to local agroecological

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conditions is essential for improving productivity (Gairhe *et al.,* 2017). Likewise, proper tillage management is particularly important for potato because root and tuber crops are highly sensitive to soil compaction, which can restrict root development and tuber expansion (Howeler *et al.,* 1993). Although conventional tillage is commonly practiced in potato cultivation, it is energy-intensive and increases the risk of soil erosion (Boligłowa and Gleń, 2003). Moreover, intensive tillage can contribute to soil degradation, nutrient losses through nitrate leaching, and accelerated erosion, ultimately threatening the long-term sustainability of potato production systems (Begum *et al.,* 2024). In addition, the genetic makeup of potato varieties strongly influences yield potential and quality traits, highlighting the importance of evaluating varietal performance under different tillage regimes (Filipović *et al.,* 2025).

Potato varieties differ considerably in their growth, yield and quality characteristics, including plant height, leaf number, maturity period, tuber size, tuber yield, disease resistance and resilience to changing climatic conditions. In Nepal, commonly cultivated potato varieties include Janakdev, Desiree, Myagdi Local, Mustang Local, Kufri Jyoti and Khumal Ujjwal (Neupane *et al.,* 2019). The performance of these varieties varies across agroecological regions, highlighting the need for location-specific evaluation and selection. To address this need within the lowland plains, this study specifically evaluated two major hill-adapted cultivars (Kufri Jyoti and Khumal Ujjwal) alongside a specialized Terai-released variety (IPY-8) to determine their site-specific suitability under the winter climate of Jhapa.

With increasing scarcity of labor, water and other agricultural inputs, conservation-oriented soil management practices are gaining importance as sustainable approaches to potato production (Alam *et al.,* 2017). Furthermore, inadequate access to improved varieties and limited adoption of appropriate cultivation technologies continue to constrain potato productivity, resulting in challenges related to crop growth, yield, harvesting efficiency and post-harvest quality (Schulte-Geldermann, 2025). Since production cost in potato cultivation are largely influenced by the production technology employed, the adoption of suitable and resource-efficient management practices is essential for reducing costs and enhancing farm profitability (Kalimullin *et al.,* 2019). Therefore, this study was conducted to evaluate the effects of different potato varieties and tillage methods on the growth and yield performance of potato under the agroecological conditions of Jhapa, Nepal, and to identify suitable variety–tillage combinations for improved and sustainable potato production.

MATERIALS AND METHODS

Experimental site

The experiment was carried out at the Horticulture research field of IAAS, Gauradaha Agriculture Campus, Gauradaha, Jhapa, which is situated about 11 km south from Padajungi, Jhapa, Nepal, at latitude 26.56°N, longitude 87.72°E, and altitude 79 meters above sea level. The study area is characterized by a tropical monsoon climate, with generally warm temperatures and high humidity throughout the year.

Temperatures typically range from about 16.4°C during the cooler winter months to around 30°C in summer. Annual rainfall varies between 1500 and 2000 mm, with the majority occurring during the monsoon period from June to September. This seasonal distribution results in humid conditions with frequent cloud cover during the rainy season, followed by relatively drier and clearer weather from November to February.

Treatment details

Experiment details

The experiment was conducted using a two-factor factorial Randomized Complete Block Design (RCBD), with variety (Kufri Jyoti, Khumal Ujjwal, and IPY-8) as Factor A and tillage practice (zero, minimum, and conventional) as Factor B. The field was divided into three blocks, each containing nine plots, making a total of 27 plots. Each plot measured 3 × 1.5 m with spacing of 60 cm between rows and 30 cm between plants, accommodating five rows and 25 plants per plot. Spacing between replications and treatments was maintained at 1 m and 0.5 m, respectively, covering a total area of 192.5 m^2 (17.5 m × 11 m). For land preparation, conventional tillage plots were thoroughly ploughed and prepared before planting. In minimum tillage plots, soil disturbance was limited to digging planting spots only, while in zero tillage plots, potato tubers were planted without any prior soil disturbance. Details of treatments are given in Table 1.

Crop management

Intercultural operations were carried out throughout the crop period. Mulching was done in all plots immediately after planting using rice straw to conserve moisture, control weeds, and protect against adverse conditions, and an additional layer was added at 45 days after planting. Pre-sowing irrigation was applied lightly to maintain soil moisture, followed by irrigation at 30 days after planting and then at 15-day intervals, which was stopped two weeks before harvesting. 0.5 tons of FYM was added before planting to improve soil health. A recommended dose of 220:140:140 kg NPK/ha was applied, where nitrogen was applied in two splits (half dose at planting and remaining half dose at 45 days after planting) and full dose of phosphorus and potassium was applied at planting (AITC, 2024). Weed management included first weeding at 30 days after planting, followed by weekly hand weeding and regular removal of weeds from bunds and surrounding areas. Insect incidence was negligible, so no control measures were taken. However, early symptoms of late blight were observed and controlled by spraying copper oxychloride 50% WP at 3 g/L. Manual harvesting was done at 98 days after planting by removing mulch and carefully lifting the plants. Samples were then evaluated for tuber weight, diameter, yield, green tuber number and total tuber number.

Table 1. Details of treatments used in the study at Jhapa

S.N.	Notation	Treatment Detail
1	T1	Kufri Jyoti × Zero Tillage
2	T2	Kufri Jyoti × Minimum Tillage
3	T3	Kufri Jyoti × Conventional Tillage
4	T4	Khumal Ujjwal × Zero Tillage
5	T5	Khumal Ujjwal × Minimum Tillage
6	T6	Khumal Ujjwal × Conventional Tillage
7	T7	IPY-8 × Zero Tillage
8	T8	IPY-8 × Minimum Tillage
9	T9	IPY-8 × Conventional Tillage

Data collection

Data were recorded from five randomly selected plants per plot, excluding border plants. Sample plants were tagged for repeated observations. Data on sprout number, plant height, canopy spread and leaf number were taken at the interval of 15 days starting from 45 days after planting. Canopy spread was measured in two directions (north-south and east-west), and the mean canopy spread was calculated. Tuber diameter was measured using vernier calipers. Tuber weight was measured using a weighing balance. For green tubers, those with more than 50% greening were classified as green.

Post-harvest data included yield, tuber weight, tuber diameter, total tuber number, and number of green tubers.

Statistical analysis

Data collected from the experimental plots were organized using Microsoft Excel 2019, and all statistical analyses were performed in R (version 4.4.1). The coefficient of variation (CV), standard error of the mean (SEM), and least significant difference (LSD at 5%) were calculated. Treatment means were compared for significant differences using Duncan's Multiple Range Test (DMRT) at a 5% probability level ($p \leq 0.05$).

RESULTS AND DISCUSSION

Plant height (cm)

Table 2. depicts that plant height at 45, 60 and 75 days after plantation was significantly affected by varieties. Maximum plant height 49.47 cm, 66.93 cm, and 73.40 cm was observed in variety Khumal ujjwal at 45, 60, and 75 days after planting, respectively. Similar observations were reported by Shrestha *et al.* (2023) in Bajhang district, where potato varieties significantly influenced vegetative growth parameters, including sprout number, plant height, leaf number, and canopy spread.

Table 2. Effect of different varieties and tillage methods on plant height (cm) of potato at Gauradaha, Nepal during the year 2025.

Treatments	Plant height (cm)		
Varieties	45 DAP	60 DAP	75 DAP
Kufri jyoti	37.64^{b}	52.91^{b}	57.36^{b}
Khumal ujjwal	49.47^{a}	66.93^{a}	73.40^{a}
IPY-8	32.73^{b}	48.53^{b}	59.73^{b}
F- test	***	***	*
LSD	5.41	5.36	7.89
	Tillage		
Zero tillage	36.00^{b}	52.31^{b}	58.87^{b}
Minimum tillage	42.71^{a}	57.47^{ab}	64.82^{ab}
Conventional tillage	41.13^{ab}	58.60^{a}	66.80^{a}
F-test	*	*	*
LSD	5.41	5.36	7.80
Mean	39.95	56.13	63.43
SEM	2.58	2.54	3.7
CV	11.18	7.86	10.11

Source: Field test, 2025
*Significant at 5% level of significance, ** significant at 1%level of significance, ***significant at 0.1% level of significance, NS: Not significant, LSD: Least significant difference, CV: Coefficient of variation

Likewise, there was a significant difference in plant height due to different tillage methods. At 45 days after planting, maximum height (42.72 cm) was observed in Minimum tillage. Meanwhile at 60 and 75 days after planting, maximum height (58.6 and 66.8 cm respectively) was recorded in Conventional tillage. Conventional tillage improves soil aeration and creates favorable conditions for microbial activity, which can enhance nutrient mineralization and availability to plants (Subbulakshmi *et al.*, 2009). These improved soil conditions may have promoted root development and nutrient uptake, thereby supporting greater vegetative growth and plant height under conventional tillage. Minimum height (36 cm, 52.31 cm, and 58.87 cm at 45, 60, and 75 DAP respectively) was observed in zero tillage.

Number of leaves

Number of leaves at 45 and 75 days after planting was significantly affected by variety but at 60 days after planting it was not significantly affected by variety. According to table 3. highest leaf number was recorded 37.95 in Kufri jyoti at 45 days where Variety IPY-8 showed minimum leaf number of 27.40. But at 75 days after planting, IPY-8 variety showed maximum number of leaf (115.48). Likewise, number of leaves at 45 and 60 days after planting was significantly affected by the type of tillage method adopted. Highest number of leaves (40.69) was observed in

Table 3. Effect of different varieties and tillage methods on number of leaves of potato at Gauradaha, Nepal during the year 2025.

Treatments	Number of leaves		
Varieties	45 DAP	60 DAP	75 DAP
Kufri jyoti	37.96[a]	66.09	73.20[b]
Khumal ujjwal	37.84[a]	66.82	77.38[b]
IPY-8	27.40[b]	69.82	115.49[a]
F test	**	NS	**
LSD	7.89	15.48	32.04
Tillage			
Zero tillage	31.73[b]	63.80[ab]	93.31
Minimum tillage	40.69[a]	78.09[a]	89.78
Conventional tillage	30.78[b]	60.84[b]	82.98
F test	**	*	NS
LSD	7.83	15.49	32.02
Mean	34.4	67.58	88.69
SEM	3.75	12.72	15.2
CV	18.87	18.86	29.72

Source: Field test, 2025
*Significant at 5% level of significance, **significant at 1%level of significance, ***significant at 0.1% level of significance, NS: Not significant, LSD: Least significant difference, CV: Coefficient of variation

Table 4. Effect of different varieties and tillage methods on canopy spread (cm) of potato at Gauradaha, Nepal during the year 2025

Treatments / Variety	Canopy spread (cm)		
	45 DAP	60 DAP	75 DAP
Kufri jyoti	37.50[a]	53.61[a]	63.30[b]
Khumal ujjwal	42.68[a]	60.44[a]	72.97[a]
IPY-8	28.50[b]	42.56[b]	61.62[b]
F test	***	***	**
LSD	6.64	7.25	8.53
Tillage			
Zero tillage	33.73	48.66	61.98
Minimum tillage	39.32	54.53	70.59
Conventional tillage	35.62	53.42	65.32
F test	NS	NS	NS
LSD	6.64	7.25	8.53
Mean	36.23	52.27	65.96
SEM	3.15	3.44	4.04
CV	15.04	11.42	10.63

Source: Field test, 2025
*Significant at 5% level of significance, ** significant at 1%level of significance, ***significant at 0.1% level of significance, NS: Not significant, LSD: Least significant difference, CV: Coefficient of variation

Minimum tillage at 45 days and 78.08 at 60 days after plantation.

Canopy spread

Canopy length at 45, 60 and 75 days after planting was significantly affected by variety. Table 4. Shows that maximum canopy length (42.68 cm, 60.45 cm, and 72.97 cm at 45, 60 and 75 days after planting, respectively) was observed in variety Khumal Ujjwal. At 45 and 60 days, varieties Khumal Ujjwal and Kufri jyoti were statistically similar. Meanwhile, at 75 days after plantation, Varieties Kufri jyoti and IPY-8 were statistically at par.

But there was no significant difference in canopy spread at 45, 60 and 75 days after plantation due to the type of tillage method adopted. This contradiction of results from previous findings may be due to the delayed effect of tillage, genetic control and environmental conditions on sprout number and canopy spread (Scavo *et al.*, 2023).

Yield (ton/ha), tuber weight (g), tuber diameter (cm)

Table 5. clarifies that yield(ton/ha), individual potato weight (gm) and potato diameter (cm) were significantly affected by the variety. Highest yield (15.4 ton/ha) was observed in variety Khumal ujjwal which is statistically similar to variety Kufri jyoti (14t/ha). Lowest yield (5.7 t/ha) was seen in variety IPY-8. This aligns with the findings of Banjade *et al*. (2019), who demonstrated that the choice of potato variety directly influences yield parameters.

Likewise, Individual tuber weight and tuber diameter was recorded highest in Khumal ujjwal which was 74.60 gm and 5.26 cm respectively. Least potato weight (40.56

Table 5. Effect of different varieties and tillage methods on yield (ton/ha), tuber weight (g), and tuber diameter (cm) of potato at Gauradaha, Nepal during the year 2025.

Varieties	Yield (ton/ha)	Tuber weight (g)	Tuber diameter (cm)
Kufri jyoti	14.07[a]	67.44[a]	4.81[b]
Khumal ujjwal	15.43[a]	74.60[a]	5.23[a]
IPY-8	5.65[b]	40.56[b]	3.98[c]
F test	***	**	***
LSD	3.49	25.81	0.36
Tillage			
Zero tillage	9.74	55.27	4.52
Minimum tillage	13.34	71.33	4.76
Conventional tillage	11.97	56	4.84
F test	NS	NS	NS
LSD	3.49	25.81	0.36
Mean	11.74	60.87	4.64
SEM	1.65	12.25	0.17
CV	24.51	34.89	6.35

Source: Field test, 2025
*Significant at 5% level of significance, ** significant at 1%level of significance, ***significant at 0.1% level of significance, NS: Not significant, LSD: Least significant difference, CV: Coefficient of variation

Table 6. Effect of different varieties and tillage methods on total tuber number and number of green tubers of potato during the year 2025.

Varieties	Green tuber	Total tuber number
Kufri jyoti	4.78[a]	8.40[a]
Khumal ujjwal	3.29[b]	6.58[ab]
IPY-8	2.42[b]	5.49[b]
F test	***	*
LSD	1.26	2.40
Tillage		
Zero tillage	4.82[a]	7.22
Minimum tillage	3.58[a]	6.80[a]
Conventional tillage	2.09[b]	6.44
F test	***	NS
LSD	1.26	2.40
Mean	3.46	6.82
SEM	0.6	1.14
CV(%)	29.68	28.96

Source: Field test, 2025
*Significant at 5% level of significance, ** significant at 1%level of significance, ***significant at 0.1% level of significance, NS: Not significant, LSD: Least significant difference, CV: Coefficient of variation

gm) and diameter (3.99 cm) were recorded in variety IPY-8. Meanwhile, there was no significant difference in yield (t/ha), individual potato weight (gm) and potato diameter (cm) due to method of tillage practice adopted.

Total tuber number and number of green tubers

Total number of tuber and number of green tubers were significantly affected by the variety used. Highest number of green tuber (4.78) was seen in variety Kufri jyoti and lowest number of green tuber (2.42) was observed in variety IPY-8. Likewise, maximum tuber number (8.4) was observed in variety Kufri jyoti and minimum number of tuber (5.48) were observed in variety IPY-8 according to table 6.

Number of green tubers was significantly affected by the type of tillage practice, but, total number of tubers was not significantly affected. Highest number of green tuber (4.82) was observed in zero tillage and lowest number of green tuber (2.08) was recorded in conventional tillage. Zero tillage and minimum tillage were statistically at par. Greening in potato is caused by accumulation of chlorophyll due to exposure of light (Tanios *et al.*, 2018). Since, in zero tillage seed potatoes were not covered by soil, light easily entered to the potato and caused greening.

Interaction effects

Table 7. depicts that there was no significant difference in plant height, sprout number, and canopy spread due to the interaction of tillage and variety. Likewise, yield parameters such as total yield(t/ha), tuber number, tuber diameter and individual tuber weight, were not significantly influenced

Table 7. Interaction effects of variety and tillage method on yield and number of green tubers during the year 2025.

Interaction	Yield	Number of green tubers
Kufri Jyoti × Zero tillage	10.80	7.40[a]
Kufri Jyoti × Minimum tillage	12.87	4.47[ab]
Kufri jyoti × conventional tillage	5.61	2.60[bc]
Khumal Ujjwal × Zero tillage	14.09	3.60[bc]
Khumal Ujjwal × Minimum tillage	19.26	3.73[bc]
Khumal Ujjwal × Conventional tillage	6.77	3.40[bc]
IPY-8 × Zero tillage	17.14	3.33[bc]
IPY-8 × Minimum tillage	14.09	1.67[bc]
IPY-8 × Conventional tillage	4.72	1.27[c]
F test	NS	*
LSD	8.34	3.01
Mean	11.74	3.46
SEM	1.65	0.6
CV	24.51	29.68

Source: Field test, 2025
*Significant at 5% level of significance, **significant at 1%level of significance, ***significant at 0.1% level of significance, NS: Not significant, LSD: Least significant difference, CV: Coefficient of variation

by the interaction between variety and tillage method. OR *et al.* (2022), observed that interaction of variety and tillage has no impact on growth and yield of sweet potato varieties which aligns with our findings.

CONCLUSION

Based on the findings of this research, variety has more influence on vegetative and reproductive growth compared to the tillage method. From this research result, it can be concluded that variety Khumal Ujjwal is superior since it showed maximum height, canopy spread, maximum yield, tuber weight, and tuber diameter. Among different tillage methods, minimum tillage is best as it reduces the cost of production and highest leaf number and tuber yield was observed on it. The choice of tillage practice did not show any effect on yield parameters except number of green tubers. Highest number of green tubers were observed on zero tillage, so to produce potato with less tedious cultural practices and low cost, thick layer of mulching should be applied in order to reduce exposure to sunlight. Combination of variety Khumal Ujjwal and minimum tillage is recommended for sustainable potato production in Jhapa, Nepal.

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CONFLICTS OF INTEREST

The author declare that there is no conflict of interest regarding the publication of this manuscript.

ETHICAL STATEMENT

This study did not involve any animal or human participant and thus ethical approval was not applicable.

AUTHOR CONTRIBUTION STATEMENT

S.B. conducted the experiment, collected and analyzed the data, and prepared the first draft of the manuscript. J.D. conceived and supervised the study, provided guidance on experimental design and data interpretation, and reviewed and edited the manuscript. Both authors read and approved the final manuscript.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author

SUPPLEMENTARY DATA

No supplementary data is available for the paper.

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PHENOTYPIC AND MOLECULAR VARIABILITY AMONG *ALTERNARIA SOLANI* CAUSING POTATO EARLY BLIGHT IN GUJARAT, INDIA

JV Patel[1*], NM Gohel[2], NB Patel[3] and Tejas C. Bosamia[4]

ABSTRACT: Early blight, caused by *Alternaria solani*, is an important foliar disease of potato and can cause substantial yield losses. This study assessed phenotypic and molecular variability among thirty-six *A. solani* isolates collected from major potato-growing regions of Gujarat, India. Thirty-six *Alternaria* isolates obtained from six major potato-growing districts of Gujarat exhibited substantial cultural, morphological and molecular variability. Conidial dimensions varied from 12.5–89.4 × 4.6–30.5 µm on potato dextrose agar and from 12.1–82.4 × 4.1–27.7 µm on Richard's agar. ITS1/ITS4 amplification and sequencing of representative isolate As1 produced an amplicon of approximately 540 bp and showed 98–99% similarity with *A. solani* sequences in Gen Bank, supporting its identification. RAPD analysis of all 36 isolates using five informative primers generated 30 scorable loci, of which 28 were polymorphic (93.3%). UPGMA analysis resolved the isolates into two major clusters. AMOVA attributed 20% of molecular variation to differences between the two geographic populations and 80% to variation within populations. The results demonstrate substantial phenotypic and RAPD-based genetic variability in the Gujarat isolate collection and provide baseline information relevant to pathogen surveillance, resistance breeding and early-blight management.

KEYWORDS: *Alternaria solani*, early blight, pathogen diversity, ITS-rDNA, RAPD marker

INTRODUCTION

Potato (*Solanum tuberosum* L.) is one of the world's most important food crops and an important source of carbohydrates, vitamins and minerals. In India, potato cultivation contributes substantially to agricultural production and food security. Its productivity, however, is constrained by several diseases, among which early blight caused by *Alternaria solani* is economically important. The pathogen also infects other solanaceous crops, including tomato, brinjal and chilli. It can survive between cropping seasons in infected plant debris, infected tubers and soil, thereby providing inoculum for subsequent crops (Rotem, 1998). Early blight affects leaves, stems and tubers and consequently reduces both yield and marketable quality.

Yield losses of 30–50% have been reported under severe disease conditions (Rouse, 1985), while Haware (1968) reported losses of up to 40%. Several *Alternaria* species infect solanaceous crops. Large-spored species include

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A. solani, *A. grandis*, *A. protenta* and *A. linariae*, while *A. alternata* and the *A. arborescens* complex represent small-spored species. *Alternaria solani* is the predominant cause of potato early blight, although other large-spored species may also cause similar symptoms (Adhikari *et al*., 2020; Ivanovic *et al*., 2022).

The disease initially appears as small, dark-brown lesions that enlarge and develop characteristic concentric rings, producing a target-like appearance. Progressive lesion development causes premature defoliation, reduces the photosynthetically active leaf area and ultimately diminishes tuber development and yield (Van der Waals *et al*., 2001). Identification of *A. solani* has traditionally been based on cultural and morphological characteristics, including colony colour, colony texture, growth pattern, conidial dimensions and septation (Ellis, 1971). However, these phenotypic characteristics may vary with the isolate, culture medium, temperature, light regime and age of the culture. Morphological observations alone may therefore be insufficient to assess relationships among isolates.

The internal transcribed spacer region of ribosomal DNA is widely used for fungal identification and DNA barcoding (Nilsson *et al*., 2009; Schoch *et al*., 2012). Nevertheless, the ITS region may have limited discriminatory power among closely related species of *Alternaria*, and multilocus or genome-wide markers generally provide stronger taxonomic and population-level resolution (Adhikari *et al*.,2021; Schmey *et al*.,2024). Random amplified polymorphic DNA markers can provide an initial and relatively inexpensive assessment of DNA polymorphism within a pathogen collection, provided that amplification conditions are standardized and only clear and reproducible bands are scored. The combined evaluation of cultural, morphological and molecular characteristics can therefore provide a broader understanding of variability within an *A. solani* collection than any single approach.

Early blight is widely observed in the principal potato-growing regions of Gujarat. However, comparative information on the cultural, morphological and genetic variability of *A. solani* isolates from geographically separated locations in the state remains limited. This constitutes an important knowledge gap because variability within a pathogen population may influence disease development, host–pathogen interactions, identification of resistant germplasm and the durability of disease-management practices. Characterization of isolates representing different potato-growing regions is therefore required to determine the extent of variability present in the local pathogen population and to provide baseline information for future epidemiological and resistance-breeding studies.

Accordingly, the present investigation aimed to characterize *A. solani* isolates collected from the major potato-growing districts of Gujarat. The specific objectives were: (i) to compare the cultural characteristics of the isolates on potato dextrose agar and Richard's agar (ii) to compare the morphological characteristics of the isolates on potato dextrose agar and Richard's agar (iii) to support the identity of a representative isolate through ITS-rDNA sequencing (iv) to assess RAPD-based genetic diversity and relationships among the 36 isolates.

MATERIALS AND METHODS

Collection of Diseased Samples/Isolates

Thirty-six isolates of *A. solani* were collected during November 2022 from major potato-growing districts of Gujarat, namely Anand, Kheda, Gandhinagar, Aravalli, Sabarkantha and Banaskantha (Table 1).

Table 1. Sources of isolates of *A. solani* collected from the major potato growing regions of Gujarat

Sr. No.	Isolate No.	Region	District	Taluka	Place	GPS Location
1	As1	Middle Gujarat	Anand	Anand	Anand-1	22.536471°N 72.980321°W
2	As2				Anand-2	22.536636°N 72.982272°W
3	As3				Bakrol	22.573503°N 72.910713°W
4	As4				Lambhvel	22.591490°N 72.937305°W
5	As5				Boriyavi	22.616162°N 72.932162°W
6	As6				Khambhodaj	22.575454°N 73.087227°W
7	As7		Kheda	Nadiad	Narsanda	22.627235°N 72.887928°W
8	As8				Chaklasi	22.657834°N 72.944251°W
9	As9				Kanjari	22.622818°N 72.913822°W
10	As10				Vadtal	22.5980023°N 72.872672°W
11	As11			Kathalal	Shahpur	22.902035°N 73.017003°W
12	As12			Kapadvanj	Unda ni muvadi	22.980844°N 73.010760°W
13	As13				Kevadiya	23.083597°N 72.992592°W
14	As14		Gandhinagar	Dehgam	Khanpur	23.233534°N 72.896837°W
15	As15				Rakhiyal	23.255550°N 72.903576°W
16	As16				Babalpura	23.214071°N 72.864214°W
17	As17	North Gujarat	Aravalli	Bayad	Borol	23.238635°N 73.219916°W
18	As18				Madhav kampo	23.192463°N 73.228671°W
19	As19				Demai	23.175435°N 73.206352°W
20	As20				Bhukhel	23.245282°N 73.183691°W
21	As21				Bibipura	23.267255°N 73.218824°W
22	As22		Sabarkantha	Prantij	Dhanpura kampa	23.238320°N 73.081441°W
23	As23				Vadrad	23.432129°N 72.893863°W

Sr. No.	Isolate No.	Region	District	Taluka	Place	GPS Location
24	As24				Dalpur	23.515901°N 72.928882°W
25	As25			Bhiloda	Bhavanath	23.787943°N 73.244761°W
26	As26			Idar	Kanpur	23.832948°N 73.100565°W
27	As27				Gorol	23.875795°N 73.129281°W
28	As28				Badoli	23.846663°N 73.068925°W
29	As29				Netramani	23.852467°N 72.967876°W
30	As30			Vadali	Chorivad	23.929413°N 73.125230°W
31	As31		Banaskantha	Deesa	Deesa-1	24.286991°N 72.156044°W
32	As32				Aseda	24.211109°N 72.209240°W
33	As33				Deesa-2	24.267374°N 72.178397°W
34	As34			Dantiwada	Dantiwada	24.325896°N 72.332206°W
35	As35				Nani bhakhar	24.280839°N 72.299247°W
36	As36				Vagharol	24.085406°N 72.244315°W

The survey was undertaken specifically for pathogen collection and characterization rather than for quantitative estimation of disease prevalence. Fields were selected based on the presence of characteristic early-blight symptoms. Potato leaves showing typical early-blight symptoms were collected and transported to the laboratory. The pathogen was isolated from symptomatic tissue by tissue isolation and purified by the hyphal-tip method. Pure cultures were maintained on PDA slants at 4°C. Isolates were identified on the basis of cultural and morphological characters described by Ellis (1971).

Pathogenicity of *A. solani* isolate As1 was tested on 30-day-old potato plants (cv. Kufri Lauvkar) under glasshouse conditions. Plants were raised in 30-cm earthen pots containing sterilized soil and farmyard manure (3:1). After surface sterilization with 1% sodium hypochlorite and washing with sterile distilled water, the leaves were spray-inoculated in the evening with a conidial suspension containing 2×10^6 conidia mL^{-1}. Ten replications and an uninoculated control sprayed with sterile distilled water were maintained. All plants were covered with polyethylene bags for 48 h to maintain high humidity. Disease development was recorded periodically. The pathogen was re-isolated from symptomatic leaves on PDA and compared with the original culture to fulfil Koch's postulates.

Cultural and morphological identification of the pathogen

All 36 isolates were cultured on PDA and Richard's agar and incubated at 28 ± 1°C. Colony colour, topography of colony, colony margin, sporulation and hyphal measurement were recorded during 15 days of incubation. Morphological observations were made from 10-day-old cultures. Conidial length and breadth, beak length and breadth and septation were measured under a compound microscope at high magnification. Representative structures were photographed. Identification was based on comparison with the diagnostic description of *A. solani* given by Ellis (1971).

Molecular characterization

Extraction of DNA:

By using the Cetyl Trimethyl Ammonium Bromide (CTAB) technique, genomic DNA was isolated from 36 pure cultures of *Alternaria* sp. (Fig 1B) for the extraction of the fungal DNA 300 mg fungal mycelium from seven days old culture grown on PDA was ground to a fine powder in liquid nitrogen (LN2), using a pre- sterilized mortar and pestle. 1 milliliter of pre-warmed CTAB extraction buffer was added in mortar and pestle and crushed up to sample turned in to liquid. The tubes were incubated in a laboratory water bath at 65 °C for 1 hour with frequent swirling. All of the tubes were filled with an equal volume of chloroform: isoamyl alcohol (24:1) and centrifuged for 15 min at 12,000 rpm at 4 °C to separate the clear phases. The supernatant was precipitated with a double volume of absolute ethanol and mixed properly. The tubes were incubated overnight at -20 °C to precipitate DNA. After overnight incubation, the sample was centrifuged (Themofisher Scientific, Sorvall Legend MicroCL 17R)at 12,000 rpm for 15 min at 4 °C. The supernatant was discarded and 200 µl of 70 per cent ethanol was added to wash the pellet and centrifuged at 6,000 rpm at 4 °C for 8 minutes. The ethanol was removed completely and the pellet was allowed to air dry on tissue paper for 5 to 10 minutes. The pellet was dissolved into 50 µl of TE buffer. 0.8 µl RNase was added to the dissolved DNA stock and incubated in a water bath at 37 °C for 45 min followed by 65 °C for 10 minutes for enzyme inactivation. The purity of the DNA was determined using 0.8% agarose gels and a Nano-drop (Gel Doc™ XR+ Imaging System (Bio-Rad Laboratories, Hercules, California, USA).

Primers used:

PCR amplification: PCR was performed with ITS-1 (5'- TCCGTAGGTGAAC CTGCGG-3') and ITS-4 (5'-TCCTCCGCTTATTGATATG C-3') (White *et al.*, 1990) as forward and reverse reaction to amplify rDNA-ITS region. Tubes were placed in thermal cycler for 35 cycles of PCR. The program consisted of three distinct steps: Denaturation 95°C 5 min, , annealing 36-38°C 45 sec, extension 72°C 45 sec, final extension 72°C 10 min.

Random amplification of polymorphic DNA (RAPD) analysis

The RAPD primers used for the analysis of random amplification of polymorphic DNA to study the polymorphism present in the isolates of *A. solani*. Total of 20 decamer primers belonging to OPA, OPB, OPC and OPE each series were screened for RAPD analysis Among 80 primers, 5 primers (OPA 11, OPA 12, OPB 9, OPC 6 and OPE 1) were selected based on repeatability. In a 2% agarose gel electrophoresis, the amplified products were seen. A gel documentation system (BioRad, USA) to acquire the digital photos.

Data scoring

The data were scored based on the presence (1) or absence (0) for analysis. If a product was present in an isolate it was considered as '1' and if absent, was considered as '0'. The data were maintained in the excel sheet format for further analysis. The polymorphism percentage was calculated as per the method suggested by (Blair *et al*., 1999).

$$\text{Polymorphism (\%)} = \frac{\text{(Total number of bands - Number of monomorphic bands)}}{\text{Total number of bands}} \times 100$$

Data analysis and dendrogram

The scores were then entered into a matrix for analysis by the numerical taxonomy and multivariate analysis system. The data generated and dendrogram was drawn in NTSYS-pc 1.8 program (Applied Biostatistics Inc., Setauket, NY, USA) (Rohlf, 1993). Clustering was performed using the unweighted pair group method using arithmetic averages (UPGMA).

RESULTS AND DISCUSSION

Isolation and pathogenicity

Thirty-six isolates were recovered from potato leaves showing characteristic early-blight symptoms collected from different potato-growing locations in Gujarat. The purified isolates were evaluated for cultural and morphological variability, while isolate As1 was selected as a representative isolate for pathogenicity and ITS-rDNA sequencing.

Spray inoculation of isolate As1 on potato cv. Kufri Lauvkar produced brown, round-to-oval necrotic lesions with characteristic concentric rings 15 days after inoculation, whereas the control plants remained symptomless. The fungus was successfully re-isolated from the inoculated leaves, and the recovered culture corresponded morphologically with the original culture, thereby fulfilling Koch's postulates and confirming the pathogenicity of isolate As1. Similar development of early-blight lesions following artificial inoculation and successful re-isolation of *A. solani* has been reported in potato and tomato by Nuwamanya *et al*., (2022) and Abdel-Hamid *et al*. (2023). However, because only As1 was tested, the pathogenicity result applies specifically to this representative isolate and does not establish differences in aggressiveness among all 36 isolates.

Identification of Pathogen through Internal Transcribed Spacer (ITS) Region

Amplification of the ITS-rDNA region of representative isolate As1 with primers ITS1 and ITS4 produced an amplicon of approximately 540 bp (Fig 1A). A BLAST comparison showed 98–99% sequence identity with the closest *A. solani* reference sequences. The sequence was deposited in GenBank under accession number MZ557830. The ITS result, together with the cultural and morphological characteristics and pathogenicity of As1, supported its identification as *A. solani*.

The ITS region is commonly used for fungal DNA barcoding; however, its ability to distinguish closely related large-spored *Alternaria* species may be limited. Ivanovic *et al*. (2022) demonstrated that potato early-blight symptoms can be associated with *A. solani*, *A. protenta*, *A. grandis* and *A. linariae*, which were differentiated using more informative loci such as GAPDH, calmodulin and RPB2. Therefore, the present ITS result should be regarded as supporting the identification of representative isolate As1 rather than independently confirming every isolate in the collection. Multilocus sequencing of representative isolates from the

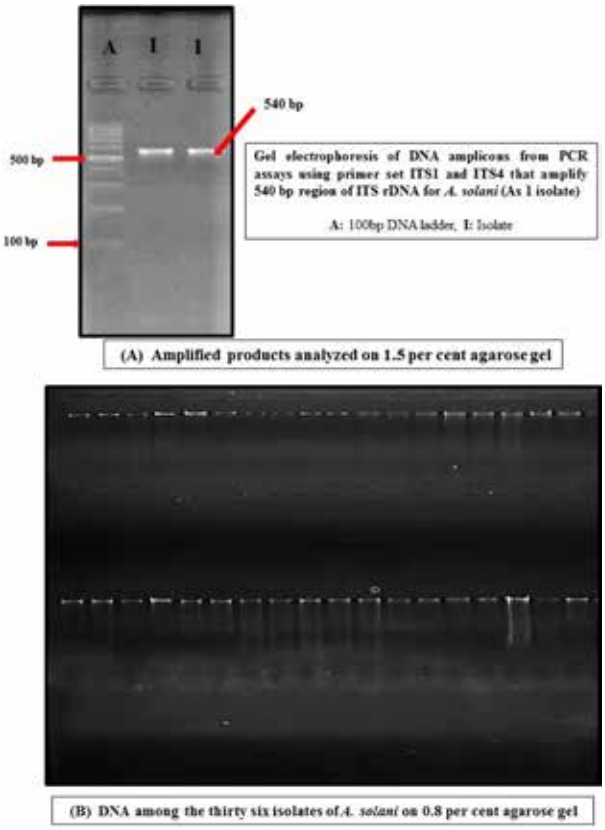


Fig 1A: Amplified product of As-1 isolate
Fig 2A: DNA of thirty-six isolates

cultural and RAPD groups would provide stronger species-level resolution.

Cultural Characterization of *Alternaria solani*:

Potato dextrose agar

Considerable cultural variability was observed among the 36 isolates on PDA. Fluffy growth was predominant (52.78%), followed by aerial (36.11%) and flat growth (11.11%). Smooth, regular margins were most frequent (41.67%), while rough regular and rough irregular margins each accounted for 25.00%. Colony pigmentation was highly variable: the black-grey/grey-to-black group was most frequent (36.11%), followed by greyish-black (19.44%) and dark-black-to-white colonies (16.67%) (Table 2).

Table 2. Frequency distribution of cultural characters of isolates on PDA medium

Sr. no	Topography	Number of isolates	Percentage
	A. Colony Topography		
1	Fluffy	19	52.78
2	Aerial	13	36.11
3	Flat	4	11.11
Total		36	100.00
	B. Type of margin		
1	Smooth Regular	15	41.67
2	Smooth Irregular	1	2.78
3	Rough Regular	9	25.00
4	Rough Irregular	9	25.00
5	Smooth flat	2	2.56
Total		36	100.00
	C. Colony appearance		
1	Black grey/grey to black	13	36.11
2	Greyish black	7	19.44
3	Dark black to white	6	16.67
4	Dark black with white or grey center	4	11.11
5	Black to white	2	5.56
6	Greenish white	1	2.78
7	Whitish black	1	2.78
8	Dark grey	1	2.78
9	Dark greyish to white	1	2.78
Total		36	100.00

Richard's agar

On Richard's agar, fluffy growth was again predominant (50.00%), followed by flat (36.11%) and aerial growth (13.89%). Smooth, regular margins were most common (41.67%), whereas rough irregular and rough regular margins accounted for 19.44% and 13.89%, respectively. Olive-green colonies and their variants formed the largest pigmentation group (27.78%), followed by dark-black-to-brown/brown variants (25.00%) and green-to-brown/dark-green variants (22.22%) (Table 3).

Table 3. Frequency distribution of cultural and morphological characters of isolates on Richard's agar medium

1. Cultural characters			
A. Colony Topography			
Sr. no	Topography	Number of isolates	Percentage
1	Fluffy	18	50.00
2	Aerial	5	13.89
3	Flat	13	36.11
Total		36	100.00
B. Type of margin			
1	Smooth Regular	15	41.67
2	Smooth Irregular	3	8.33
3	Rough Regular	5	13.89
4	Rough Irregular	7	19.44
5	Regular flat	3	8.33
6	Irregular flat	3	8.33
Total		36	100.00
C. Colony appearance			
1	Olive green and its variants	10	27.78
2	Dark black to brown and brown variants	9	25.00
3	Green to brown and dark green variants	8	22.22
4	Black to grey and grey variants	5	13.89
5	Pale cream with olive-green margin	2	5.56
6	Dark brown	2	5.56
Total		36	100.00

Differences in the frequencies of growth patterns and colony pigmentation between the two media indicate that cultural expression was influenced by both isolate genotype and medium composition. The predominance of fluffy colonies was similar on both media, but aerial growth was more frequent on PDA, whereas flat growth was more frequent on Richard's agar. Comparable isolate-dependent variation in colony colour, growth pattern, margin and pigmentation has been reported among *A. solani* isolates by Mugao *et al*. (2021) and Nuwamanya *et al*. (2022). These studies also observed substantial phenotypic heterogeneity among isolates collected from different locations. Consequently, colony characteristics are useful for describing variability within an isolate collection but should not be used alone for definitive species identification.

Morphological Characterization of *Alternaria solani*:

Marked variation was recorded in conidial and beak dimensions among the isolates (Table 4). On PDA, conidial length ranged from 12.5 to 89.4 µm and conidial breadth from 4.6 to 30.5 µm. Beak length ranged from 4.9 to 43.4 µm, while beak breadth ranged from 0.6 to 9.5 µm. Isolate As25 exhibited the widest conidial-length range of 24.8–89.4 µm, whereas As12 included the lowest recorded conidial length, with a range of 12.5–51.8 µm.

Conidia produced on PDA contained up to three longitudinal and seven transverse septa. A longitudinal-septation range of 0–2 was most frequent and occurred in 17 isolates, whereas a transverse-septation range of 2–4 occurred in 16 isolates. Isolates As13 and As18 produced conidia with up to three longitudinal septa, while As18 exhibited the maximum of seven transverse septa.

On Richard's agar, conidial length ranged from 12.1 to 82.4 µm and breadth from 4.1 to 27.7 µm. Beak length ranged from 4.6 to 37.0 µm, while beak breadth ranged from 0.4 to 9.1 µm. Conidia produced on this

Table 4: Morphological characters of isolates on Potato Dextrose Agar and Richard's agar medium

Sr. no.	Character	PDA (Range)	Richard's agar (Range)
1	Conidial length (µm)	12.5–89.4	12.1–82.4
2	Conidial breadth (µm)	4.6–30.5	4.1–27.7
3	Beak length (µm)	4.9–43.4	4.6–37.0
4	Beak breadth (µm)	0.6–9.5	0.4–9.1
5	Vertical septa	0–3	0–4
6	Horizontal septa	2–7	0–7

medium contained up to four longitudinal and seven transverse septa. A longitudinal-septation range of 0–2 was observed most frequently, occurring in 19 isolates, whereas a transverse-septation range of 1–4 occurred in 12 isolates. Isolates As1 and As11 produced conidia with up to four longitudinal septa, while As1 showed the maximum of seven transverse septa.

Despite their quantitative variation, the isolates produced pigmented, muriform and beaked conidia consistent with the morphological description of large-spored *Alternaria*. Variation in conidial dimensions, septation and beak size among isolates grown under standardized conditions suggests substantial phenotypic heterogeneity within the Gujarat collection. Yadav and Pathak (2011), Marak *et al.* (2014), Pachori *et al.* (2016), Kaur *et al.* (2020), Mugao *et al.* (2021) and Nuwamanya *et al.* (2022) similarly reported significant isolate-to-isolate variation in conidial shape, dimensions and septation among *A. solani* isolates. The differences observed between PDA and Richard's agar in the present investigation also demonstrate that the culture medium can influence the expression of diagnostic morphological characteristics. Morphological measurements should therefore be interpreted in combination with pathogenicity and molecular evidence.

Molecular Characterization of *Alternaria solani* with the use of RAPD primers:

Of the 80 RAPD primers initially screened, five primers—OPA-11, OPA-12, OPB-09, OPC-06 and OPE-01—generated clear and reproducible amplification profiles and were selected for analysis of the 36 isolates. Together, these primers produced 30 scorable loci, of which 28 were polymorphic, corresponding to an overall polymorphism of 93.3% (Table 5). The number of loci amplified per primer ranged from five to seven. OPA-11, OPC-06 and OPE-01 showed 100% polymorphism, whereas OPA-12 and OPB-09 showed 83.3 and 85.7% polymorphism, respectively. OPA-11 exhibited the highest polymorphic information content of 0.44 and the highest resolving power of 4.22, indicating that it was the most informative of the five primers for differentiating the isolates (Fig 3).

The high proportion of polymorphic loci indicates considerable RAPD-based genetic variability among the Gujarat isolates. Molecular heterogeneity among *A. solani* isolates has also been reported using RAPD, AFLP, microsatellite and sequence-based markers. Abdel-Hamid *et al.* (2023) demonstrated RAPD-based differentiation among potato isolates of *A. solani* from different Egyptian locations. Adhikari *et al* (2020) detected high nucleotide diversity and

Table 5: RAPD marker characteristics, polymorphism and informativeness among 36 *A. solani* isolates

Sr. No.	Primers	Primer sequence (5'-3')	TB	TL	NPL	PP	PIC	Rp	MI
1	OPA 11	CAATCGCCGT	90	6	6	100.0	0.44	4.22	2.66
2	OPA 12	TCGGCGATAG	116	6	5	83.3	0.29	2.22	1.43
3	OPB 9	TGGGGGACTC	132	7	6	85.7	0.30	2.89	1.81
4	OPC 6	GAACGGACTC	102	6	6	100.0	0.39	3.44	2.33
5	OPE 1	CCCAAGGTCC	38	5	5	100.0	0.31	2.11	1.54
		Total	478	30	28	93.3	1.73	14.88	-

TB: total number of bands amplified across 36 isolates, TL: Total number of loci, NPL: number of polymorphic loci, PP: percentage polymorphism, PIC: polymorphic information content, Rp: resolving power, MI: marker index

admixed haplotypes among *Alternaria* species associated with potato and tomato, while Adhikari *et al.* (2021) reported high genotypic diversity within *A. solani* and related *Alternaria* populations. Collectively, these findings indicate that considerable genetic diversity can occur within geographically sampled *Alternaria* populations.

Clustering and PCoA

UPGMA analysis separated the 36 isolates into two major clusters, A and B. Cluster A contained nine isolates, including the distinct placement of As8, whereas cluster B contained the remaining 27 isolates distributed among several subclusters (Fig. 2) The clustering pattern

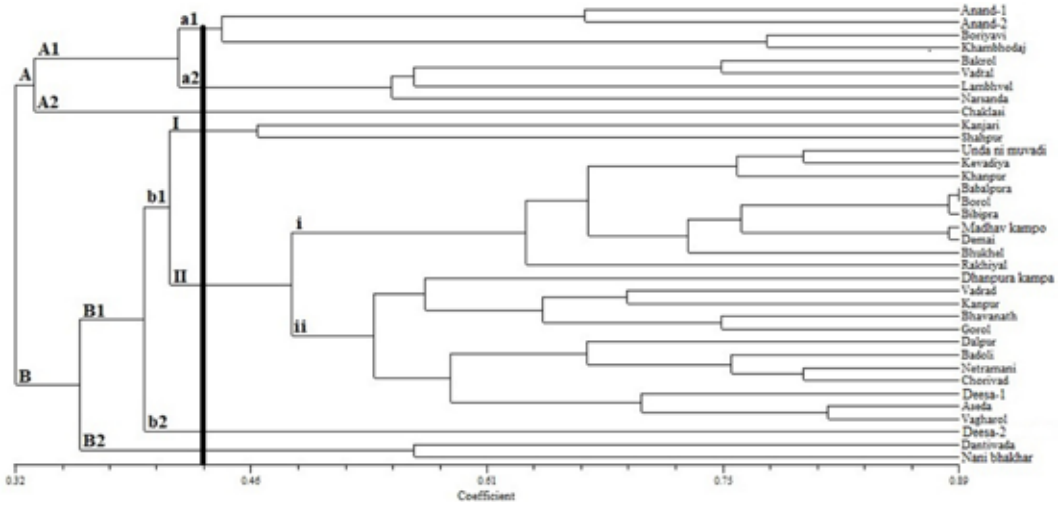


Fig 2: RAPD UPGMA dendrogram of thirty-six isolates of A. solani based on Jaccard's similarity coefficient

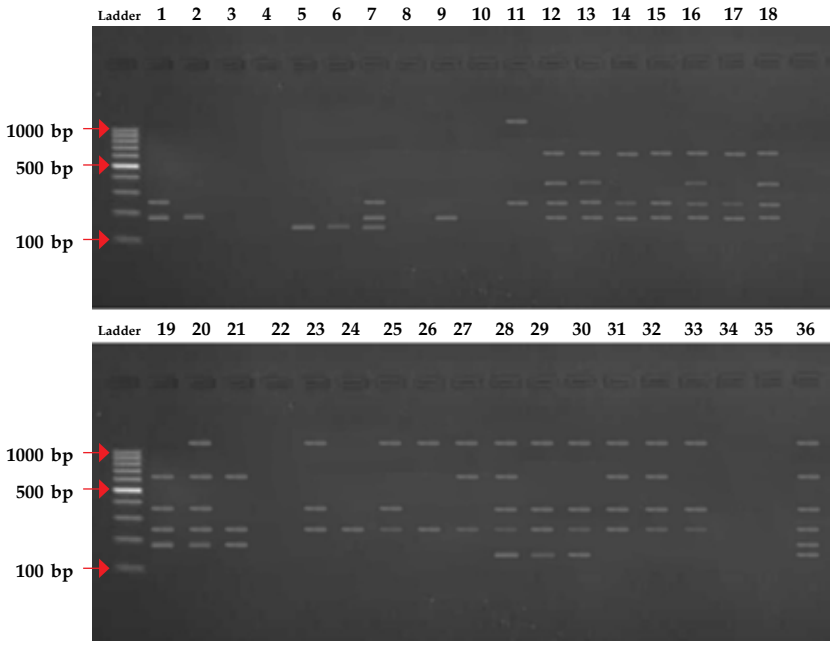


Fig 3: RAPD profile of OPA-11 primer

was not strictly associated with district of collection because isolates originating from different districts frequently occurred within the same subcluster. Conversely, isolates from geographically separated locations occasionally showed high genetic similarity. The complete placement of individual isolates is presented in the dendrogram rather than repeated in the text.

The PCoA supported the broad differentiation observed by UPGMA. The first and second principal coordinates explained 21.65 and 18.59% of the variation, respectively, and together accounted for 40.24% of the total RAPD variation. The third coordinate explained a further 8.99%. Similar weak associations between molecular clustering and geographical origin were observed by Nuwamanya *et al.* (2022) and Adhikari *et al.* (2021). Abdel-Hamid *et al.* (2023) also found that the molecular relationships among *A. solani* isolates were not determined solely by their geographical distribution.

Population diversity and AMOVA

The North Gujarat population showed greater RAPD-based diversity than the Middle Gujarat population. North Gujarat had higher values for the observed number of alleles or band states (Na = 1.93 ± 0.04), effective number of alleles (Ne = 1.50 ± 0.05), Shannon's information index (I = 0.48 ± 0.03), expected heterozygosity (He = 0.32 ± 0.03) and percentage of polymorphic loci (93.33%). Six private RAPD bands were recorded in North Gujarat, whereas no private bands were detected in Middle Gujarat (Table 6). Part of this difference may be attributable to the larger number of isolates sampled from North Gujarat; consequently, direct comparison of diversity estimates between the two populations should be interpreted cautiously.

Nei's unbiased genetic distance between the Middle and North Gujarat populations was low (D = 0.064), while their genetic identity was high (0.938). AMOVA attributed 80% of the total molecular variation to differences within populations and 20% to differences between populations, with ΦPT = 0.198 (Table 7). Thus, most genetic variation was distributed within the two geographical populations rather than between them. Adhikari *et al.*, (2021) similarly found that more than 85% of the genetic variation in *Alternaria* populations from potato and

Table 6: Genetic diversity estimates for different geographic populations of *A. solani* across Gujarat.

Pop	N	Na	Ne	I	He	uHe	PAL	%P
Middle Gujarat	13.0	1.5±0.15	1.30±0.06	0.30±0.05	0.190±0.03	0.20±0.03	0	73.33
North Gujarat	23.0	1.9±0.04	1.50±0.05	0.48±0.03	0.32±0.03	0.32±0.03	6	93.33
Mean	36.0*	1.7±0.08	1.4±0.04	0.39±0.03	0.25±0.02	0.26±0.02	6	83.33

N = number of individuals, Na = number of different alleles, Ne = number of effective alleles, I = Shannon information index, He = expected heterozygosity, uHe = unbiased expected, heterozygosity, PAL = private alleles, % P = percent polymorphism among population. Analyses were performed at a 95% confidence interval using GenAlEx version 6.5 software.

Table 7: Analysis of molecular variance (AMOVA) among and within different geographic populations of *A. solani*.

Source of variation	df	SS	MS	Variance component	Variation (%)
Among populations	1	24.35	24.35	1.18	20
Within populations	34	161.98	4.76	4.76	80
Total	35	186.33	–	5.94	100

df, degrees of freedom; SS, sum of squares; MS, mean squares; VC, variance component; Var (%), percentage of total molecular variation.

tomato occurred within populations, with limited population subdivision according to geographical location.

The high genetic identity between the two Gujarat populations, the predominance of within-population variation and the occurrence of isolates from different districts in the same UPGMA subclusters indicate only partial geographical structuring. Movement of infected planting material and dispersal of airborne conidia could contribute to the distribution of related genotypes across potato-growing areas, although these mechanisms were not directly investigated. The observed diversity nevertheless emphasizes the importance of including isolates from multiple locations when screening potato germplasm for early-blight resistance or evaluating disease-management practices.

RAPD is a dominant marker system and can be sensitive to amplification conditions. Therefore, the clusters obtained in the present study represent RAPD-based phenetic relationships and should not be interpreted as definitive phylogenetic lineages. Furthermore, the isolates were collected during a single season, pathogenicity was assessed only for representative isolate As1, and only As1 was subjected to ITS sequencing. Future investigations should combine multiyear sampling with pathogenicity, fungicide-sensitivity testing and multilocus or genome-wide sequencing to clarify the biological and geographical significance of the variability observed among Gujarat isolates.

CONCLUSIONS

The study revealed substantial cultural, morphological and RAPD-based genetic variability among 36 *A. solani.* isolates collected from major potato-growing regions of Gujarat. ITS-rDNA sequencing of representative isolate As1 supported its species identification, while RAPD analysis demonstrated high polymorphism and measurable population structure across the isolate collection. Most molecular variation occurred within rather than between the two predefined geographic populations. The observed diversity emphasizes the need to consider pathogen variability in early-blight surveillance, resistance breeding and integrated disease-management programmes. The single-season sampling, sequencing of only one representative isolate and use of dominant RAPD markers limit taxonomic and population-genetic inference; broader multi-season sampling with multilocus or genome-scale sequencing is recommended.

AUTHOR CONTRIBUTIONS

JVP: methodology, investigation, data curation, writing—original draft. NMG: conceptualization, supervision, data curation. NBP: validation, writing—review and editing. TCB: software and data analysis. All authors reviewed and approved the manuscript.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors.

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GENOME-WIDE DISTRIBUTION AND CHARACTERIZATION OF HIGH TEMPERATURE SHOCK TRANSCRIPTION FACTOR GENES FOR DROUGHT AND HIGH TEMPERATURE STRESS IN *SOLANUM TUBEROSUM* L.

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ABSTRACT: Abiotic stresses, mainly drought and high temperature affect potato production greatly. Molecular mechanisms associated with high temperature and drought stresses are yet to be deciphered fully. In many crops "high temperature shock transcription factors" (*hsf*) play important role in providing tolerance to plants under these stresses however, the role of *hsf* family in potato (*Solanum tuberosum*) in relation to abiotic stress is not fully explored yet. We performed detailed genome-wide analysis of *hsf* genes in potato. Fifteen *hsf* genes were identified in the potato genome which were found to be scattered on all chromosomes except chromosomes 1, 3 and 5. The structural analysis of predicted potato *hsf* genes indicated presence of only one intron in potato *hsf* genes. The lengths of deduced *hsf* proteins were found to be ranging from 55 to 536 amino acids, having molecular weights in the range of 12.20 kDa to 60.25 kDa with theoretical pI values from 4.71 to 9.58. The grand average of hydropathy (GRAVY) values was found to be negative for all the fifteen potato *hsfs*, suggesting their hydrophilic nature. Of the fifteen *hsf* genes identified in the potato genome, five were cloned and sequenced (partially) and their sequences were submitted to NCBI GenBank and were provided NCBI accession numbers. In response to drought, higher expression of all the five cloned genes was observed in drought tolerant cultivar- Kufri Jyoti (in leaf as well as root tissues) as compared to that in drought susceptible cultivar- Kufri Pukhraj. In response to high temperature stress, although the expression of most of the cloned *hsf* genes decreased in both high temperature tolerant (Kufri Surya) as well as susceptible cultivar (Kufri Chandramukhi), however, the decrease was comparatively more in case of K. Chandramukhi (high temperature susceptible cultivar) as compared to that in Kufri Surya (high temperature tolerant cultivar). The study indicated involvement of these *hsf* genes in imparting tolerance to drought and high temperature stress and thus, can be utilized for developing more climate resilient potato cultivars.

KEYWORDS chromosome location, phylogenetic, expression analysis, potato genome, abiotic stress.

INTRODUCTION

Potato (*Solanum tuberosum* L.) is the world's third most important food crop in terms of human consumption (FAOSTAT 2026, Dutt *et al*, 2017). Potato production in India has been increasing over the years, with an increase of almost 21 times in production between 1961 and 2022 (FAOSTAT 2026).

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In the year 2025-26, the volume of potato produced across India has been estimated to be around 60 million metric tons making India second largest producer after China (Area and Production of Horticulture crops for 2025-26, 2nd Advance Estimates; FAOSTAT 2026; https://agriwelfare.gov.in/en/StatHortEst). The impact of climate change on potato production in India is significant (Jatav *et al*., 2017), with the Indo-Gangetic Plains (IGP) being the main potato growing region. Climate change is projected to reduce potato yields by approximately 2.5%, 6%, and 11% in the IGP region in 2020, 2050, and 2080, respectively (Muthoni and Shimelis, 2020). High temperature and drought are major factors contributing to these yield reductions.

Potato is a cool-season crop that is highly sensitive to drought and high-temperature stress, both of which substantially impair plant growth, tuberization, yield and tuber quality. Water deficit causes stomatal closure, reduced leaf expansion and photosynthetic activity, altered assimilate partitioning and accelerated senescence, ultimately restricting tuber initiation and bulking (Obidiegwu *et al*., 2015; Hill *et al*., 2021). High temperature, similarly affects photosynthesis, respiration, hormonal balance and source–sink relationships; although vegetative growth is favored at approximately 20–25°C, optimum tuber growth occurs at about 15–20°C, and temperatures above 25°C can markedly delay or inhibit tuberization (Dahal *et al*., 2019). Night temperature is a particularly important environmental determinant of potato (*Solanum tuberosum* L.) growth and tuberization. Relatively cool nights favour tuber induction and subsequent tuber growth, whereas elevated night temperatures, particularly above about 18–22°C, can markedly inhibit or delay tuber formation and favour the allocation of assimilates towards vegetative growth rather than tubers (Menzel, 1980; Levy and Veilleux, 2007). High night temperature can prolong stolon growth and tuber setting, delay the onset of rapid tuber bulking, and reduce carbohydrate partitioning to developing tubers. Consequently, plants may produce greater above-ground biomass but exhibit a lower harvest index, fewer large tubers and reduced tuber yield. In a field study, increasing night temperature by approximately 4°C during tuber initiation reduced tuber yield by 17.2% and the proportion of large tubers (>100 g) by 53.7%, primarily through delayed tuber development rather than inhibition of photosynthesis (Kim and Lee, 2019). Thus, increasing night temperatures associated with climate warming may pose a substantial constraint to potato productivity, particularly in tropical, subtropical and warmer potato-growing regions. High temperature and drought also promote oxidative stress through excessive accumulation of reactive oxygen species, requiring activation of antioxidant and other protective mechanisms. When drought and high temperature occur simultaneously, their effects may be particularly damaging because elevated temperature increases evaporative demand and intensifies plant water deficit. Consequently, improving drought and heat tolerance through physiological, biochemical, molecular and genetic approaches is an important priority for sustaining potato productivity under changing climatic conditions (Dahal *et al*., 2019; Gervais *et al*., 2021). To mitigate the effects of climate change on potato production, adaptation strategies are essential.

The response to high temperatures and drought in a plant is a complex adaptive, biochemical, and physiological phenomenon that gets triggered by a cascade of events usually governed by transcription factors (TFs), which starts with stress perception and ends with an expression of a set of

target genes. These genes produce important enzymes and metabolic proteins, thereby protecting cells from stress. They also have a role in regulation of signal transduction and gene expression by synthesizing regulatory proteins (Lata and Prasad, 2011; Nakashima *et al.,* 2012). TFs are regulatory proteins which play a critical role in association with cis-acting elements of the promoter region of various stress-responsive genes to convert stress signal to stress-responsive gene expression in the signal transduction processes. As a result of which signalling cascades activate the whole network of genes which enhances plant tolerance to adverse environmental conditions (Akhtar *et al*., 2012). In case of plant genomes, ~7 % of the coding sequences code for TFs (Udvardi *et al*., 2007). These TFs often belong to large gene families as compared to animals and yeasts, like high temperature shock transcription factors (*hsf*) family (Baniwal *et al*., 2004; Udvardi *et al*., 2007). In plants, *hsfs*, also known as heat shock transcription factors, are the terminal components of signal transduction chain and studies have indicated the roles of *hsfs* in abiotic stresses including high temperature stress (HS) (Scharf *et al.,* 2012). Though *hsfs* play significant roles in stress signal transduction, gaps are still there in the proper understanding of their role. Present study was envisaged with this objective to have better insights into potato *hsfs* in relation to drought and high temperature stress.

MATERIALS AND METHODS

Genome-wide Identification and phylogenetic analysis

To identify *hsf* gene family members, we searched genes annotated as *hsf* using the keyword "High temperature Shock Factor" in the Plaza database (https://www.vandepoelelab.be/plaza/) to extract *Solanum tuberosum*-specific *hsf* gene sequences. The gene and protein sequences of the *hsf*s were downloaded and used for phylogenetic analysis and *in-silico* characterization. Phylogenetic analysis was performed to elucidate the relationships among *hsf* genes of potato genome. Phylogenetic analysis of the protein sequences was performed using https://itol.embl.de/ (Letunic *et al*., 2024).

Gene structure analysis and chromosomal location

To further explore the structural details of *hsf* genes, advanced bioinformatics tools and resources were used. Deciphering the gene structures Dicots PLAZA 4.0 server (https://www.vandepoelelab.be/plaza/) and tools were used to obtain the exon-intron organization, splice variants, and putative regulatory elements of the genes. The software, MapChart, (Voorrips, 2002) was used for physical mapping of locations of *hsf* genes on the chromosomes of *S. tuberosum.*

In-silico characterization of *hsf* proteins

To get more information about the nature of the *hsf* protein, the grand average of hydropathy (GRAVY), Isoelectric point (pI), and molecular weight of the potato *hsf* proteins were estimated. For this purpose, various tools including ProtParam tool available on Expert Protein Analysis System (ExPASy) proteomics server (https://web.expasy.org/cgi-bin/protparam/protparam; Gasteiger *et al*., 2005) were used.

Plant material and growing conditions

Previously reported drought tolerant cultivar (Kufri Jyoti) and drought susceptible cultivar (Kufri Pukhraj) (henceforth referred to as K. Jyoti and K. Pukhraj, respectively) were used in the present study. For studies pertaining to temperature, high temperature tolerant cultivar, Kufri Surya, and high temperature susceptible cultivar Kufri

Chandramukhi (henceforth referred to as K. Surya and K. Chandramukhi, respectively) were used. Freshly harvested good quality breeder seed potatoes were procured from ICAR- Central Potato Research Institute, Regional Station Modipuram, Uttar Pradesh, India. The tubers were kept at ambient temperature under dark conditions for chitting. Well sprouted tubers of each of these cultivars were planted in plastic pots and grown in poly house and /or controlled environment plant growth chambers (M/s Conviron, Model E-15, Canada) for imposing drought and high temperature stress, respectively.

Imposition of drought condition

Drought experiment was conducted in the controlled environment poly house. Well sprouted tubers of K. Jyoti and K. Pukhraj were planted in plastic pots and grown in poly house. Till 30 days of Planting, the plants were watered to the full field capacity. The filed capacity of the pots was previously calculated as per the standard method. After 30 days of planting, one set of plants were watered and maintained at 50% of the field capacity (and named as drought treated plants). While the other set was maintained at full field capacity (control plants). On 60th day of planting leaf samples from the fixed leaf position (4th leaf position from the top) were picked from both the control plants as well as those under drought. Approximately 100 mg leaf samples were weighed and frozen in liquid nitrogen and subsequently, stored at -80°C till further use.

Imposition of high temperature condition

For high temperature stress experimentations, previously reported high temperature resistant and susceptible cultivars K. Surya and K. Chandramukhi, respectively were used for the study. The experiment was conducted in controlled environment chambers (M/s Conviron, Model E-15, Canada). Initially, in both the chambers, the plants were grown at 16 h photoperiod with day and night temperature of 22°C, and 18°C, respectively. For imposing high temperature stress on one set of plants; after 30 days of planting the temperature of one of the two growth chambers were changed. The constant temperature of 26°C ± 2°C with the same photoperiod of 16 h was set and maintained. At 60th day of planting roots, and leaf samples (from the 4th leaf position from the top) were picked from both the control plants as well as those under high temperature. Approximately 100 mg leaf as well as root samples were weighed and frozen in liquid nitrogen and subsequently, stored at -80°C till further use.

RNA isolation and cloning of the *hsf* genes

Leaf and root tissue samples collected from the plants and stored at -80°C were used for RNA isolation. Total RNA was isolated using NucleoSpin® RNA kit (M/s Macherey-Nagel, USA) following the user's instruction. Complementary DNA (cDNA) was synthesized from 2 µg of DNase-treated total RNA as a template in 20 µl reaction volume by using cDNA synthesis kit (Invitrogen, USA) (Dutt *et al*, 2023). Degenerate primers for various *hsf* genes were designed from the conserved regions for all the 15 *hsf* genes. The partial gene sequences were amplified by PCR. The amplicons were cloned in pGEM-T Easy Vector (Promega, USA), plasmids were isolated using Fermentas GeneJET™ Plasmid Miniprep Kit (Fermentas Inc., USA), and sequencing was performed using Big Dye terminator cycle sequencing mix (Version 3.1; Applied Biosystems, USA) using an

automated DNA sequencer (ABI 3130 xl Genetic Analyzer, Applied Biosystems, USA). Protocols were followed essentially as described by the respective manufacturer.

Semi-quantitative expression analysis by RT-PCR

Semi-quantitative RT-PCR based expression analysis was performed to study the expression level of cloned *hsf* genes in response to drought and high temperature stress *vis-a-vis* respective controls. The RNA isolated from the plant tissue (leaf and root in case of drought, and leaf in case of high temperature experiment) as mentioned above. To analyze the expression level of the cloned genes, total RNA was isolated from leaf tissue (100 mg) using the NucleoSpin® RNA kit (M/s Macherey-Nagel, USA) following the user's instruction. cDNA was synthesized from DNA-free RNA using SuperScript® III Reverse Transcriptase (Invitrogen, USA). The cDNA was used as a template for Reverse transcription-PCR reaction using gene specific primers and cycling conditions were optimized to obtain amplification under the exponential phase (Table 1). 26S rRNA based primer pair was used as internal control for expression studies (Singh *et al*., 2004). The amplicons were analysed and quantified using the Alpha Digi Doc Gel Documentation and Image analysis system (Bio-Rad Molecular Imager ChemiDoc XRS Imaging system, USA). Each experiment was repeated at least twice with three biological replicates each time and the representative figure of one experiment is shown in the manuscript. Integrated density values (IDV) of the amplicons were calculated and compared after normalization for the control gene (26S *rRNA*).

Table 1. Primer and PCR conditions used for expression analysis of hsf genes of potato

S. No.	Name of primer	Sequence of primers (5'-3')	PCR condition
1	HP1-F	CACATGGTCCAGATGGAGTG	Initial denaturation at 94 °C for 3 min, followed by 35 cycles of 94 °C, 30 s; 55–60 °C, 40 s; 72 °C, 50 s. Final extension at 72 °C for 7 min
2	HP1-R	TTTCTCCTTCCCCATCTCCT	
3	HP2-F	CGGTAGAGAATGGGACCAAA	
4	HP2-R	CACTCGGATGGGTTTGAGAT	
5	HP4-F	AGAGAAGAGGCCACAGCAAA	
6	HP4-R	GACGAAGGCGAGGATTGATA	
7	HP9-F	GCAGCAACAGCAGAGTACGA	
8	HP9-R	GACCTGACATTGCTGCTTGA	
9	HP10-F	TCGTTGTTTGGAATCCACCT	
10	HP10-R	CCGCAGATGACTGAAGCATA	

RESULTS AND DISCUSSION

hsf genes, their distribution in potato genome and their structures

Fifteen *hsf* genes were identified in the potato genome from Dicots PLAZA 4.0. The chromosomal locations of these genes revealed that three *hsf* genes found to be scattering on chromosomes 2, 4, 6,7, 8, 9,10,11,12 (Fig. 1). Of the 15 *hsfs*, three each were found to be located on chromosome 2 (PGSC0003DMG400028416, PGSC0003DMG400041361, PGSC0003DMG401004023) and chromosome 8 (PGSC0003DMG400017846, PGSC0003DMG400008223, PGSC0003DMG400014811). Two *hsf* genes were located each on chromosomes 4 (PGSC0003DMG400027283, PGSC0003DMG400007962) and chromosome 10 (PGSC0003DMG401008167, PGSC0003DMG402008167). Remaining 5 *hsf* genes were found to be present on chromosomes 6 (PGSC0003DMG400027036), 7 (PGSC0003DMG400032793), chromosome 9 (PGSC0003DMG400006447), chromosome 11 (PGSC0003DMG400043234), chromosome 12(PGSC0003DMG400000380) (Fig. 1, Table 2)

The structural analysis of predicted potato *hsf* genes (Fig. 2) indicated the presence of only one intron in potato *hsf*

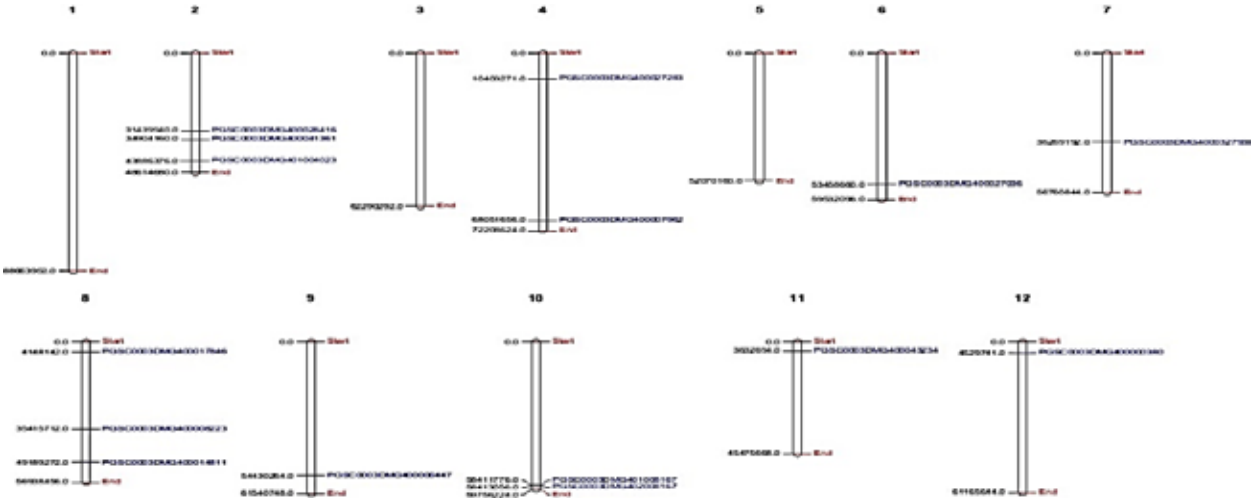


Fig. 1. Locations of hsf genes on different chromosomes of potato.

genes (Fig. 2) The *hsf* gene accession no. PGSC0003DMG402008167 was found to be intron-less (Table 2 and Fig. 2). The length of cDNAs in present studies ranged from 0.826 kbp to 6.315 kbp. The variation in gene length and exon-intron structure could indicate different regulatory roles or adaptability mechanisms among the *hsf* genes in potato.

Our findings offer a detailed examination of the *hsf* gene family in potato, including its distribution, structure, evolutionary history and functional expression under stress conditions. The number of *hsf* gene family members varies among different species. For example, *Triticum urartu* has 17 members (Li *et al*. 2021), *Arabidopsis thaliana* has 21 *hsf* members (Li *et al*. 2003), *Aegilops tauschii* has 19 members (Yang *et al*. 2014) and maize (*Zea mays*) has 25 members (Lin *et al*. 2011). The uneven distribution of genes on various chromosomes suggests specific evolutionary pressures or functional diversifications associated with particular chromosomal locations. The structural analysis revealed that most *hsf* genes possess two exons. The variation in gene length and exon-intron structure could indicate different regulatory roles or adaptability mechanisms among the *hsf* genes.

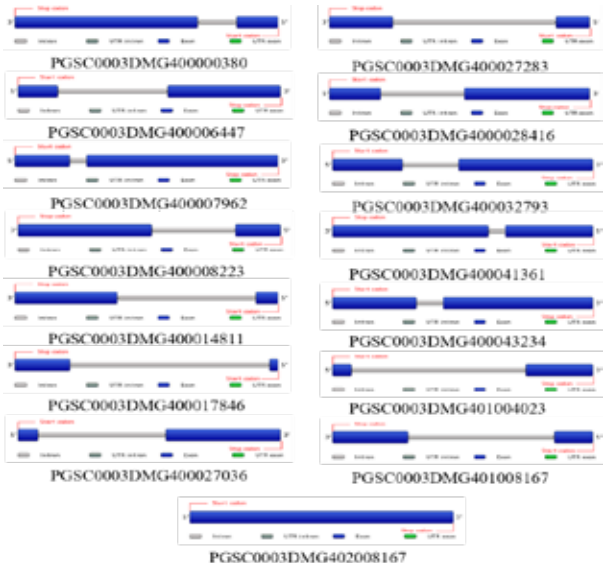


Fig. 2. Gene structure of potato hsf genes of potato genome.

In silico characterization of deduced *hsf* proteins of potato

After moving from genome exploration to protein-level analyses, the work investigated *hsf* proteins using *in silico* analysis. During this phase, the Expert Protein Analysis System (ExPASy) (https://www.expasy.org/) server became a crucial tool for

Table 2. Details of *hsf* genes structure in potato.

Sr. no.	Gene ID	Chr. number	mRNA coordinates		Exon	Intron	Size (Kbp)
			Start	End			
1.	PGSC0003DMG400028416	2	31439941	31441450	2	1	1.510
2.	PGSC0003DMG400041361	2	34904161	34905484	2	1	1.324
3.	PGSC0003DMG401004023	2	43886377	43889920	2	1	3.544
4.	PGSC0003DMG400027283	4	10409271	10411469	2	1	2.199
5.	PGSC0003DMG400007962	4	68051653	68053098	2	1	1.446
6.	PGSC0003DMG400027036	6	5348661	53463194	2	1	4.543
7.	PGSC0003DMG400032793	7	36269190	36271391	2	1	2.202
8.	PGSC0003DMG400017846	8	4148142	4154456	2	1	6.315
9.	PGSC0003DMG400008223	8	35415712	35418551	2	1	2.840
10.	PGSC0003DMG400014811	8	49189274	49194971	2	1	5.698
11.	PGSC0003DMG400006447	9	54430264	54432804	2	1	2.541
12.	PGSC0003DMG401008167	10	5841178	5841061	2	1	2.284
13.	PGSC0003DMG402008167	10	58413057	58414061	1	0	1.005
14.	PGSC0003DMG400043234	11	3632694	3633519	2	1	0.826
15.	PGSC0003DMG400000380	12	4529741	4531488	2	1	1.748

predicting important protein parameters as the molecular weight, instability index, isoelectric point (*p*I), and grand average of hydropathy (GRAVY). These parameters play a pivotal role in understanding the physicochemical characteristics of proteins, shedding light on their stability, structure, and potential functional roles within cellular processes. *In silico* analysis was performed on the 43 *hsf* deduced protein sequences obtained from NCBI and 15 *hsf* deduced protein sequences obtained from Dicots PLAZA 4.0. The lengths of *hsf* proteins were found ranging from 55 amino acids (PGSC0003DMG402008167) to 536 amino acids (XP_015160911.1 and XP_015160909.1) having molecular weights ranging from 12.20 kDa to 60.25 kDa, respectively (Table 3). Theoretical pI values ranged from 4.71 to 9.58. All the 15 *hsf* proteins of potato were found to have negative GRAVY value which ranged from -0.931 to-0.387. The negative GRAVY values of *hsf* suggested hydrophilic nature of these proteins. The maximum GRAVY value of -0.387 was for protein PGSC0003DMG402008167 and minimum for XP_006363482.1 and PGSC0003DMG400006447 *hsf* gene proteins (-0.931) (Table 3).

In silico analysis of *hsf* proteins demonstrated considerable variability in protein length and molecular weight. This diversity in protein size and characteristics may reflect functional specialization within the *hsf* gene family. The theoretical pI values and GRAVY scores suggested a range of hydrophilic properties, potentially influencing the protein's stability and interaction with other cellular components. Although all the *hsf* proteins were found to be hydrophilic nature, yet their degree of hydrophilicity difference from each other as evidenced by different GRAVY value of these *hsf* proteins of potato. The GRAVY is an important physicochemical parameter that reflects the overall hydrophobic or hydrophilic nature of a protein. Proteins with

Table 3. Molecular weight, theoretical *p*I and GRAVY value of predicted potato HSF gene proteins.

S. no.	Protein ID	Numbers of nucleotide in CDS/ ORF	Numbers of amino acids in deduced protein	Mol. Wt. of deduced protein kDa	Theoretical *p*I	GRAVY
1.	PGSC0003DMG400000380	1107	368	40.97	5.86	-0.614
2.	PGSC0003DMG400006447	1089	362	42.26	5.46	-0.931
3.	PGSC0003DMG400007962	1119	372	42.38	7.76	-0.714
4.	PGSC0003DMG400008223	1062	353	40.71	4.92	-0.659
5.	PGSC0003DMG400014811	1497	498	55.72	5.01	-0.671
6.	PGSC0003DMG400017846	1527	508	56.25	5.15	-0.658
7.	PGSC0003DMG400027036	1446	481	54.42	5.17	-0.578
8.	PGSC0003DMG400027283	744	247	28.70	8.68	-0.754
9.	PGSC0003DMG400028416	1023	340	38.45	6.59	-0.909
10.	PGSC0003DMG400032793	1086	361	41.76	5.28	-0.825
11.	PGSC0003DMG400041361	1236	411	46.95	4.92	-0.809
12.	PGSC0003DMG400043234	741	246	28.71	9.30	-0.651
13.	PGSC0003DMG401004023	909	302	33.29	5.75	-0.754
14.	PGSC0003DMG401008167	735	244	28.38	6.13	-0.857
15.	PGSC0003DMG402008167	168	55	6.02	8.12	-0.387

positive GRAVY values are generally more hydrophobic and are often associated with membranes or lipid environments, whereas proteins with negative GRAVY values are more hydrophilic, making them more likely to be soluble in aqueous environments. GRAVY analysis provides valuable insights into protein solubility, folding, stability, membrane association, and subcellular localization. Proteins with lower GRAVY values are generally more hydrophilic, which might be advantageous in stress conditions where solubility and interactions with water-soluble molecules are critical.

Phylogenetic analysis of potato *hsf* genes

This phylogenetic framework (Fig. 3) provided a comprehensive overview of the evolutionary dynamics, gene duplication events, and divergence patterns within the potato *hsf* gene family, shedding light on their evolutionary history and potential functional specialization. This analysis involved 58 *hsf* protein sequences. All ambiguous positions were removed for each sequence pair (pairwise deletion option). Total of three major groups were deduced from the phylogenetic

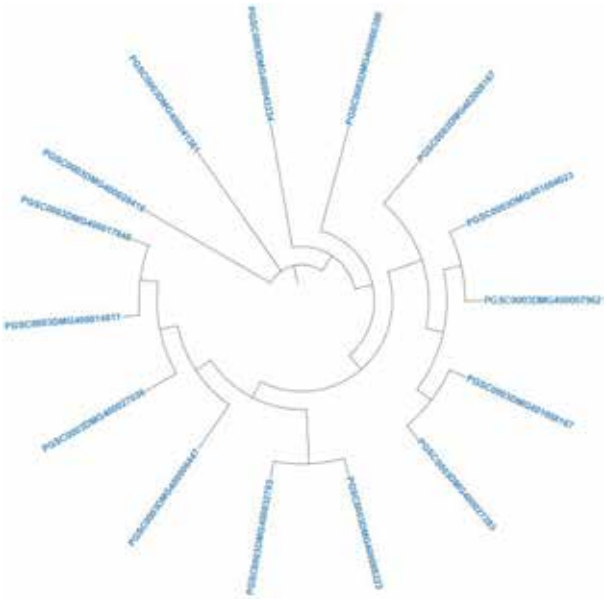


Fig. 3. Phylogenetic tree of potato hsf genes.

tree (Fig. 3). Yu *et al.* 2022 comprehensively identified 2950 *Hsf* family genes from the whole genome of 111 representative plants and conducted systematic comparative analysis to reveal their basic characteristics, conserved motif, duplications and losses, evolutionary, expression patterns, and phylogenetic relationships. The phylogenetic analysis of potato *hsf* genes revealed three major groups, each possibly representing different evolutionary lineages or functional specializations. This classification provides insights into the evolutionary dynamics and gene duplication events within the potato *hsf* gene family. The phylogenetic relationships and groupings observed in our study align with known patterns of gene evolution and functional diversification in plants, highlighting the complexity of stress response mechanisms. The genome evolutionary mechanisms and expansions of gene families are mainly depended on gene duplication events. The major duplication patterns for gene families are tandem duplication and segmental duplication (Vision *et al.* 2000; Kong *et al.* 2007).

Amplification and cloning and sequencing of *hsf* genes

Of the primers designed for all the fifteen *hsf* genes, only five *hsf* genes viz., *HP1*, *HP2*, *HP4*, *HP9*, and *HP10*, from various potato tissue samples, were successfully amplified. The amplicons were then cloned and sequenced. In order to establish the identity of the cloned genes the obtained nucleotide sequences were subjected to BLAST analysis. The Blast analysis confirmed the identity of the amplified and sequenced amplicons to be *hsf* genes. Sequences of partially amplified genes viz: *HP1*, *HP2*, *HP4*, *HP9*, and *HP10* were redesignated as St_*hsf*1, St_*hsf*2, St_*hsf*4, St_*hsf*9 and St_*hsf*10 high temperature shock transcription factor gene, respectively. These partial gene sequences were submitted to NCBI and were allocated accessions nos. MW001209, MW001210, MW001211, MW001212, and MW001213, respectively. The deduced amino sequences of these cloned genes are presented in Fig. 4.

Expression analysis of amplified genes

In order to gain insights into the role of HSPs in potato under abiotic stresses, the expression dynamics of the cloned *hsf* genes (*HP1, HP2, HP4, HP9* and *HP10*) in response to drought and high temperature stress was studied. As described under Materials

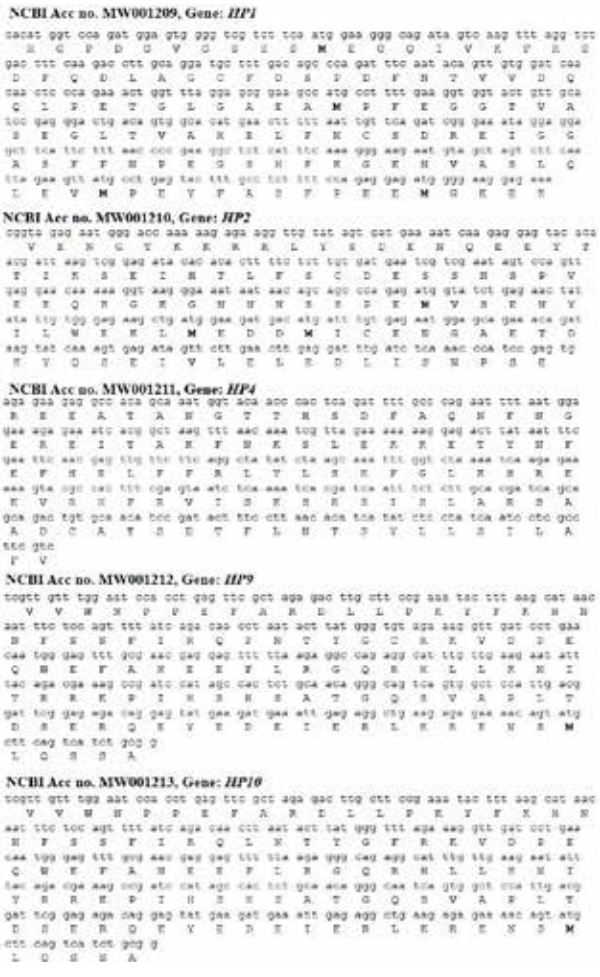


Fig. 4. Accession numbers, nucleotide sequences and the deduced amino acid sequences of partially cloned hsf genes from potato

and methods section, K. Jyoti, K. Pukhraj cultivars of potato were used for drought. And for high temperature stress K. Surya and K. Chandramukhi potato cultivar were used. Integrated density value (IDV) based expression analysis of selected amplified *hsf* genes in K. Jyoti, K. Pukhraj for drought stress while K. Surya and KCM (KCM) for high temperature stress conditions. The expression analysis of amplified genes (*HP1, HP2, HP4, HP9* and *HP10*) was performed under drought and high temperature stress conditions in potato.

In case of drought tolerant cultivar i.e. K. Jyoti expression of all the *hsf* genes i.e. HP1, HP2, HP4, HP9 and HP10 were increased both in leaf as well as root tissues (Fig. 5), In comparison to control, increase in expression in leaf tissue of plants under drought, was found to be 51%, 1263 %, 232 %, 66 % and 1042 % of HP1, HP2, HP4, HP9 and HP10, respectively. In roots, 126%,448%, 13911%, 501%,94% higher expression of HP1, HP2, HP4, HP9 and HP10 was observed in roots of plants exposed to drought (Fig. 5).

On the other hand, expression of all these 5 *hsf* genes was found to decrease in leaf tissue of plants under drought as compared to that in respective control (Fig. 5). The decrease in expression was 35 %, 23%, 96%, 24% and 62%, of HP1, HP2, HP4, HP9 and HP10, respectively. In roots, 86 %, 95%, 94% and 97% decrease in expression was observed of HP2, HP4, HP9 and HP10, respectively (Fig. 6). However, 28% increased expression of HP1 was observed in roots of plants under drought, as compared to the respective control (Fig. 6)

In case of high temperature stress, the expression analysis showed that expression of most of the cloned *hsf* genes decreased in both high temperature tolerant (K. Surya) as well as susceptible cultivars (K. Chandramukhi) (Fig. 7). However, the decrease was comparatively more in case of K. Chandramukhi (high temperature susceptible cultivar) as compared to that in K. Surya (high temperature tolerant cultivar). Seventy-seven, and 32% decrease in expression of HP2 and HP10 genes was observed in leaves of K. Surya exposed to high temperature as compared to respective control. Not much change in expression was observed of HP1, HP4 and HP9 genes. In case of K. Chandramukhi, the decrease in expression was observed to be 44%, 62%, 87%, 98% and 83% of HP1, HP2, HP4, HP9 and HP10, respectively (Fig. 7).

Differential expression dynamics of these five *hsfs* suggests that these *hsf* genes

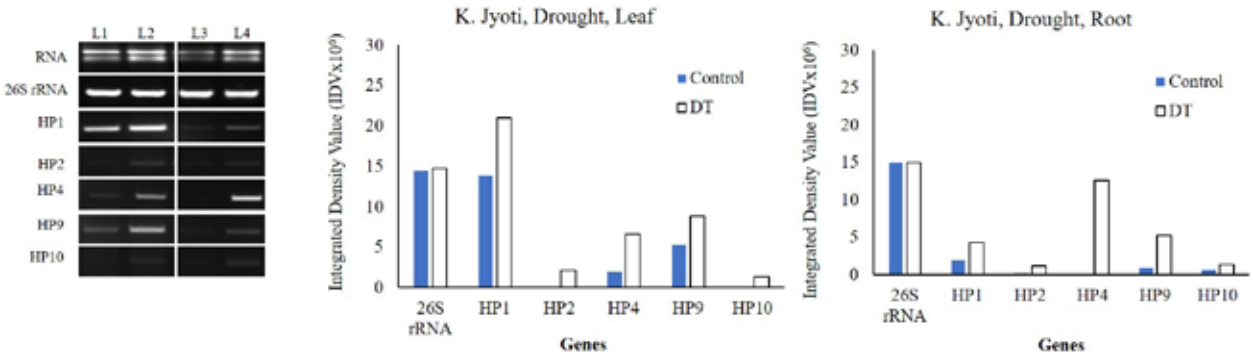


Fig. 5. Expression pattern of hsf genes in response to drought in potato leaf. Total RNA was extracted from leaves of potato plants subjected to different levels of water stress vis-a vis control; and subjected to semi-quantitative RT-PCR based expression analysis. A constitutive 26S rRNA gene was used as an internal control for equal loading. Lane L1: K. Jyoti, Leaf, Control; L2: K. Jyoti, Leaf, Drought Treatment; L3: K. Jyoti, Root, Control; L4: K. Jyoti, Root, Drought Treatment.

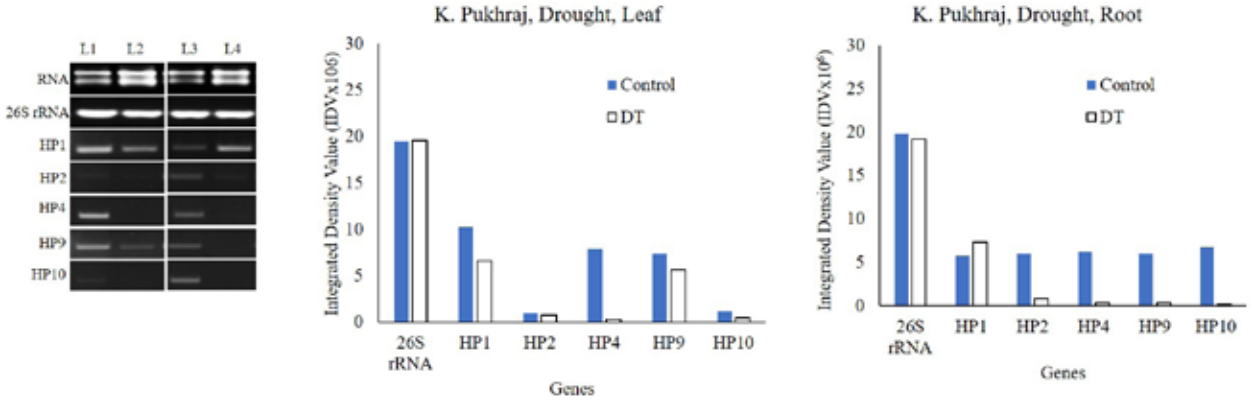


Fig. 6. Expression pattern of hsf genes in response to drought in potato root. Total RNA was extracted from root of potato plants subjected to different levels of water stress vis-a vis control; and subjected to semi-quantitative RT-PCR based expression analysis. A constitutive 26S rRNA gene was used as an internal control for equal loading. Lane L1: K. Pukhraj, Leaf, Control; L2: K. Pukhraj, Leaf, Drought Treatment; L3: K. Pukhraj, Root, Control; L4: K. Pukhraj, Root, Drought Treatment.

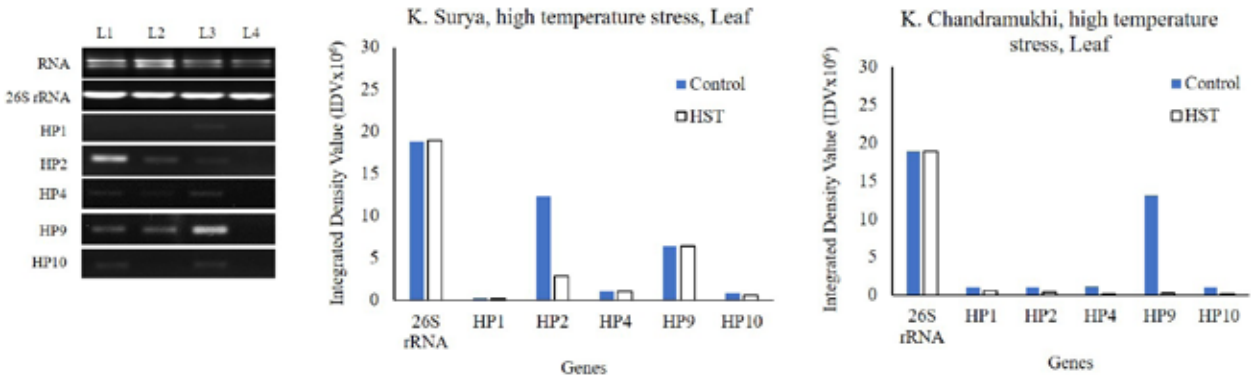


Fig. 7. Expression pattern of hsf genes in response to high temperature stress in potato. Total RNA was extracted from leaves of potato plants subjected to high temperature (vis-a vis control); and subjected to semi-quantitative RT-PCR based expression analysis. A constitutive 26S rRNA gene was used as an internal control for equal loading. Lane L1: K. Surya, Leaf, Control (18°C); L2: K. Surya, Leaf, high temperature stress (26°C); L3: K. Chandramukhi, Leaf, Control (18°C); L4: K. Chandramukhi, Leaf, high temperature stress (26°C).

may be playing diverse roles in potato in response to various abiotic stresses like drought and high temperature stresses. Mishra *et al*. 2002 generated transgenic tomato plants with altered expression of high temperature stress transcription factor *HsfA1*. *HsfA1a* has been reported as an exceptional master transcription factor of induced high temperature tolerance in tomato but no similar h*sfs* were found in *Arabidopsis* (Lohmann *et al*., 2004; Von Koskull-Döring *et al*., 2007). Previous researchers have also contributed valuable insights into the *hsf* gene family and their roles in stress responses. Tang *et al.* (2016) identified twenty-seven *hsf* members by bioinformatics and phylogenetic analyses, classifying them into A, B, and C groups according to their structural and phylogenetic features. They found that the *hsfs* were located on 10 of the 12 chromosomes, except chromosomes 1 and 5, and that 18 of these genes formed 9 paralogous pairs. Expression profiles of *hsfs* in 12 different organs and tissues revealed distinct spatial expression patterns and potential roles in growth and development. Promoter and quantitative

real-time PCR analysis demonstrated that these genes responded to various stresses, indicating their diverse regulatory roles under adverse conditions. Additionally, Zhao *et al.* (2018) identified 48 putative potato *Hsp20* genes and found that most possessed no, or only one, intron. Their phylogenetic analysis grouped these genes into 12 subfamilies and identified stress response cis-elements in nearly all of them. Real-time quantitative PCR showed that the *Hsp20* genes responded to multiple abiotic stresses, with significant upregulation under high temperature stress. Furthermore, Zhu *et al.* (2021) analysed the *hsf* gene *SpHsfA4c* isolated from a wild potato (*Solanum pinnatisectum* Dun), showing that *SpHsfA4c* encodes a protein with conserved *HsfA* characteristics. Overexpression of *SpHsfA4c* in potato lines resulted in enhanced high temperature tolerance, improved cell membrane stability, increased antioxidant capacity and osmotic adjustment ability; demonstrating its positive regulation of high temperature tolerance and potential as a candidate gene for genetic engineering in potato breeding.

The expression patterns of *hsf* genes in different tissues have been described in many species, such as *Arabidopsis*, pepper, rice and tomato in several different researches (Siddique *et al.,* 2008; Guo *et al*., 2015; Ouyang *et al.,* 2009; Yu *et al*., 2016). There is no uniform gene expression pattern for *hsf* genes in different plants. According to the RNA-seq data of potato different *hsf* proteins might have diverse functions and different *hsf* genes such as *StHsp20-22* and *StHsp20-41* exhibited incompatible expression patterns in various tissues (Zhao *et al.,* 2018).

CONCLUSION

The present study reveals that all genome-wide landscape of *hsf* genes in potato genome and difference and similarities in their structure and biochemical properties. Higher expression of the cloned *hsf* genes in drought and high temperature tolerant as compared to that of in susceptible potato cultivars suggests their involvement in imparting stress tolerance to potato plants. These results highlight the importance of *hsf* genes in regulating plant responses to high temperature and drought stresses, thus providing a model which could be used for enhancing plant resilience. The integration of molecular, bioinformatics and functional analyses in this study provides a robust framework for further research. In conclusion, our study confirms the critical roles played by *hsf* in a stress response system and sets the stage for future studies that aim at building more climate resilient potato cultivars. Future studies should focus on functional characterization of these genes to elucidate their specific roles in stress tolerance.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CONFLICT OF INTEREST

"Som Dutt and Hemant B. Kardile are the Editor-in-Chief and Senior Editor of Potato Journal, respectively and were not involved in the editorial review or decision-making

process for this manuscript. The peer review and editorial handling were managed entirely independently by an alternative editor." Other authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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QR CODES: A PATHWAY TO TECH-LED DISSEMINATION OF AGRICULTURAL INFORMATION

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ABSTRACT: Quick Response (QR) codes have emerged as a powerful tool to bridge the gap between digital information and users by providing instant and easy access to online resources. The present study evaluated the effectiveness of QR code-based dissemination of potato extension publications and identified demographic factors influencing farmers' successful access to these digital resources. The study involved 100 farmers from western Uttar Pradesh participating in training programmes organized at ICAR–Central Potato Research Institute, Regional Station, Modipuram, Uttar Pradesh. QR codes linked to online extension publications were provided to participants and their ability to access the documents was recorded. Information on age, gender and education was collected and analysed using binary logistic regression. Overall, 65% of respondents successfully accessed the QR code publications. The regression model was significant (LR χ^2 = 34.04, P < 0.001) with 75% prediction accuracy. Age negatively influenced QR code access (P = 0.007), while educational level had a significant positive effect (P = 0.015); gender was non-significant. Follow-up assessment indicated that most respondents found the publications useful, whereas preference for printed materials, limited smartphone access and lack of awareness remained important constraints. The findings demonstrated the potential of QR codes as a low-cost and scalable tool for agricultural information dissemination.

KEYWORDS: QR code technology, Digital extension, Demographic determinants, Binary logistic regression, Potato

INTRODUCTION

The rapid advancement of digital technology has transformed the way agricultural information is generated, disseminated and accessed. Among the emerging digital communication tools, Quick Response (QR) codes, a type of two-dimensional barcode, have become an effective means of connecting users with digital content by providing instant and convenient access to online resources through smartphones. Their widespread adoption has enhanced information dissemination across diverse sectors, including education, healthcare, marketing and agriculture. In the agricultural sector, QR codes have recently gained attention as a simple, low-cost and user-friendly technology for linking farmers to digital advisory services, technical publications and multimedia extension resources (Atheequlla *et al*., 2024). Similarly, smartphone-based agricultural applications have been reported to improve farm management, facilitate timely access to technical information and contribute to enhanced agricultural productivity (Meena *et al*., 2018).

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Agricultural extension and communication plays a pivotal role in transferring research-based technologies from scientific institutions to farmers. However, conventional methods of disseminating extension literature, such as printed bulletins, folders and leaflets, are often constrained by high printing costs, limited distribution, delayed delivery and restricted accessibility (Davis, 2008; Feder and Savastano, 2006). Consequently, the diffusion of technologies developed by research organizations to the farming community remains relatively slow. With the rapid penetration of smartphones and internet connectivity in rural India, QR codes offer an efficient alternative for delivering digital extension materials directly to farmers, enabling instant access to updated information while substantially reducing the cost and logistics associated with printed publications (Faure *et al*., 2012).

Within agricultural sector, potato crop has a prominent role to play in Indian food and nutritional security and the economic growth as its diversified utilization is increasing consistently by way of processing and export. According to the Final Advance Estimates (2023–24) released by the Ministry of Agriculture and Farmers' Welfare, India recorded a production of 57.05 million tonnes of potato from an area of 2.32 million hectares, with an average productivity of 24.6 tonnes per hectare. The crop registered a compound annual growth rate (CAGR) of 4.2 per cent per annum in production (Anonymous, 2025) (Fig 1). However, there is still huge scope of harnessing the potential of this crop as if the single indicator of productivity per unit area is analyzed critically in comparison to developed global economies. Researchers at the ICAR–Central Potato Research Institute, India, estimated that under current farm management practices, actual potato yields in the country reach only 42–45 percent of their potential, but could increase to approximately 80 percent through the adoption of modern technologies (Singh *et al*., 2015).

Analysis of variations in yield in different states of the country also points towards magnitude of adoption level of modern potato agro-technologies by the potato growers. In Indian states such as Chhattisgarh, Jharkhand, Odisha and most of North East India, potato yields remain low, at only 7–15 t/ha, which may be attributed, among other factors, to limited knowledge and skills related to modern cultivation technologies (Kharumnuid *et al*., 2022; Anonymous, 2025).

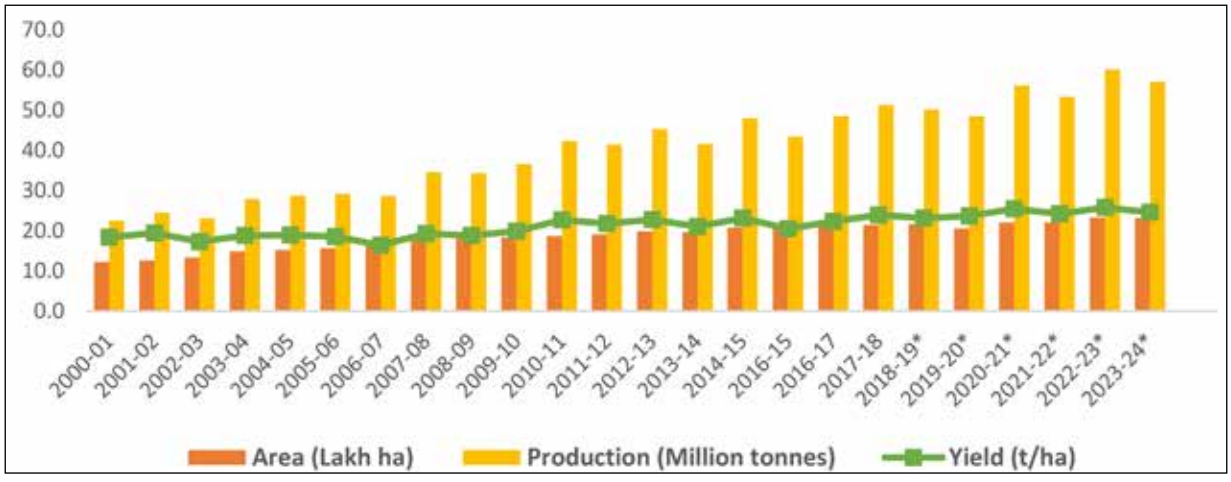


Fig. 1. Area, production and productivity of potato in India (2000-2024) (Anonymous, 2025)

These observations suggested that potato growers of different regions with lower potato productivity have difficulty in access to modern technologies developed by the research institutions. Although smartphones are increasingly available among farmers, limited empirical evidence is available regarding the practical use of QR codes as a mechanism for delivering agricultural extension publications. Furthermore, the socio-demographic factors affecting farmers' ability to access QR-enabled extension material remain poorly understood

Against this background, the present study was undertaken to evaluate the effectiveness of QR codes as a digital tool for disseminating potato extension publications among farmers. Specifically, the study aimed to assess farmers' ability to access QR code-linked publications, identify the demographic factors influencing successful QR code utilization using binary logistic regression analysis and assess farmers' perceptions regarding the usefulness of QR code publications for agricultural information dissemination. The findings are expected to provide useful insights for research organizations, extension agencies and policymakers in developing efficient, scalable and farmer-friendly digital extension systems that complement conventional information dissemination approaches.

MATERIALS AND METHODS

Development of QR Code publications

ICAR-Central Potato Research Institute (CPRI) and the All India Coordinated Research Project on Potato (AICRP-Potato) collectively undertake over 95% of potato research in India (Singh *et al*., 2015). The institute consistently publish and update numerous farmer-focused, region-specific publications, including technical and extension bulletins, folders and leaflets to address evolving needs. To facilitate timely and cost-effective dissemination of knowledge, selected key publications have been digitized and made accessible via QR codes, enhancing outreach to farming communities. The methodology involved uploading the extension bulletins to the internet and obtaining the corresponding weblinks. QR codes for these documents were generated using online QR Code generator (https://www.qrcode-monkey.com). For this study, standard black-and-white QR codes with the ICAR logo were used to maintain simplicity, clear identity and compatibility with all participants' mobile devices.

Collection of data

The generated QR codes were printed on plain white sheets, with each QR code linked to a specific extension publication hosted online. During the training programmes, the printed QR codes were presented to the participating farmers. Respondents were guided to scan the QR codes using the camera application of their smartphones. Upon scanning, the corresponding web link appeared on the mobile screen, enabling participants to access and view or download the publication. For each respondent, demographic information including gender, age and educational level was recorded using a structured schedule. The primary outcome variable was successful access to the QR-code publication, defined as the participant's ability to successfully view or download the linked publication after scanning the QR code. This outcome was recorded as a binary response (1 = successfully viewed/ downloaded the publication; 0 = unable to view/download the publication). During the subsequent crop season, participants were contacted through structured follow-up interviews to assess their utilization and their perceived usefulness and effectiveness of the shared QR code publications.

Data analysis

Collected data were compiled in Microsoft Excel and analysed in R programming language. Descriptive statistics, including frequencies and percentages, were used to summarize the demographic characteristics of the respondents and the utilization pattern of QR-code publications. Binary logistic regression analysis was employed to identify the demographic factors influencing successful access to QR-code publications. The dependent variable was successful QR-code access (1 = successfully viewed/downloaded the publication; 0 = unsuccessful). Independent variables included age (years), gender (Male = 1, Female = 0) and educational level, which was treated as an ordinal variable representing increasing educational attainment.

Following Demaris (1992), the logistic regression model for the log-odds of adoption of QR code publications can be expressed as:

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1(\text{Gender}) + \beta_2(\text{Age}) + \beta_3(\text{Education}) + \varepsilon$$

where represents the probability of successful QR-code access, β_0 is the intercept, β_1–β_3 are regression coefficients for the explanatory variables, and ε is the random error term. Model performance was evaluated using the likelihood ratio chi-square statistic, pseudo-R^2, prediction accuracy and odds ratios (OR). Statistical significance was considered at $P < 0.05$.

RESULTS AND DISCUSSION

Demographic profile of respondents

Demographic profile of the respondents of the QR code publications survey revealed distributions across gender, age, educational attainment and technology utilization patterns, providing crucial insights for understanding QR code adoption barriers and facilitators (Fig. 2).

Gender

The results revealed that male respondents comprise 94% of respondents compared to only 6% female. In India, women constitute nearly 47% of the agricultural workforce; however, only 13% have access to agricultural extension services and a mere 6% receive formal training (Singh *et al.*, 2025; GoI, 2019). This could be due to the fact that in India, male farmers are better access to resources, decision-making power and exposure to extension services. As a result, men mainly assume responsibility for technology adoption and farm management decisions (Aryal *et al.*, 2020).

Age

The age distribution showed that most respondents (49%) are over 50 years old, followed by 40% in the 35-50 age group. The predominance of older farmers poses challenges for QR code adoption due to lower digital literacy and resistance to new technology, yet their extensive agricultural knowledge and networks can aid technology diffusion once barriers are addressed. Only 11% of respondents are under 35, reflecting broader rural youth migration trends that contribute to an aging agricultural workforce. However, this younger segment demonstrated higher digital literacy and greater openness to innovation, positioning them as key drivers for QR code adoption. Research from rural India suggests that age-tailored training and simplified user interfaces improve acceptance among older and female farmers (Kushwaha, 2025; Jadhav, 2024). To encourage youth engagement in agri entrepreneurship, capacity-building initiatives and ICT-enabled agricultural technology transfer are essential for creating sustainable business opportunities (Kushwaha, 2025).

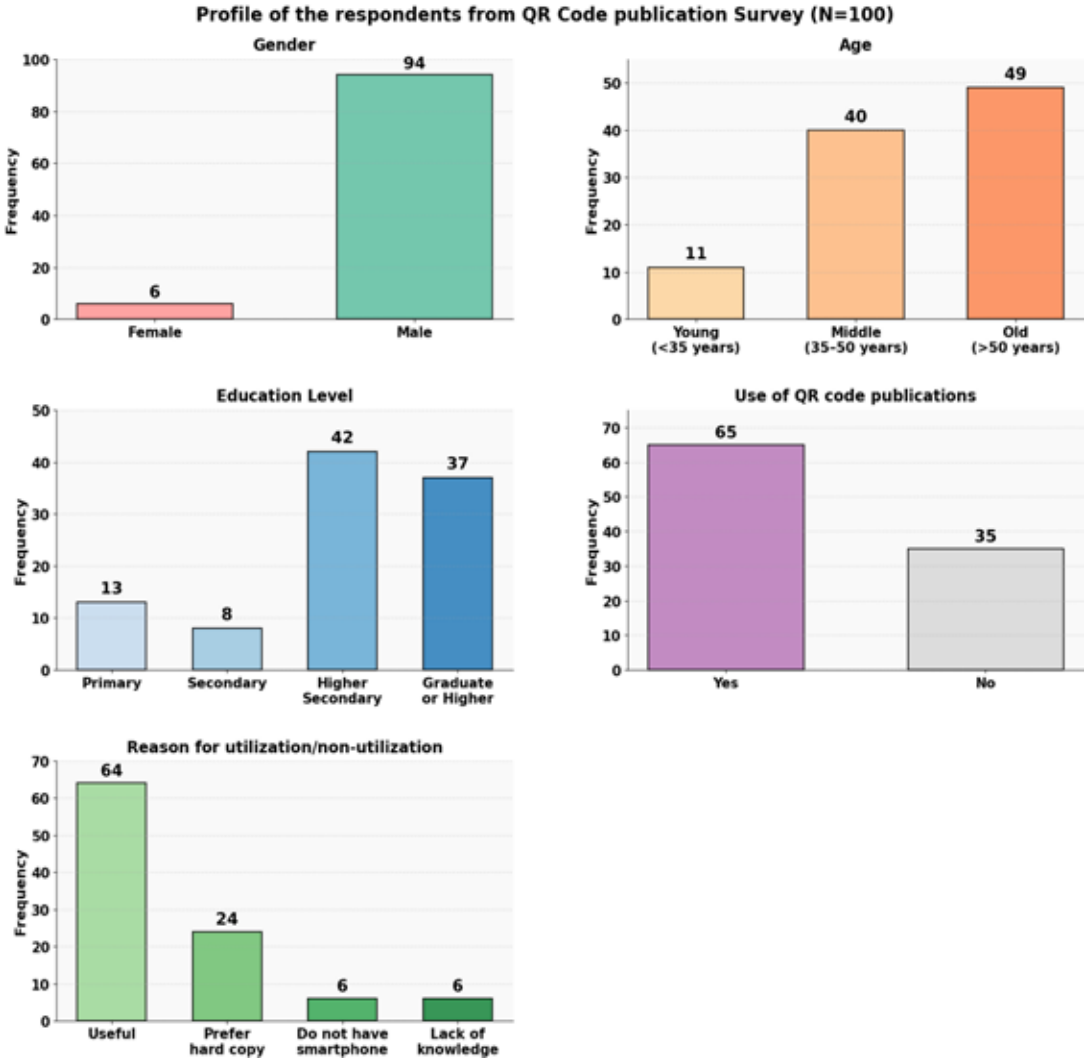


Fig. 2. Demographic distribution and utilization patterns of QR code publications among farmers (N=100)

Education

The educational profile reveals a relatively well-educated respondent base, with 42% having completed higher secondary education and 37% holding graduate or higher degrees. Primary and secondary education collectively account for 21% of respondents. This distribution suggests favorable conditions for QR code adoption, as higher education correlates positively with technology acceptance among Indian farmers (Kushwaha, 2025; Jaiswal *et al.*, 2024; Bajpai & Beriya, 2022). Nonetheless, the presence of respondents with lower educational attainment underscores the necessity for inclusive design and multilingual support systems to ensure equitable access across India (Kushwaha, 2025; Bajpai & Beriya, 2022).

QR-code access and utilization

The primary objective of the study was to evaluate farmers' ability to access agricultural publications using QR codes. The results showed that 65% of the respondents successfully viewed or downloaded the QR-

code-linked publications, whereas 35% were unable to access the documents (Fig. 2). This relatively high success rate demonstrates that QR codes can serve as an effective mechanism for disseminating agricultural information through smartphones. Similar observations have been reported by Atheequlla et al. (2024), who highlighted the usefulness of QR codes in improving access to horticultural information among stakeholders.

Out of 65% of the respondents who utilize QR code publications, 64% report finding them useful. This aligns with the Technology Acceptance Model in India, which identifies perceived usefulness as a key driver of adoption intent among farmers (Mishra *et al*. 2024; Zhang *et al*., 2024; Bhushan & Reddy, 2020). Non-adoption primarily stems from preference for traditional hard copy materials (24%), lack of smartphone access (6%) and unawareness of QR code functionality (6%). The dominance of hard copy preference underscores entrenched habits favoring conventional information sources, along with limited smartphone use and technological literacy issues. (Sangeethmon *et al*., 2025; Cole & Fernando, 2021; Atheequlla, 2024). These findings underline the critical need for targeted educational initiatives to enhance QR code literacy and facilitate equitable technology adoption among Indian farmers.

Follow-up assessment of QR-code publications

A brief follow-up assessment conducted during the subsequent crop season indicated that 64% of the respondents considered the QR-code publications useful for obtaining agricultural information. Among those who did not continue using the publications, 24% preferred conventional printed extension literature, 6% reported lack of smartphone availability, and 6% indicated limited awareness regarding QR-code technology (Table 1). These findings suggest that although farmers readily appreciate the convenience of digital publications, traditional extension materials continue to play an important role, particularly among respondents with lower digital literacy or limited access to smartphones. Similar findings have been reported by Cole and Fernando (2021), Mishra et al. (2024) and Atheequlla et al. (2024), who identified perceived usefulness, accessibility and digital literacy as important determinants of ICT adoption in agriculture.

Determinants of successful QR-code access

To identify the demographic factors influencing successful access to QR-code publications, binary logistic regression analysis was performed using successful QR-code access as the dependent variable and age, gender and educational level as explanatory variables (Table 2). The overall regression model was statistically significant (LR $\chi^2 = 34.04$, $P < 0.001$), indicating that the selected variables jointly explained a significant proportion of the variation in successful QR-code access. The model exhibited satisfactory performance, with a pseudo-R^2 value of 0.266 and an overall prediction accuracy of 75%, suggesting acceptable explanatory power for behavioural studies involving technology adoption.

Educational level emerged as a significant positive predictor of successful QR-code access ($\beta = 0.3028$, OR = 1.35, $P = 0.015$). The

Table 1. Follow-up feedback of respondents regarding QR-code publications

Parameter	Respondents (%)
Publications found useful	64
Preference for hard-copy publications	24
Lack of smartphone availability	6
Lack of awareness about QR-code technology	6

Table 2. Determinants of utilization of QR Code publications by respondent farmers

Variables	Coefficient	SE	Wald	z	P>|z|	Odds ratio
Gender	0.7594	1.0882	0.4869	0.6978	0.4853^{NS}	2.1369
Age	-0.0779	0.0289	7.2485	-2.6923	0.0071*	0.9250
Education	0.3028	0.1240	5.9574	2.4408	0.0147**	1.3536
const	0.3511	2.4279	0.0209	0.1446	0.8850	1.4207

Model Fit Statistics:
Number of observations = 100
LR chi^2 = 34.04
Prob > chi^2 = 0.00000
Pseudo R^2 = 0.2655
Log likelihood = -47.08
Accuracy of prediction = 75.0%

*Significant at P < 0.05, ** Significant at P < 0.01, NS: Not significant, OR=Odds Ratio

results indicate that respondents with higher educational attainment were more likely to successfully access QR-code publications than those with lower levels of education. Education enhances digital literacy, improves confidence in handling smartphone applications and increases the ability to retrieve online information. Similar relationships between educational attainment and digital technology adoption among farmers have been reported by Bajpai and Beriya (2022), Jaiswal *et al.* (2024) and Yap *et al.* (2025).

Age was negatively associated with successful QR-code access (β = –0.0779, OR = 0.925, P = 0.007), indicating that the probability of successfully accessing QR-code publications decreased with increasing age. Older respondents were comparatively less familiar with smartphone-based applications and digital interfaces, whereas younger farmers generally demonstrated greater confidence and proficiency in using mobile technologies. These findings corroborate the observations of Rogers (2003), Jadhav (2024) and Kushwaha (2025), who reported that younger farmers exhibit greater readiness to adopt digital innovations.

Gender did not significantly influence successful QR-code access (P = 0.485). However, this result should be interpreted cautiously because female respondents constituted only 6% of the study sample. Therefore, although gender was not a significant predictor within the present sample, the limited representation of women restricts broader generalization. Previous studies have similarly reported that gender differences in digital technology use often reflect disparities in access to smartphones, training opportunities and digital literacy rather than differences in the ability to use the technology itself (Venkatesh *et al.*, 2012; Saha *et al.*, 2024).

Implications for agricultural extension

The findings demonstrate that QR codes offer a practical, economical and scalable mechanism for disseminating agricultural information. Unlike printed extension materials, QR-code publications enable farmers to access updated recommendations instantly using smartphones, thereby reducing printing and distribution costs. Nevertheless, the study also highlighted that the effectiveness of QR-code-based extension depends largely on farmers' educational level and digital literacy. Therefore, QR codes should complement rather than replace conventional extension approaches. Capacity-building programmes focusing on digital literacy, particularly for older and less

educated farmers, along with multilingual publications and simple user interfaces, will be essential for maximizing the effectiveness and inclusiveness of QR-code-enabled agricultural extension systems.

CONCLUSION

QR codes demonstrated considerable potential as a rapid and low-cost mechanism for disseminating agricultural information, with 65% of participating farmers successfully accessing the digital publications. Age and educational level were significantly associated with successful QR-code access, whereas gender was not significant in the present sample. Follow-up feedback further indicated that perceived usefulness was high, although preference for printed material, limited smartphone access and low awareness of QR-code functionality remained important barriers. The findings suggest that QR-enabled extension materials should complement rather than immediately replace conventional publications. Digital literacy support, age-appropriate training and simplified access procedures may further improve adoption among diverse farming communities.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICAL APPROVAL

The study involved farmer participants attending training programmes. Participation in the survey was voluntary, and informed consent was obtained before recording demographic information and responses. No personally identifiable information is reported in the manuscript.

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YIELD GAP OF POTATO IN MEGHALAYA: A SEASONAL ANALYSIS

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ABSTRACT: Potato cultivation in Meghalaya is peculiar owing to its high consumption and cultivation in all the four seasons. Hence, the study was conducted during the year of 2022-23 in the state to investigate the yield gap and factors affecting it in two seasons, *viz.*, summer and winter, by employing both primary and secondary data. The Yield Gap I and II (YG I and YG II) were higher for winter potato whereas, summer potato had higher realized experimental yield. Size of farm, late blight incidence, lack of access to markets and prices of chemicals were positively related with the yield gap having the highest effect. Among the negatively related factors, the climate had the highest significant effect followed by fertilizer application. The study found that winter potato was not cultivated by many farmers due to higher cost of cultivation and concluded that the YG I was higher than the YG II. Given that YG I is largely limited by environmental and genetic factors, efficient demonstrations of technologies in farmer's field by ICAR institutes and CAU scientists along with the low-cost organic inputs to farmers can narrow down the yield gap II even more efficiently.

KEYWORDS: Factors, Potato, Seasons, Yield and Yield gap

INTRODUCTION

Potato (*Solanum tuberosum*) is a major cash crop that grows in temperate climatic conditions, however, currently they are being cultivated under diverse climatic conditions. It is one of the world's widely cultivated tuber crops being often referred to as "King of Vegetables" (Bhajantri, 2011; Mondal and Lah, 2022). Potatoes are the rich source of carbohydrates with starch content varying from 70 to 90 per cent on a dry matter basis according to the varieties (Nofrarias *et al.*, 2009). Owing to high nutritional value and as a major player in food security across South America, Africa and Asia, potatoes rank third in terms of consumption after rice and wheat (Devaux *et al.*, 2014). Subsequently from 1960s, the expansion of production area of potato in emergent nations have rapidly overtaken all other food crops. As per the year of 2024, China is the world's largest producer of potato with a production of 94.81 million tonnes, followed by India with 57.05 million tonnes. These two countries, together, accounted for approximately 38.9 per cent of the global potato production of 390.32 million tonnes. (FAOSTAT, 2025).

In India, people were acquainted with potato cultivation during the early 17th century (Lama and Bordoloi, 2017), which has been currently adopted for cultivation in various agro-climatic conditions across all states of the country.

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However, due to the low temperature requirements to acquire the maximum yield, potatoes are cultivated extensively in the hilly regions of the country (CPRI, 2020). In the North-Eastern (NE) region of India, potato is grown in all states, accounting for 2.15 per cent of the country's total potato production (Indiastatagri, 2021). Assam, Meghalaya and Tripura had the highest production of potato in NER with the prominent cultivated varieties of *Kufri Jyoti* and *Kufri Megha* (GoM, 2020). Meghalaya is the second largest producer of potato after Assam in North East region. The unique cultivation of potatoes on a seasonal basis is identified in Meghalaya where the farmers cultivate the crop in all four seasons that varies based upon the districts. East Khasi and West Khasi hills districts are accustomed to the cultivation of spring and summer potatoes, whereas West Khasi hills and West Garo Hills are adapted to the cultivation of autumn and winter potatoes, respectively (GoM, 2020).

Potatoes are the highest produced vegetable in the country, with an estimated production of 59.89 million tonnes during 2025-26 (GoI, 2026). Numerous studies on potato (Rajavardhan *et al.,* 2020; Pandey *et al.,* 2018; Lama and Bordoloi, 2017; Sagolsem *et al.,* 2017; Rani and Mathur, 2013; Pandit and Chandran, 2011) only depicted the scenario of potato area, production and yield in terms of trend analysis that resulted in a positive growth over the years from all the three aspects in the country. However, the focus on yield of potato and its difference between the research field and farmers' field were relatively less in India.

Yield gap analysis studies the differences in the yield obtained at three different fields *viz.,* research station, demonstration fields and farmers' fields. This illustrates the extent of adoption of technologies and packages of practices by the farmers as recommended by the scientists. Around the country, yield gap researches (Kemboi *et al.,* 2021; Singh and Sheikh, 2017; Lalit *et al.,* 2015; Kumbhare *et al.,* 2014) had been carried out in milk, rice cultivars, red gram and pigeon pea, respectively. However, studying this difference in the highest produced vegetable of the country, potato, was lacking, especially in Meghalaya. Hence, the present study was undertaken in the East Khasi Hills of Meghalaya with the following specific objectives:

1. To assess the yield gap of summer and winter potato cultivated in the study area
2. To identify the factors determining the yield gap of potato in the study area

MATERIALS AND METHODS

Study Area and Sampling

The study was conducted in the East Khasi Hills district of Meghalaya using a multi stage sampling technique, where the state and district were purposively selected owing to the highest area and production of potato (GoM, 2020). Followed by, the blocks of Mawryngkneng and Laitkroh Khatarshnong were selected due to the highest area and production of both summer and winter potatoes as per the secondary data provided by the district office, Department of Horticulture (DoH). Two villages each from the selected blocks were selected purposively based on the highest potato growers as reported by the Horticulture Development Officers (HDOs). Based on the proportionate to population technique, a sample size of 78 potato growers altogether were enumerated from the four villages. The quantitative data on yield of potato for summer and winter seasons were collected separately from each respondent and a combination of quantitative and qualitative data for factors were also gathered.

Data collection

The use of both primary and secondary data were carried out for the study. The primary data were collected from the respondents using a pre-tested and well-structured interview schedule. The secondary data for experimental station or research station yield was taken from the annual report of Central Potato Research Institute (CPRI, 2020) and the data on potential yield or demonstration yield was taken from the annual report of ICAR-Agricultural Technology Application Research Institute, Zone VII (ICAR-NEH ATARI, 2020). They were then used in the respective formulae of yield gap to obtain the difference.

Analytical Framework

Descriptive analysis

The inference from the results were drawn with the help of the descriptive tools such as sum, differences, averages and percentages for both the seasons of potato cultivation.

Empirical analysis

The analysis of yield gaps from cultivation of potato during the two seasons in the study area was carried out by employing the standardized yield gap concepts and formulae. The differences between the respective yields were calculated for both the seasons separately that resulted in two yield gaps *viz.,* YG I and YG II. Finally, the total yield gap was determined by summing up both the yield gap I and II.

Yield Gap I = Experimental Station Yield (Y_r) – Potential Farm Yield (Y_p)

Yield Gap II = Potential Farm Yield (Y_p) – Actual Farm Yield (Y_f)

Total Yield Gap = Yield Gap I + Yield Gap II

The index of the realized potential yield and index of realized potential farm yield were also calculated for both the seasons separately resulting in two different indices.

Additionally, the percentage of yield gap was also calculated for YG I and percent of YG II using the below formulae;

$$\text{Percentage of yield gap (YGI)} = \left(\frac{\text{Yield gap}}{\text{Potential farm yield}}\right) \times 100$$

$$\text{Percentage of yield gap (YGII)} = \left(\frac{\text{Yield gap}}{\text{Actual farm yield}}\right) \times 100$$

Finally, for the factors affecting the yield gap, a total of 27 factors were taken into consideration and were grouped into six categories, *viz.,* producer factors (X_1,X_2,X_3), physical factors (X_4,X_5,X_6), production factors (X_7,……,X_{15}), biotic factors (X_{16},……. X_{19}), economic factors (X_{20},……,X_{24}) and extension factors ($X_{25,}$……,X_{27}). Multiple linear regression analysis was carried out with the total yield gap (summing up the yield gap I and II for both summer and winter potatoes for each respondent) as the dependent variable. The qualitative independent variables of desirable categories were regressed as dummy variables based on the response from the farmers as 0 for "Yes" and 1 for "No". The model specified for the regression analysis with the independent variables are presented below.

$$Y = f(X_1, X_2, X_3, X_4, \ldots\ldots\ldots\ldots\ldots\ldots, X_{27})$$

Where,

Y	Yield gap	X14	Availability of machine labour
X1	Size of farm	X15	Availability of human labour
X2	Experience	X16	Weed competition
X3	Education	X17	Seed-borne diseases
X4	Climate	X18	Late blight incidence
X5	Topography	X19	Bacterial wilt
X6	Landslides/ Erosion	X20	Price of tubers
X7	Variety of potato	X21	Cost of labour
X8	Planting practices	X22	Price of chemicals

X9	Prolonged usage of farm saved seeds	X23	Price of output
X10	Irrigation	X24	Lack of access to markets
X11	Application of fertilisers	X25	Lack of new technology
X12	Quantity of input application	X26	Adoption of technology
X13	Timing of input application	X27	Contact between farmers and extension workers

RESULTS AND DISCUSSION

In the study, efforts were taken to determine the yield gaps obtained during the cultivation of potato in summer and winter seasons individually and finally summing them up to obtain the total yield gap. Finally, the factors responsible for creating this gap were also evaluated and interpreted under two sections *viz.*, yield gap of potato across various seasons and various factors affecting yield gap of potato.

Yield Gap of potato across various seasons

The yield gap was calculated for two different seasons *viz.*, summer and winter, and finally the total yield gap was estimated as in Table 1. The yield gap I (YG I) and yield gap II (YG II) were the highest in winter potato than summer, contributing to 38.89 per cent and 29.07 per cent of yield gap, respectively (similarly reported by Kumar *et al.*(2011) on rapeseed and mustard and Mondal (2011) on Wheat). It may be because, most of the farmers did not cultivate potato during winter season owing to the bad weather, market conditions and higher cost of cultivation. On the other hand, the lower yield gap for summer potato may be attributed to the prevalent cultivation of potatoes during this season as the local demand used to be high. Similar findings were reported by Hiremath and Hilli (2012) on chilli and Mondal (2011) on potato.

Table 1. Seasonal variation in yield gaps and realized potential yield of potato

Particulars	Summer potato	Winter potato	Difference
Yield Gap I (kg/ha)	4217	5409	1192
Yield Gap II (kg/ha)	1434.49	2471.51	1037.02
Total Yield Gap (kg/ha)	5651.49	7880.51	2229.02
Percentage of Yield Gap I (%)	27.42	38.89	11.47
Percentage of Yield Gap II (%)	12.85	29.07	16.22
Index of realized potential yield	0.70	0.43	0.27
Index of realized potential farm yield	0.87	0.71	0.16

The Index of realized potential yield revealed that farmers were able to realize about 70 per cent of the experimental yield in summer season and 43 per cent in winter. Similarly, 87 per cent of the demonstration yield was realized by the farmers in summer season and 71 per cent in winter season. This reveals that farmers were able to reach the higher level of experimental and potential yield during summer but only potential yield in winter season. Also, the farmers' cultivation practices were better and improving as they were nearing to achieve the potential yield (Front Line Demonstrations (FLDs) in both the seasons. However, the achievement of experimental yield by the farmers was more lacking in winter than summer, indicating that the technological gap (YG I) is greater than that of the extension gap (YG II). It reveals that farmers were better aware about the practices and technologies and applied it wisely to reap better returns.

Various factors affecting yield gap of potato

The information on factors affecting yield gap were collected from the potato growers and analyzed using multiple linear regression as presented in Table 2.

The null hypothesis stated that the factors were statistically insignificant. However, among 27 factors, 13 factors were significant

Table 2. Regression coefficients of independent variables influencing potato yield gaps

Categories	Independent variables	Regression coefficient	p-values
Producer factors	Size of farm	1016.72	0.013**
	Experience	6.7452	0.884
	Education	-1518.8	0.000***
Physical factors	Climatic conditions	-6242.57	0.000***
	Topography	-1730.68	0.008***
	Landslides/Erosion	-460.77	0.486
Production factors	Variety of potato	283.76	0.693
	Planting practices	-2308.16	0.009***
	Prolonged usage of farm saved seeds	616.16	0.540
	Irrigation	-2567.21	0.001***
	Application of fertilisers	-4112.94	0.000***
	Quantity of Input application	-77.56	0.904
	Timing of input application	834.05	0.191
	Availability of machine labour	-1774.64	0.008***
	Availability of human labour	829.77	0.284
Biotic factors	Weed competition	1420.35	0.134
	Seed-borne diseases	-12.99	0.989
	Late blight incidence	2288.46	0.014**
	Bacterial wilt incidence	110.75	0.903
Economic factors	Price of tubers	651.84	0.508
	Cost of labour	-845.54	0.397
	Price of chemicals	2358.74	0.011**
	Price of output	-17.13	0.985
	Lack of access to markets	1721.45	0.078*
Extension factors	Lack of new technology	-189.04	0.792
	Adoption of technology	-4108.66	0.000***
	Contact between farmers and extension workers	-4584.95	0.000***

Note: ***, ** & * indicates significance at 1, 5 and 10 per cent level

with lower p-values and hence, the null hypothesis was rejected. Of the 13 significant factors, 10 were significant at 1 per cent level indicating the highest effect of the factors on YG, whereas two were significant at 5 per cent level and one was significant at 10 per cent level.

The significant producer factors were Size of farm and Education, in which the former was positively related indicating the importance of utilization of recommended package of practices than the area of farm. The negative relationship of Education reveals that, if farmers are highly educated, efficient resource allocation and use was possibly, leading to decreased YG. Similarly, among the physical factors, climatic conditions and topography had significant but an inverse effect indicating that a state like Meghalaya with high rainfall pattern, crop losses occur which leads to widening of gap. Also, it was observed that during dry season incidence of cut worm caused crop losses and hence yield gap occurred.

Among the production factors, four factors were significant at 1 per cent level of significance with an inverse relationship to yield gap. The major factor was the non-adoption of recommended package of practices by the farmers, where majority were planting tubers in buns rather than ridges and furrows and none of them irrigate or apply fertilizer as recommended due to dependency on rainfall and higher cost of the chemicals, respectively. Moreover, given the slope of the study area, usage and hiring of machines became very tedious procedure for the farmers. In the biotic factors category, it was identified that the increase in the late blight incidence led to flaring of yield gap and it was directly related.

The major economic factors were price of chemicals and lack of access to markets, both having a direct effect on YG. The extension factors such as adoption of technology and contact of farmers with extension workers had inverse relationship with YG indicating that increased adoption and enhanced contact would narrow the yield gap.

CONCLUSION

The study revealed the existence of substantial yield gaps in cultivation of potato in Meghalaya, where potato cultivation in winter season recorded higher gaps. The farmers were able to realize yields beyond the experimental yields in both seasons and the realization of yield was highly observed during summer season. The findings highlight the scope for improving productivity through better management practices, identifying and promoting season-specific production practices suited to the agro-climatic conditions of the state. Hence, greater emphasis must be given to bridge the gap between the available production potential and its realization at the farm level. The significant factors such as farm size, late blight incidence, input prices and access to transportation highlights the need for affordable crop protection measures and improved access to locally suitable plant protection technologies. The strengthening of extension support for integrated nutrient, pest management and timely dissemination of location-specific advisories can contribute in narrowing the yield gap.

Therefore, the policy interventions should focus to improve the farmer's access to low-cost and environmentally sustainable inputs such as bio-fertilizers and bio-pesticides, in line with the state's emphasis on organic and sustainable agriculture. Seasonal recommendations should be developed based on local agro-climatic conditions, with greater attention to winter potato production as productivity constraints were more pronounced. Additionally, regular technical guidance from ICAR institutes, Central Agricultural University and the state agricultural extension system should be strengthened along with relevant government programs to translate the available production potential into higher and more stable farm-level productivity. Hence, a coordinated approach of research institutions, extension agencies and state government would enhance potato productivity and strengthen potato-based livelihoods and food security in the state and the wider North-Eastern region.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICAL STATEMENT

The authors ensure that the study is completely original and does not contain any data or information from studies conducted by any of the authors.

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POTATO TRADE DYNAMICS IN INDIA: A MARKOV CHAIN ANALYSIS

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ABSTRACT: An attempt has been made in this paper to study direction of trade of Indian potato. The study is based on secondary data collected for the periods 2003-04 to 2022-23 on area, production and productivity of potato in India and period 2014-15 to 2023-24 on destination-wise export of potato from India. Besides simple tabular analysis, compound growth rates (CGRs), Coppock's instability index and Markov Chain analysis were used to derive the inferences of the study. In India, area, production and productivity of potato have registered positive and significant growth rate of 2.80, 4.83 and 1.97 per cent per annum, respectively. This clearly indicates that the production of potato in India increased due to area expansion followed by yield improvement. The instability index in area, production and productivity was 4.91, 8.85 and 6.86 per cent, respectively which may be considered relatively low. It was further found that Nepal was the most stable country among major importers of Indian potato as reflected by its high probability of retention (78%). All other countries (Oman, Malaysia, Sri Lanka and UAE) had zero probability of retention, hence are most unstable.

KEYWORDS: Compound Growth Rate, Coppock's Instability Index, Markov Chain Analysis

INTRODUCTION

Agricultural sector is playing an important role in linking Indian farmers to ultimate consumers in the domestic and international markets. Indian agricultural sector is playing an important role in supplying sufficient food to meet the food demand for fast growing population of the country, raw materials for agro-based industry, export surplus and employment opportunity to 42.60 percent population in the country.

The share of agriculture and allied sector to India's total gross value added (Rs 452081.8 billion) at current price was 21.10 per cent in 2022-23 (Agricultural statistics at a glance, 2023). India's agricultural sector has gone to a remarkable transformation from food-deficit to the exportable surplus generation after meeting the domestic requirements of the fast-growing population of the country (Singh and Sain, 2003). India is blessed with 15 agro-climatic zones, 141 million ha of net cropping area, a diverse group of the population, and their internal demand for food which is supported by 48.9% of the working population in agriculture (Panigrahy and Kalamkar, 2024). Horticulture occupies only 5.6 percent of gross cropped area of the country but contributes about 25 per cent to agriculture GDP of India (Goyal *et al*., 2020)

At global level potato is one of the most important crops as it is produced in almost every corner of the world. Its production at world level reached at 374.7 million tonnes

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covering 17.78 million hectare and 21.06 t/ha yield during the year 2022 (FAO, 2022). Export of Indian potato has increased from almost 166 thousand tonnes to around 442 thousand tonenes in the year 2022 which signifies the importance of the crop at global level. Nepal has always been the best export destination for export of potato from India as it has ranked number one in term of the total quantity exported from India. India is the second largest producer of potato after China with a total production of 56.17 mt contributing around 15 per cent of total global production (FAO, 2022). In India, five major potato producing states *viz*. Uttar Pradesh, West Bengal, Bihar, Gujrat, Madhya Pradesh, together produce about four-fifth of total production in the country. And most of potato in India (85-90%) is produced during rabi season. In *kharif* season it is cultivated in Karnataka, Maharashtra, Himachal Pradesh and Uttarakhand. (Pant *et al*., 2020).

Despite a leading role of the nation in potato area, production and productivity, the same have been fluctuating from one year to another. A very few studies have been conducted in the recent years which describes the growth and instability in potato. Moreover, a very rare studies calculated the growth and instability of potato at national level. Additionally, there is a lack of literature to analyze the direction of trade of potato from India. Although a sufficient literature is available for the other fruits and vegetable. Moreover, the majority of current research tends to be predominantly descriptive and fails to sufficiently reflect the evolving dynamics of export markets over time. In this regard, employing a Markov Chain methodology to analyze trade direction offers a more rigorous and scientific framework, facilitating a better comprehension of transitional probabilities and the stability of export markets. This method allows for the identification of both loyal and emerging markets, thus providing more profound insights into the structural transformations within India's potato trade.

The present study tries to fill the gap to analyze the trends in area, production and productivity of potato in India over a period of last 20 years. Further this study tries to find the direction of trade of potato from India. India is the second largest producer of potato at global level whereas it ranks 10th in term of global export which enhances the importance to study the direction of trade of Indian potatoes.

MATERIAL AND METHODS

The study is based on secondary data on area, production, productivity, export quantity and export earnings of potato from India. The data were collected from different published sources such as; APEDA, Indiastat and FAO for the periods 2003-04 to 2023-24. The timeframe from 2014–15 to 2023–24 was chosen for the analysis of exports due to the presence of reliable and up-to-date data, which accurately represents the prevailing trade patterns and developing trends in the export of potatoes from India.

Growth rate analysis

Compound growth rates (CGR) were calculated to find out trend in area, production and productivity of potato in India for the period of last 20 years *i.e.* 2003-04 to 2022-23. The compound growth rates were computed using the exponential function of the form:

$$Y_t = ab^t u_t$$

$$\text{Log } Y_t = \text{Log } a + t \text{ Log } b + \text{Log } u_t$$

Where,

Y_t = Area/production/productivity/export of potato in year 't'

t = Time elements which take the value 1, 2, 3, …..,n

a = Intercept

b = Regression coefficient

u_t = Error term

Compound growth rates were worked out as follow:

Compound growth rate (r) = (antilog b-1) ×100

The standard error of the growth rate was estimated and tested for its significance with 't' statistic.

Instability – Coppock's instability index

A number of statistical measures are available in literature to measure the instability index. Coppock (1962), MacBean (1966), Massel (1970), Weber and Sievers (1985), Singh and Byerlee (1990), Cuddy and Della Valle (1978) and Wasim (1997) have made use of different techniques of measuring instability index. In this study, the instability was estimated using Coppock's instability index (Coppock, 1962). Coppock's instability index is a close approximation of the average year to year per cent variation adjusted for trend. The estimated form is given below:

$$CII = \left[(\text{Antilog})\sqrt{V\log - 1}\right] x100$$

Where:

$$V\log = \frac{1}{N-1}\sum(\log X_{t+1} - \log X_t - M)^2$$

$$M = \frac{1}{N-1}\sum(\log X_{t+1} - \log X_t)$$

N = Number of years

X = Value of parameter

M = Arithmetic mean of the differences between logs of X_t, X_{t+1} and X_{t+2}, etc.

Markov chain model

The major potato importing countries from India are Nepal, Oman, Malaysia, Sri Lanka and U Arab Emirates. Annual export data of potato were used for analyzing the direction of trade and changing pattern of Indian potato export. The trade directions of Indian potato exports were analyzed using the first order Markov chain approach. The Markov Chain methodology is especially effective for examining trade dynamics, as it summarizes the probabilistic transitions and variations in export shares across various importing nations over time. Additionally, it aids in evaluating the stability and retention ability of export markets. The lingo software was adopted to study the transition probability matrix. Central to Markov chain analysis is the estimation of the transitional probability matrix 'P' whose elements, P_{ij} indicate the probability of exports switching from country 'i' to country 'j' over time. The diagonal element P_{ij} where i=j, measures the probability of a country retaining its market share or in other words, the loyalty of an importing country to a particular country's exports. Annual export data for period 2014-15 to 2023-24 were used to analyze the direction of trade and changing pattern of Indian potato export. In this context, major potato importing countries *viz.*, Nepal, Oman, Malaysia, Sri Lanka and U Arab Emirates, remaining countries clubbed as other countries. The average exports to a particular country were considered to be a random variable which depends only on the past exports to that country, which can be denoted algebraically as

$$E_{jt} = \sum_{i=0}^{n} E_{it-1} * P_{ij} + e_{jt}$$

Where,

E_{jt} = exports from India to the j^{th} country in the year t

E_{it-1} = exports of i^{th} country during the year t-1

P_{ij} = the probability that exports will shift from i^{th} country to j^{th} country

e_{jt} = the error term which is statistically independent of E_{it-1}

n = the number of importing countries

The transitional probabilities P_{ij}, which can be arranged in a (c x n) matrix, have the following properties:

$$\sum_{i=1}^{n} P_{ij} = 1 \quad \text{and} \quad 0 \le P_{ij} \le 1 = 1,$$

Thus, the expected export share of each country during period 't' is obtained by multiplying the exports to these countries in

the previous period (t-1) with the transitional probability matrix.

RESULTS AND DISCUSSION

Trends in area, production, productivity of potato in India

The trend in area, production and productivity of potato in India is shown in Table 1 and Figures 1 to 3. The table shows that the area under potato was 1289.2 thousand ha during 2003-04 which increased to 2332.2 thousand ha during 2022-23 registering an increase by 4.04 per cent per annum, the average yield increased from

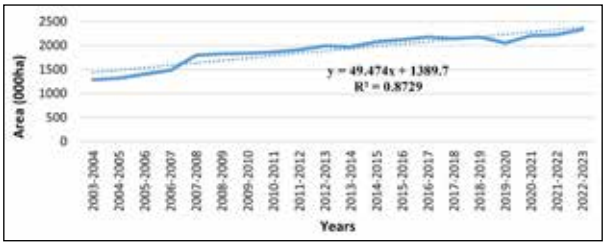


Fig. 1. Trends in area of potato in India



Fig. 2. Trends in production of potato in India

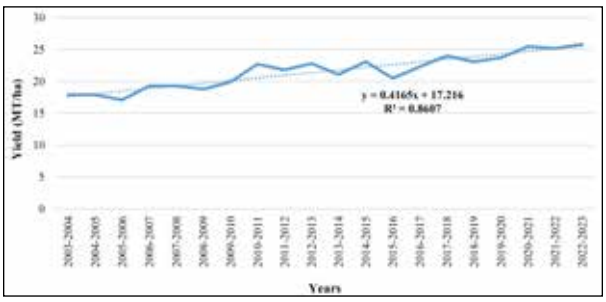


Fig. 3. Trends in productivity of potato in India

Table 1. Trends in area, production and productivity of potato in India

Year	Area (000 Hectare)	Production (000 MT)	Productivity (In MT/ Hectare)
2003-2004	1289.2	23060	17.9
2004-2005	1318.5	23631	17.9
2005-2006	1401.4	23905	17.1
2006-2007	1482.3	28600	19.3
2007-2008	1795.0	34658	19.3
2008-2009	1828.3	34391	18.8
2009-2010	1835.3	36577	19.9
2010-2011	1863.2	42339	22.7
2011-2012	1907.0	41483	21.8
2012-2013	1992.2	45344	22.8
2013-2014	1973.2	41555	21.1
2014-2015	2075.9	48009	23.1
2015-2016	2117.0	43417	20.5
2016-2017	2179.0	48605	22.3
2017-2018	2142.0	51310	24.0
2018-2019	2173.0	50190	23.1
2019-2020	2051.0	48562	23.7
2020-2021	2203.0	56173	25.5
2021-2022	2225.7	56176	25.2
2022-2023	2332.2	60142	25.8
Average	1909.22	41906.35	21.59
Annual % age change	4.04	8.04	2.21
CAGR	2.80**	4.83**	1.97**
Instability	4.91	8.85	6.86

Note: **Significant at 1 per cent probability level

17.9 MT/hectare during 2003-04 to 25.8 MT/ hectare during 2022-23 registering an increase by 2.21 per cent per annum. Due to positive growth in area as well productivity, the total production of potato in India which was 23060 thousand MT in 2003-04 increased to 60142 thousand MT in 2022-23 registering an annual increase of 8.04 per cent.

The figures 1 to 3 depicts that during the last 20 years, area, production and productivity of potato crop in India registered an annual increase at the rate of 49.47 thousand ha,

1827 thousand tonnes and productivity 0.41 MT/ha, respectively. The yearly compound growth rates reveals that the increase in production (4.83%) was mainly contributed to the expansion of area (2.80%) and yield (1.97%) under potato. This implies that although technological advancements have had an impact, the growth area remains a significant factor, underscoring the potential for additional productivity improvements through better varieties and management techniques.

The instability in area, production and productivity was 4.91, 8.85 and 6.86 percent, respectively.—The comparatively greater instability in production, when contrasted with area and yield, indicate the susceptibility to external factors such as variations in weather and fluctuations in the market. This highlights the necessity for stabilization policies, which may encompass enhanced storage infrastructure and mechanisms for price support.

Destination of potato export from India in 2023-24

The destination-wise export country-wise percentage share in total quantity and total value of potato and for the year 2023-24 is presented in Table 2. It is evident from the table that total potato export in 2023-24 was 500.54 thousand tonnes with the total export value of ₹83261.48 lakh. It is also clear from the table that in terms of quantity exported, Nepal with 47.33 percent share was the highest importer followed by Oman (8.74%), Malaysia (3.49%), Sri Lanka (2.88%) and UAE (2.67%). In terms of export earnings also, Nepal with 30.76 percent share of total export value from India topped the list. Oman (12.42%) stood at 2nd place followed by Malaysia (5.23%), Sri Lanka (3.97%) and UAE (3.86%), etc. The predominance of Nepal as a significant export destination reflects a considerable market concentration, potentially rendering Indian exports vulnerable to regional demand fluctuations. Consequently, it is crucial to diversify into alternative markets to mitigate dependency and strengthen export resilience.

Table 2. Destination-wise export of potato from India to major importing countries, 2023- 24.

Sr. No.	Country	Quantity (MT)	% in total quantity	Value (₹ Lakh)	% in total value
1	Nepal	236883.43	47.33	25611.73	30.76
2	Oman	43739.00	8.74	10340.61	12.42
3	Malaysia	17473.48	3.49	4358.35	5.23
4	Sri Lanka	14417.95	2.88	3309.34	3.97
5	U Arab Emts	13381.61	2.67	3215.76	3.86
6	Others	162715.71	32.51	33514.05	40.32
	Total	500541.25	100.00	83261.48	100.00

Note: Export values are at constant prices: base year - 2011-2012

Direction of trade of Indian potato export

The knowledge of changing export trade across the destinations is of paramount importance. The Markov chain analysis was employed to study the structural changes in export proportion of Indian potato to the major destinations. The transitional probability matrix was computed for export of potato. The Transitional probability Matrix revealed a broad indication of changes in the direction of export of potato from India for the study period (2014-15 to 2023-24). The transitional probability matrix was obtained for the study period by using the actual proportion of exports to different importing countries. This matrix explains the changing direction of trade among the importing countries.

The row elements in a matrix indicate the probability of loss in trade on account of competing countries. The column elements indicate the probability of gain in trade from

other competing countries. The transitional probability matrix for Indian potato exports is presented in Table 3 which gives a broad indication of change in direction of potato trade for the study period (2014-15 to 2023-24). The top five importing countries considered for the study were Nepal, Oman, Malaysia, Sri Lanka and U Arab Emts. The exports to other than these countries were pooled under the broad head "Others".

The table indicates the probability matrix ~~indicates that~~ during the current period (2023-24) which reveals that Nepal is the most stable market amongst the studied markets as it has retained to the extent of about 78 per cent of its share. On the other hand, 5 per cent of its share was lost to Oman, 5 percent to Sri Lanka and 8 percent to 'Others'. The transition probabilities indicate considerable volatility across the majority of markets, with the exception of Nepal, which points to a lack of strong market retention in alternative destinations. This observation implies restricted long-term trade relationships and possible competitiveness challenges within these markets. The complete shifts in market shares observed for countries like Oman, Malaysia, Sri Lanka, and the UAE indicate unstable trade connections, which may be attributed to factors such as price competitiveness, variations in quality, or evolving import preferences.

The other countries could retain only 16 percent, losing its share to the extent of 55 per cent to Nepal, 13 percent to Oman and gaining 8 per cent from Nepal. The major gainers among importers of Indian potato during the reference period were Nepal, Oman and 'Others'. Nepal and Oman gained 100 percent share from Sri Lanka and UAE, respectively. Other countries gained 100 percent share from Oman and Malaysia.

Thus, transitional probability matrix presented in the Table 3 indicated that Nepal was the most stable country among major importers of Indian potato as reflected by its high probability of retention (78%). All other countries (Oman, Malaysia, Sri Lanka and UAE) had zero probability of retention, hence are most unstable.

From a policy point of view, the results underline the importance of encouraging export diversification strategies by investigating new markets outside of conventional destinations such as Nepal. Furthermore, enhancing supply chain efficiency, quality standards, and trade agreements can facilitate better market retention. Additionally, reinforcing cold storage infrastructure and export-oriented value chains can further mitigate instability and enhance competitiveness in global markets.

CONCLUSION

The research indicates a notable and significant increase in the area, production,

Table 3. Transitional Probability Matrix of Indian potato exports (2014-24)

Destination	Nepal	Oman	Malaysia	Sri Lanka	U Arab Emts	Others
Nepal	**0.78448**	0.04729	0.02363	0.04660	0.01455	0.08345
Oman	0	**0**	0	0	0	1
Malaysia	0	0	**0**	0	0	1
Sri Lanka	1	0	0	**0**	0	0
U Arab Emts	0	1	0	0	**0**	0
Others	0.55435	0.13905	0.09203	0	0.05456	**0.15994**

and productivity of potatoes in India, accompanied by relatively low instability levels. The trade analysis shows that Nepal is the most stable export destination, characterized by a high retention probability of 78 percent, whereas other markets demonstrate considerable instability. The concentration of exports in a limited number of countries underscores the risks associated with market dependence. From a policy point of view, it is essential to encourage export diversification by investigating new and emerging markets. Enhancing supply chain infrastructure, elevating quality standards, and boosting competitiveness can contribute to stabilizing current markets and expanding India's footprint in the global potato trade.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the author.

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ASSESSMENT OF DIFFERENT POTATO VARIETIES TO ENHANCE PRODUCTIVITY IN NALANDA DISTRICT UNDER ZONE-IIIB OF BIHAR

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ABSTRACT: Potato is a major crop of the Solanaceae family, ranks fourth globally in food consumption after rice, wheat and maize. India, the second-largest potato producer, contributes about 15.0% of global production, with Bihar emerging as a key potato-producing state, particularly Nalanda district, which is known for its higher-than-average yield of 36.46 t/ha. However, during 2023–24, a comparatively lower yield of this important crop was recorded, possibly due to the lack of quality, disease-free and heat-tolerant varieties suitable for the agro-climatic conditions of Bihar. Significant variability was observed for traits such as main stem height, number of tubers per plant, plant height, tuber dimensions, average tuber weight and yield. Kufri Pukhraj and Kufri Uday showed superior performance with higher tuber numbers, greater average tuber weight and higher yields, indicating their potential as superior genotypes. High heritability and genetic advance were observed for yield and tuber weight, suggesting good potential for direct selection. Moderate heritability for plant height and tuber diameter indicates the need for indirect selection and improved environmental management. Cluster analysis revealed grouping of yield-attributing traits such as tuber weight, number of tubers and plant density in a primary cluster, highlighting their combined influence on yield. These findings will help in formulating effective breeding strategies for developing high-yielding and disease-resistant potato varieties suitable for intensive cropping systems in Bihar, thereby contributing to sustainable agriculture and food security.

KEYWORDS: Potato varieties, Genetic Variability, Clustering, Correlation, Yield

INTRODUCTION

Potato (*Solanum tuberosum* L.) is considered as the king of vegetables that comes under Solanaceae family, which contains 100 genera and 2,500 species (Olmstead *et al*., 2008). It is also considered as staple food and ranks fourth after rice, wheat and maize in terms of food consumption (Li *et al*, 2026). It has been recognized as a wholesome food and the richest source of energy where it forms an important component of the daily diet. As efficient starch producing plants it contains more carbohydrates per unit area and time, rich in digestible protein, minerals, vitamins and high-quality dietary fibre. According to FAOSTAT (2024), China is the leading producer, contributing 25.5% of the global production, followed by India i.e., 15.0%. In India, the major potato-producing states include Uttar Pradesh (15.89 million tonnes),

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West Bengal (12.6 million tonnes), Bihar (9.13 million tonnes), Gujarat (3.78 million tonnes), Madhya Pradesh (3.58 million tonnes), Punjab (2.85 million tonnes), Haryana (0.77 million tonnes), Assam (0.762 million tonnes) and Jharkhand (0.73 million tonnes). Nalanda district in Bihar is particularly known for potato production with an average yield of 36.46 t/ha, which is higher than the state average of 27.60 t/ha (Anonymous, 2021). However, there is a huge possibility for increasing the potato yield in Bihar while, the key challenge for enhancing potato yields is the lack of availability of healthy, disease-free seed tubers along with awareness about new improved varieties developed by ICAR-CPRI, Shimla.

Globally potato is a major cash crop, consumed everyday by millions of people (FAO, 2015), and this wonder crop originated from the mountains of South America, where they have been a staple food for centuries. Increasing potato productivity per unit of farmland is crucial to meeting the global demand for this crop. Low yield of potato is due to use of local seed tubers and cultivation of old varieties (Ibrahim *et al*., 2018). It is important for breeders to provide food at cheaper rate to the millions of people numbers around the world by increasing the production of potatoes per unit area and per unit time (Zeleke *et al*., 2021). The presence of enough genetic variability in the population for yield and yield related traits should be considered as prerequisite support for any breeding programme. Moreover, the application of perfect breeding method is dependent on estimation of genetic gain of the characters for successful selection as to develop desirable traits (Umiyah *et al*., 2010). Genetic variability is the basis of all crop improvement programmes (Basvaraj *et al*., 2005). The nature of variability and association of yield with its components traits is important for identification of superior parents in any breeding program (Rahman, 2015). Therefore, the present study was conducted to assess the genetic variability of improved potato genotypes with the prime objective to identify superior high yielding and good quality potato varieties for the agro-climatic conditions of Bihar.

MATERIALS AND METHODS

The present research work was conducted at the research farm of NCOH Noorsarai. The site is located at 24.47°–25.16°N latitude and 84.12°–85.27°E longitude, at an altitude of 67 meters above mean sea level in the Indo-Gangetic plains of northeastern India. The varieties include Kufri Neelkanth, Kufri Lima, Kufri Pukhraj, Kufri Thar-2, Kufri Mohan, Kufri Uday/ Yushimap, BARI Aloo/7015 and Kufri Sangam, its mini-tubers (G_0) were procured from the Potato Technology Centre, Shamgar (Karnal). These varieties were assessed in the Agro-climatic Zone-IIIB of Bihar during the *Rabi* 2023-2024. The mini-tubers (G_0) used in this experiment were the purest seed material and almost free from viruses, diseases and pests.

The soil was sandy loam with a pH of 7.2, providing adequate fertility for crop growth. The region experiences a tropical to subtropical climate with hot summers and cold winters. Average temperatures range from 9°C to 43°C and the relative humidity fluctuates between 65% to 90%. The average annual rainfall was 1,035 mm, with 90% of it occurring during the southwest monsoon. Weather parameters, such as weekly precipitation, temperature and relative humidity, were recorded throughout the cropping season.

The data were analyzed using Analysis of Variance (ANOVA) as described by Panse and Sukhatme (1978). The genotypic (Vg) and phenotypic (Vp) variances were calculated

using standard statistical formulas. The genotypic coefficient of variation (GCV) and phenotypic coefficient of variation (PCV) were estimated by applying the methods proposed by Burton (1952). Heritability in the broad sense (h^2b) was determined according to Lush (1940) and the expected genetic advance as a percentage of the mean was calculated using the approach of Burton and Devane (1953) and Johnson et al. (1955).

RESULTS AND DISCUSSION

Performance of Potato Genotypes

The evaluation of eight potato genotypes under the agro-climatic conditions of Zone-IIIB of Bihar revealed considerable variability for most of the studied traits, indicating substantial scope for genetic improvement. Significant differences among genotypes were observed for traits such as main stem height, number of tubers per plant, number of plants per hill, plant height, maturity duration, tuber length, tuber diameter, average tuber weight and yield (q/ha).

The data presented in Table 1 indicated statistically significant variation among the genotypes. The height of the main stem varied significantly, with Bari Aloo-7015 exhibiting the tallest stems (69.00 cm), whereas Kufri Neelkanth recorded the shortest stems (42.90 cm). Such variation in stem height may be attributed to both genetic and environmental factors, as genotype × environment interactions often influence vegetative growth (Gupta *et al*., 2021).

The number of tubers per plant showed significant variation among the genotypes. Kufri Sangam (12.77) and Kufri Uday (12.67) produced the highest number of tubers per plant, indicating their potential contribution to higher yield. Bari Aloo-7015 showed the highest plant height (70.26 cm), followed by Kufri Pukhraj (68.76 cm), which is in agreement with the findings of Singh *et al*. (2019).

The varieties Kufri Mohan (12.33) and Kufri Sangam (12.00) recorded the highest number of plants per hill, an important parameter for efficient utilization of resources and yield stability, as reported by Mishra *et al*. (2020). Among the evaluated genotypes, Kufri Uday (Yusimap) showed the earliest maturity (100 days), making it suitable for regions with shorter growing seasons and enabling its integration into intensive cropping systems. Similar observations were reported by Gupta *et al*. (2018).

Table 1. Mean value of morphological traits in different potato varieties

Genotypes	Height of main stem	No. of tuber/ plant	Plant height (cm)	No. of plant/ hill	Maturity duration (days)	Tuber length (cm)	Tuber diameter (cm)	Average tuber weight (g)	Tuber yield (q/ ha)
Kufri Neelkanth	42.90*	10.73	58.65*	10.67	105.00	8.07*	5.17	89.53*	290.32
Kufri Mohan	47.10*	11.47	60.31*	12.33*	101.67*	7.13	4.77	92.23*	317.49*
Bari Aloo- 7015	69.00	11.33	70.26	10.00	108.67	7.00	5.20	88.82	301.98*
Kufri Pukhraj	46.53*	11.45	68.76	10.00	107.67	7.63	5.43*	95.21*	326.82*
Kufri Uday/ Yusimap	62.83	12.67	62.22	10.67	100.00*	7.50	4.97	82.81	314.85*
Kufri Sangam	50.67	12.77*	62.77	12.00*	110.67	7.33	4.63	71.22	272.32
Kufri Lima	49.03*	10.33	59.11*	10.67	113.67	7.83*	5.77*	94.93*	294.00
Kufri Thar-2	43.67*	10.13*	63.02	11.33*	109.33	8.10*	5.13	93.20*	282.91
CV (%)	18.30	8.60	6.77	7.90	4.30	5.41	7.02	9.11	13.18
CD at 5% d.f.	7.14	0.74	3.24	0.70	3.50	0.31	0.30	6.11	17.31

Regarding tuber characteristics, Kufri Thar-2 produced the longest tubers (8.10 cm), whereas Kufri Lima recorded the largest tuber diameter (5.77 cm), traits that are often preferred in the consumer market. The highest average tuber weight was observed in Kufri Pukhraj (95.21 g) followed by Kufri Lima (94.93 g), which are important yield-contributing traits as supported by Prakash *et al*. (2021); Kumar *et al*. (2025).

Overall, the superior performance of Kufri Pukhraj and Kufri Uday may be attributed to their higher tuber numbers, favorable tuber size and greater average tuber weight. These findings are consistent with Kumar *et al*. (2021), who emphasized the importance of identifying high-yielding genotypes for improving potato productivity in similar agro-climatic regions.

GCV, PCV, Heritability and Genetic advance

The genetic parameters including genotypic coefficient of variation (GCV), phenotypic coefficient of variation (PCV), heritability and genetic advance as percentage of mean were estimated and are presented in Table 2. In general, PCV values were slightly higher than GCV values for all traits, indicating the influence of environmental factors on the expression of these traits. However, the relatively small differences between GCV and PCV suggest that most of the variability observed was primarily genetic in nature. Similar results were reported by Seid et al. (2020), Zeleke *et al*. (2021), Annigeri and Hiremath (2022), Anoumaa *et al*. (2022) and Gebreselassie (2023).

High heritability estimates were observed for tuber length (93.08%), tuber diameter (85.54%) and average tuber weight (83.82%), indicating that these traits are largely governed by genetic factors and can be effectively improved through direct selection. Moderate heritability was recorded for plant height (29.27%), suggesting that environmental factors play a relatively larger role in determining this trait.

Tuber yield showed moderate heritability (9.97%) but relatively higher genetic advance, indicating the possibility of improving yield through selection based on associated yield-contributing traits. The highest genetic advance was observed for tuber yield, suggesting strong selection potential for improving productivity. Similar findings were reported by Luthra *et al*. (2018), Narasimhamurthy *et al*. (2018), Prajapati *et al*. (2020), Gadissa *et al*. (2020), Tessema *et al*. (2022) and Zanzam *et al*. (2023).

Table 2. GCV, PCV, Heritability and GA% of mean in potato genotypes

Character	GCV (%)	PCV (%)	Heritability (h^2b)	GA	GA% of mean
Height of main stem	17.44	19.91	76.71	6.12	11.90
No. of tubers/ plant	11.76	5.28	16.79	0.87	7.70
Plant height (cm)	5.04	9.31	29.27	3.51	5.56
No. of plant/ hill	2.44	13.19	3.42	0.86	7.88
Maturity duration (days)	3.16	5.94	1.98	3.80	3.54
Tuber length (cm)	5.35	5.54	93.08	0.25	3.31
Tuber diameter (cm)	6.83	7.38	85.54	0.23	4.41
Average tuber weight (g)	8.83	9.64	83.82	5.10	5.76
yield (q/ha)	0.04	13.90	9.97	24.90	8.30

Correlation Analysis

Correlation analysis revealed important associations among yield and its component traits. The height of the main stem showed a negative genotypic correlation with tuber length (−0.611). Plant height exhibited a moderate positive genotypic correlation with yield-related traits, indicating that increased vegetative growth may contribute to improved photosynthetic capacity and ultimately higher productivity. Similar findings were reported by Prakash and Pathak (2021).

Tuber length and tuber diameter showed moderate correlations with yield. Phenotypically, tuber length showed a strong positive association with yield (0.849), suggesting that larger tuber size may contribute significantly to overall productivity. These results are consistent with the observations reported by Kumar *et al*. (2021).

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was used to visualize the relationships among potato genotypes and agronomic traits. The PCA biplot revealed that the first principal component (PC1) accounted for 37.7% of the total variation, while the second principal component (PC2) explained 28.7% of the variation (Table 3). Together, PC1 and PC2 explained 66.4% of the total variability, indicating that the biplot provided a reliable representation of the relationships among genotypes and traits (Fig 1).

Traits positioned close to each other in the biplot indicated positive correlations, whereas traits located in opposite directions indicated negative correlations (Abdi and

Table 3. Genotypic and Phenotypic Correlation

Traits	Correlation	Height of main stem	No. of tubers/ plant	Plant height (cm)	No. of plant/hill	Maturity duration (days)	Tuber length (cm)	Tuber diameter (cm)	Average tuber weight (g)	yield (q/ha)
Height of main stem	Genotypic	1.000*								
	Phenotypic	1.000*								
No. of tubers/plant	Genotypic	0.367NS	1.000*							
	Phenotypic	0.610*	1.000*							
Plant height	Genotypic	0.381NS	0.199NS	1.000*						
	Phenotypic	0.381NS	0.098NS	1.000*						
No. of plant/hill	Genotypic	-0.074NS	0.060NS	0.218NS	1.000*					
	Phenotypic	-0.054NS	0.047NS	0.133NS	1.000*					
Maturity duration	Genotypic	-0.028NS	-0.312NS	-0.024NS	0.054NS	1.000*				
	Phenotypic	-0.017NS	-0.259NS	0.022NS	0.089NS	1.000*				
Fruit length	Genotypic	-0.611*	-0.407*	-0.511*	0.011NS	0.031NS	1.000*			
	Phenotypic	-0.693*	-0.388NS	-0.519*	0.020NS	-0.010NS	1.000*			
Fruit diameter	Genotypic	-0.109NS	-0.436*	-0.210NS	-0.380NS	0.299NS	0.394NS	1.000*		
	Phenotypic	-0.219NS	-0.442*	-0.074NS	-0.436*	0.273NS	0.400NS	1.000*		
Average fruit weight	Genotypic	0.234NS	-0.440*	0.136NS	-0.206NS	0.074NS	0.323NS	0.558*	1.000*	
	Phenotypic	-0.348NS	-0.418*	0.050NS	-0.246NS	0.274NS	0.378NS	0.530*	1.000*	
yield (q/ha)	Genotypic	0.197NS	0.672*	0.314NS	-0.106NS	-0.317NS	-0.147NS	0.018NS	0.365NS	1.000*
	Phenotypic	0.322NS	0.551*	0.274NS	-0.177NS	-0.383NS	-0.128NS	-0.012NS	0.329NS	1.000*

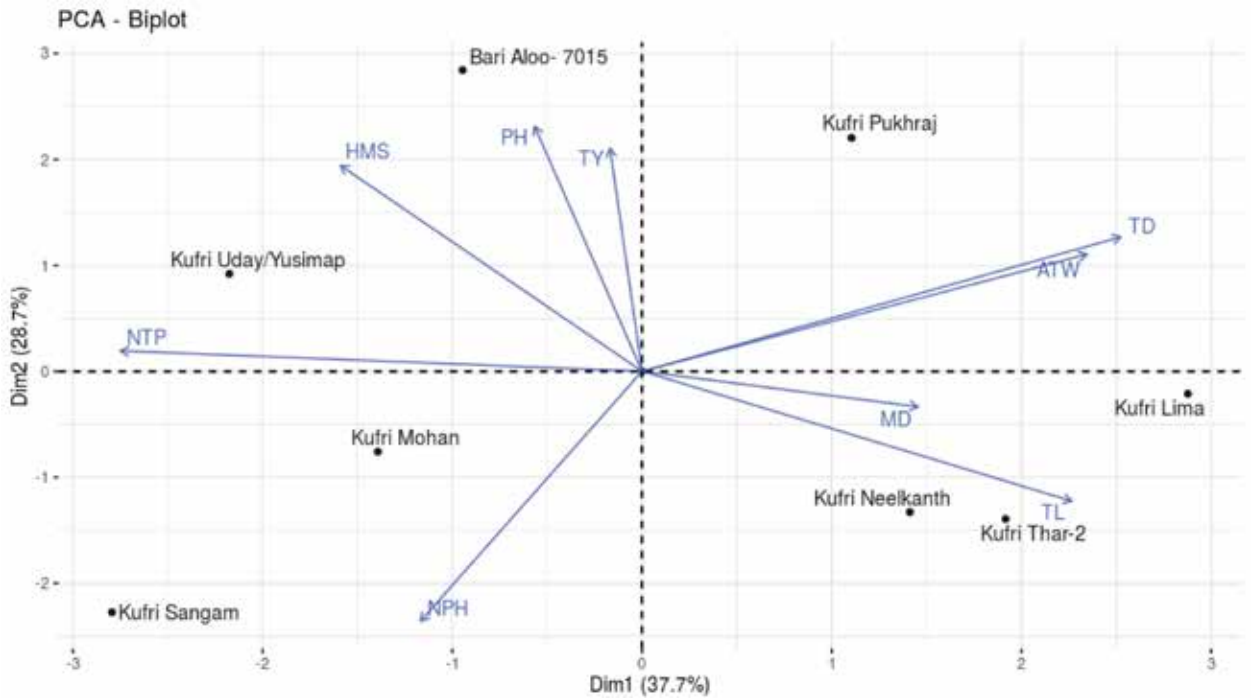


Fig. 1. Principal Component Analysis of Potato Varieties

Williams, 2010). The length of the vectors represented the magnitude of contribution of each trait to the total variation.

Traits such as average tuber weight and total yield were located in the positive region of PC1 and were closely clustered, indicating a strong positive association between these traits. PCA is widely used in potato breeding programs as it helps identify key traits contributing to genetic variability and assists breeders in selecting promising genotypes (Manrique *et al*., 2019).

The genotypes Kufri Mohan and Kufri Pukhraj were positioned close to each other, indicating similar trait performance, whereas Bari Aloo-7015 and Kufri Sangam were located farther apart, suggesting greater divergence among their agronomic traits. The dispersion pattern observed in the PCA plot corroborated the cluster analysis results, confirming the existence of substantial genetic variability among the evaluated genotypes.

Cluster Analysis

The dendrogram constructed using hierarchical clustering of the eight potato genotypes based on Euclidean distance clearly illustrated the genetic similarity and dissimilarity among the varieties. Two distinct genotype pairs exhibited close similarity: Kufri Neelkanth and Kufri Thar-2 showed the lowest Euclidean distance, indicating a high degree of similarity in their agronomic characteristics. Similarly, Kufri Mohan and Kufri Uday were also closely associated, suggesting comparable performance across several evaluated traits (Fig.2). The results are in conformity with the findings of Kumar *et al*. (2025).

From the hierarchical classification, Bari Aloo-7015 and Kufri Pukhraj formed an independent cluster, which later merged with a larger cluster comprising Kufri Lima, Kufri Neelkanth and Kufri Thar-2. Finally, all genotypes converged into a single cluster at

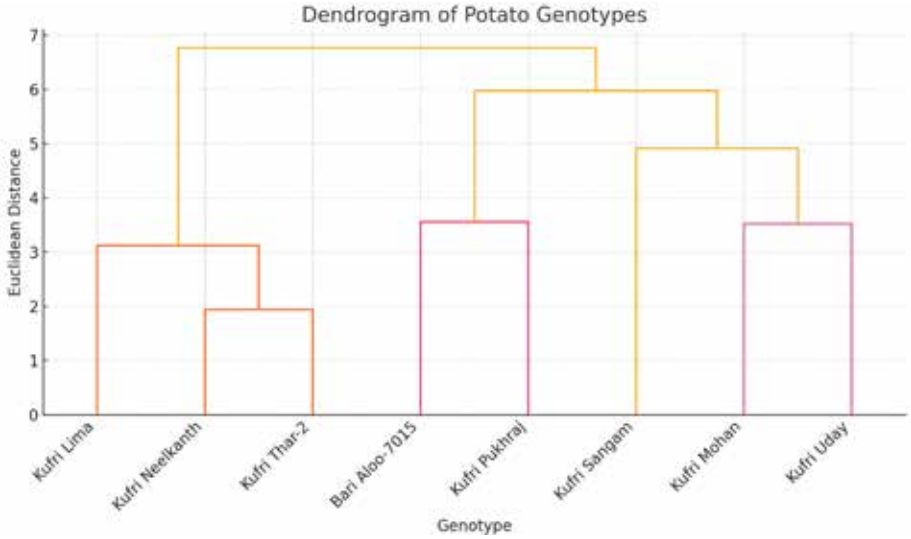


Fig. 2. Dendrogram showing the clustering of eight potato genotypes based on their agronomic traits

a higher Euclidean distance (6.8), indicating the presence of significant genetic divergence among the major groups.

Such clustering patterns provide valuable insights for breeders in selecting genetically diverse parents for hybridization programs aimed at improving yield and other desirable traits.

CONCLUSION

Among the evaluated genotypes, Kufri Uday (Yusimap) and Kufri Pukhraj emerged as the most promising varieties, showing superior performance in terms of tuber number, average tuber weight and overall yield. These traits exhibited positive genotypic and phenotypic associations with yield, highlighting their importance as key yield-contributing characters.

The observed variability in maturity duration, plant height and tuber characteristics indicate the presence of substantial genetic diversity among the tested genotypes. Such diversity can be effectively utilized in breeding programs to develop high-yielding and disease-resistant potato varieties suitable for the agro-climatic conditions of Bihar.

Overall, the results provide valuable insights for potato improvement programs and support the development of potato varieties adapted to intensive cropping systems, thereby contributing to sustainable agricultural production and food security, particularly in Zone-IIIB of Bihar.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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COMPARATIVE EVALUATION OF POTATO CULTIVATION AND STORAGE CONSTRAINTS FOR POTATO PRODUCTION IN WEST BENGAL

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ABSTRACT: Potato is the second most important and widely cultivated crop after cereals in West Bengal. The state's high potato production is primarily attributed to the favourable climatic conditions in the districts of Hooghly, Paschim Medinipur, Purba Bardhaman, and Bankura. However, farmers in these four districts face numerous challenges related to potato cultivation and storage, which adversely affect both yield and the edible quality of potatoes. Through focus group discussions and interviews with key stakeholders, fifteen major constraints in potato cultivation and storage were identified. Data on these fifteen constraints were collected based on four response variables *severity*, *occurrence*, *detection*, and *environmental impact* via a survey conducted in sixteen major potato-growing blocks across these four districts during the year 2025. The relative weights of the four response variables were determined using the Fuzzy-AHP (Fuzzy Analytic Hierarchy Process) method, and the fifteen constraints were ranked using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) approach with statistical analysis of the survey data. The TOPSIS analysis revealed considerable variation in the relative criticality of the identified constraints affecting potato cultivation and storage. Among the 15 constraints evaluated, Constraint 1: "access to quality seeds at an affordable price," obtained the lowest TOPSIS score of 0.3320, indicating that it was the most critical constraint in the study area. In contrast, Constraint 14: "pest attack during storage," recorded the highest TOPSIS score of 0.8214, and was consequently ranked as the least critical or most favourable constraint among the 15 constraints. Thus, the findings can assist policymakers, agricultural extension agencies, seed suppliers, cold-storage operators, and other stakeholders in developing targeted and priority-based interventions rather than adopting a uniform approach to all identified constraints.

KEYWORDS: Potato; Cultivation; Constraints; Fuzzy- AHP; TOPSIS.

INTRODUCTION

The potato (*Solanum tuberosum* L.) is a worldwide essential and important staple crop, widely produced and consumed due to its affordability, large scale production and easy accessibility in free markets. It offers essential nutrients including carbohydrates, dietary fiber (mainly in the skin) and various vitamins and minerals such as magnesium, potassium, and iron (Campos and Ortiz 2020; Devaux *et al*., 2021; Raigond *et al*., 2020).

West Bengal with unique geographical position, varied soil classification and different climatic condition, produce a wide variety of cereals, oil seed, fruits and vegetables is the second largest potato producer state

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in India after Uttar Pradesh (Bhattacharyya and Mitra 2014; Islam et al., 2024). Potato is particularly important for farmers in districts such as Hooghly, Paschim Medinipur, Purba Bardhaman, and Bankura in West Bengal, where a considerable area is devoted to potato cultivation. Potato is affected similar to other crop by a lot of abiotic and biotic stresses (Kroschel *et al*., 2020 and Singh *et al*., 2021). These abiotic and biotic stresses are serious potato cultivation constraints in potato producing field (Okonya *et al*., 2014). They are ranged from the attach of insect developing blemishes and therefore the tuber quality and yield are significantly reduced (Demirel 2023; Demirel *et al*., 2020; Misganaw 2016; Sahu *et al*., 2023) The effective potato crop protection management strategies would be implemented during growth, harvesting, post harvesting and storage by removing these stresses to improve the potato productivity in West Bengal (Kitinoja 2013 and Sen *et al*., 2018). A cold chain arrangement is required because of perishable nature of potato (Aung and Chang 2014; Pinhero *et al*., 2009) It helps to maintain the quality and extend the shelf – life, if consumption is not meant immediately after harvest (Alamar *et al*., 2017). In the absence of sufficient cold storages and related cold chain facilities, the farmers of West Bengal are being forced to sell their product immediately after harvest which results in glut situation and low-price realization. A cold storage facility accessible to them will go a long way in removing the risk of distress sale and ensure better returns (Datta *et al*., 2015). Beyond its critical contribution to global food security, the potato possesses distinct genetic characteristics and a deep cultural heritage, rendering the crop highly valuable for both agricultural production and genetic studies (Mangal *et al*., 2024).

Despite of high production potential, potato cultivation and post-harvest management in West Bengal are affected by several interconnected technical, climatic, economic, infrastructural, and institutional constraints. Although individual constraints have been discussed extensively in agricultural research, identifying the relative criticality of multiple constraints simultaneously remains a challenging decision-making problem. Different constraints may vary considerably in terms of their severity, frequency of occurrence, detectability, and environmental consequences. Moreover, the assessment of agricultural constraints generally involves expert judgments and farmers' perceptions, which are inherently subjective and uncertain. Conventional ranking approaches based only on individual indicators may therefore fail to adequately represent the complexity and uncertainty associated with potato production and storage constraints. A systematic prioritization framework is consequently required to identify the most critical constraints and provide a rational basis for intervention and resource allocation. To address this gap, the present study employs an integrated Fuzzy-AHP and TOPSIS framework for systematic prioritization of potato cultivation and storage constraints in West Bengal. Fuzzy-AHP is particularly suitable for determining the relative importance of evaluation criteria because it can incorporate the vagueness and uncertainty inherent in human judgments. Instead of requiring experts to provide precise numerical assessments, fuzzy numbers can represent linguistic evaluations and thereby provide a more realistic representation of expert knowledge. The method is therefore appropriate for assigning criterion weights when the assessment of agricultural constraints involves subjective perceptions and incomplete information.

The study has been undertaken to (i) identify the major constraints affecting potato

cultivation and storage in West Bengal, (ii) evaluate the identified constraints based on severity, occurrence, detection, and environmental impact and (iii) prioritize and rank the constraints to identify the most critical factors requiring management intervention.

Through focus group discussions with relevant stakeholders, fifteen key constraints related to potato cultivation and storage were identified. These constraints were analysed using multivariate statistical tools such as mean vector analysis, correlation matrix, and hypothesis testing. Finally, the constraints were ranked using the Fuzzy-AHP and TOPSIS method.

MATERIALS AND METHODS

Survey area

The survey was conducted in four major potato-producing districts of West Bengal, India, located between 85°50′ and 89°50′ east longitude and 21°25′ to 27°13′ north latitude. The study area comprised 16 potato-growing blocks within the districts of Hooghly, Paschim Medinipur, Purba Bardhhaman and Bankura. These blocks are Tarakeswar, Singur, Khanakul, Pursura, Chandrakona, Gerbeta, Daspur, Keshpur, Aushgram, Memari, Ketugram, Raina, Taldangra, Kotulpur, Patrasayar, and Joypur. For the purpose of study, these blocks are coded as to B1 to B16. A multistage sampling procedure was adopted to select potato-growing farmers from the above four major potato-producing districts of West Bengal. Fig.1 illustrates the study area.

Data Collection and Constraint Identification

Fifteen major constraints related to potato cultivation and storage were identified through focus group discussions and expert

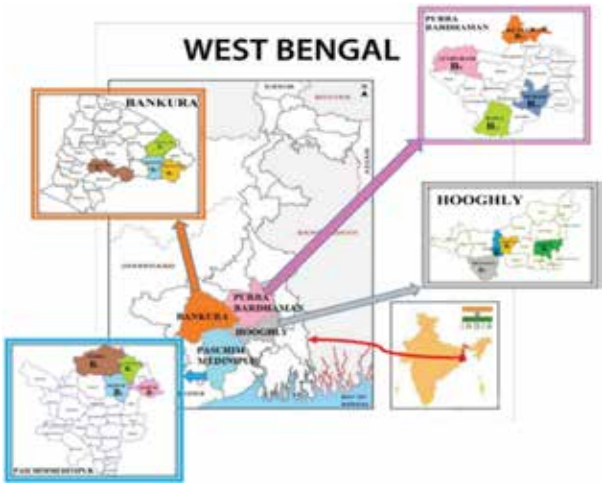


Fig. 1. Study area

interviews. 1 to 10 scale data corresponding to these fifteen identified constraints, along with four response variables severity, occurrence, detection, and environmental impact were collected through a survey conducted among 400 farmers, comprising 25 farmers from each of the 16 blocks within the study area.

The use of a common 1–10 scale also facilitates the aggregation of heterogeneous farmers' perceptions. Since the purpose of the scoring was to establish the relative importance and comparative performance of the constraints rather than to measure an absolute physical quantity, the numerical values were treated as structured preference ratings. Thus, the 1–10 scale provides a transparent and reproducible mechanism for transforming farmers' linguistic judgments into a standardized decision matrix for constraint prioritization.

The fifteen identified constraints and the four response variables were considered as alternatives and criteria, respectively, for constructing decision matrix. These constraints (alternatives) and response variables (criteria) are denoted as A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8, A_9, A_{10}, A_{11}, A_{12}, A_{13}, A_{14}, A_{15} and C_1, C_2, C_3, C_4, respectively, for

further analysis. The detailed descriptions of the constraints are presented in Table 1. A brief description of the criteria has been presented in Table 2.

Statistical analysis on the survey data

To improve recommendations from land suitability analysis to yield prediction, multiple area-specific criteria should be considered. Besides key factors like soil, water, fertilizer, and seasonal variations, additional aspects such as proximity to research institutes, markets, roads, and agro-centres are also important. Considering these factors requires an effective prediction approach; thus, multi-dimensional analysis on agriculture data is the most suitable for such complex evaluations (Ahrari *et al.*, 2024; Deepa *et al.*, 2020; Divya *et al.*, 2021;

Table 1. Constraints in potato cultivation and storage with responses from 400 respondents.

Types of Constraints	Constraints Number	Constraint's Description	Frequency	Percentages (%)	Input data Matrix X_n
Cultivation	A_1	Ensuring availability of high-quality seeds at reasonable prices.	366	91.50	X_1
	A_2	Farmers face low and unpredictable prices during peak harvest periods.	277	69.25	X_2
	A_3	Preventing pest and disease.	285	71.25	X_3
	A_4	Farmers face yield losses and crop failure risks from moisture stress driven by unreliable rainfall.	328	82.00	X_4
	A_5	Inadequate irrigation infrastructure.	79	19.75	X_5
	A_6	Insufficient farmer training centres.	87	21.75	X_6
	A_7	Limited and costly access to pesticides and fertilizers when most needed.	269	67.25	X_7
	A_8	Weed overgrowth.	85	21.25	X_8
	A_9	Labour scarcity.	255	63.75	X_9
	A_{10}	Soil nutrient management & technology.	167	41.75	X_{10}
Storage	A_{11}	Inadequate modern cold storage infrastructure.	301	75.25	X_{11}
	A_{12}	Cold storage charge	311	77.25	X_{12}
	A_{13}	Inadequate transport infrastructure.	181	45.25	X_{13}
	A_{14}	Pest attack in storage.	67	16.75	X_{14}
	A_{15}	Efficient cold storage management & technology.	87	21.75	X_{15}

Table 2. Description of the Criteria

Criterion	Code	Description
Severity	C_1	Severity refers to the extent of crop damage or yield loss caused by a particular constraint. It explains the level of impact on potato yield and edible quality. Severity is considered a non-beneficial (cost) criterion in this study.
Occurrence	C_2	Occurrence represents the likelihood or probability of a particular constraint arising. It indicates how frequently a constraint is expected to occur. Like severity, occurrence is also a non-beneficial (cost) criterion in the algorithm.
Detection	C_3	Detection reflects the effectiveness of preventive and maintenance measures against a given constraint. It indicates the ability to identify or prevent the occurrence of a problem. Thus, a higher detection score represents better detectability and is treated as a beneficial criterion for this study.
Environmental impact	C_4	Environmental impact refers to the adverse environmental effects resulting from the use of fertilizers and pesticides. It encompasses factors such as water and air pollution, soil degradation, and nutrient runoff (sulphur, nitrogen, and phosphorus) that lead to the contamination of freshwater and eutrophication. This is also considered a non-beneficial criterion in the study.

Piekutowska et al., 2021; Raghav et al., 2025). For the present study following statistical measures have been computed for the analyse of potato cultivation and storage constraints.

Input data matrix

Primary data were collected from 400 farmers across sixteen major potato-growing blocks in four districts of West Bengal. Fifteen major potato cultivation and storage constraints were identified through focus group discussions, expert opinions, and farmer cooperation. Each constraint includes four response variables as severity, occurrence, detection and environmental impact rated on a 1–10 scale, forming one input data matrix. Hence, fifteen constraints yield fifteen input data matrices X_1, X_2, X_3 … X_{15}, where each $X_n = [a_{ij}]_{16\times4}$ (n = 1, 2, …, 15). The fifteen-input data matrix of the constraints along with 1 to 10 scale data reported by the farmers are presented in Table 3.

Mean vector

Mean vector ($\overline{X}_n$) corresponding to input data matrix is formed in the following way.

$$\overline{X}_n = \frac{1}{p} X_n^T \cdot I = [\bar{a}_j]_{4\times1} \quad \ldots\ldots (1)$$

$$X_n = [a_{ij}]_{16\times4} \quad \ldots\ldots (2)$$

Where the sample size which is equal to sixteen (number of blocks) and I is the unit column matrix of 16 rows. Average value of the j_{th} response variable is $\bar{a}j$.

Covariance Matrix

Covariance matrix $\overline{X}_n$ corresponding to the input data matrix $\overline{X}_n$ is formed in the following way.

Table 3. Survey data with 1 to 10 scale to form input data matrix

Input data matrix	Response variables	Blocks															
		B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}
X_1	Severity	7	9	8	9	6	9	8	8	7	7	9	9	6	9	9	8
	Occurrence	7	8	6	6	5	4	6	8	5	4	7	6	7	5	7	5
	Detection	5	4	3	4	6	4	3	3	5	4	3	4	5	3	5	3
	Environmental impact	6	7	5	6	5	6	5	4	6	5	5	6	4	6	7	4
X_2	Severity	6	7	4	3	5	6	4	5	5	4	3	7	6	7	4	4
	Occurrence	8	6	5	4	7	8	6	4	7	5	6	5	7	5	7	6
	Detection	9	5	6	4	6	8	5	5	8	4	8	4	8	4	6	7
	Environmental impact	5	6	5	5	6	5	4	5	4	4	4	5	4	5	6	4
X_3	Severity	8	6	5	6	8	9	7	6	8	5	9	7	6	8	6	8
	Occurrence	7	5	6	8	4	7	5	6	8	5	5	6	7	5	7	5
	Detection	6	4	3	4	3	5	4	3	4	6	3	3	4	5	3	4
	Environmental impact	6	5	4	5	5	6	3	5	5	5	5	6	4	6	5	4
X_4	Severity	10	9	8	9	10	7	10	9	8	9	10	8	9	10	9	9
	Occurrence	5	4	3	4	4	5	3	4	6	3	3	4	5	3	4	4
	Detection	4	3	2	4	3	3	3	5	5	2	2	3	2	2	3	2
	Environmental impact	6	5	4	5	5	6	5	3	5	4	5	5	4	5	6	4
X_5	Severity	6	4	3	7	5	5	4	6	7	4	4	5	5	6	4	5
	Occurrence	5	3	4	4	3	6	3	4	4	6	5	3	3	4	3	4
	Detection	3	4	2	4	5	3	2	2	4	2	3	2	3	3	4	2
	Environmental impact	4	5	3	5	4	4	4	3	5	3	4	5	3	5	6	3

Input data matrix	Response variables	Blocks															
		B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}	B_{11}	B_{12}	B_{13}	B_{14}	B_{15}	B_{16}
X_6	Severity	7	6	8	5	5	4	7	6	6	7	5	5	8	5	6	6
	Occurrence	5	3	3	4	5	4	3	5	4	4	3	5	6	3	3	4
	Detection	4	3	2	2	4	3	3	4	2	5	2	2	3	3	4	2
	Environmental impact	5	4	3	4	5	4	5	3	5	5	4	4	4	5	6	4
X_7	Severity	8	6	7	7	5	9	6	8	7	7	8	6	7	7	8	6
	Occurrence	7	5	6	7	6	5	6	6	7	5	8	5	5	6	7	5
	Detection	3	4	2	3	5	2	2	3	3	4	2	3	4	2	3	3
	Environmental impact	5	6	4	5	4	5	4	4	5	4	4	5	3	5	4	4
X_8	Severity	8	7	6	9	8	6	5	5	8	7	6	8	9	6	7	7
	Occurrence	5	3	4	4	3	3	6	5	3	5	3	4	4	5	3	4
	Detection	3	4	2	3	3	4	4	2	2	3	4	2	3	4	3	2
	Environmental impact	4	6	4	5	4	5	4	3	4	5	4	5	4	5	6	3
X_9	Severity	7	5	6	7	8	5	5	4	7	6	7	5	5	7	6	6
	Occurrence	6	4	5	4	6	5	7	4	4	5	6	4	5	4	6	5
	Detection	4	3	2	3	3	4	2	3	4	2	3	4	2	3	4	2
	Environmental impact	5	6	3	5	4	5	4	4	5	4	4	5	3	5	6	4
X_{10}	Severity	6	5	4	5	3	7	5	4	6	5	7	3	5	6	4	5
	Occurrence	5	4	3	5	4	4	3	5	3	4	3	3	5	5	4	4
	Detection	4	5	4	3	5	4	3	5	3	4	3	3	5	5	4	4
	Environmental impact	5	6	4	5	5	6	5	4	4	3	4	4	3	6	5	3
X_{11}	Severity	8	7	9	8	8	9	7	9	6	5	6	7	5	6	5	7
	Occurrence	7	5	6	6	5	7	6	5	7	4	8	6	7	5	5	7
	Detection	5	3	4	4	3	3	5	5	4	4	3	3	5	5	4	4
	Environmental impact	6	5	5	6	4	5	4	3	5	5	3	5	4	6	6	3
X_{12}	Severity	6	4	3	5	6	7	4	5	6	7	5	5	4	3	6	4
	Occurrence	5	3	4	4	6	3	3	4	5	3	5	4	3	4	4	4
	Detection	4	6	3	3	4	5	3	3	5	6	3	3	4	5	3	4
	Environmental impact	5	6	4	5	5	4	4	3	4	4	5	4	3	5	5	3
X_{13}	Severity	7	5	6	8	5	6	5	7	5	6	6	7	5	8	5	5
	Occurrence	5	4	6	3	7	4	6	5	5	7	4	4	6	4	5	5
	Detection	3	4	2	3	2	4	5	2	2	3	3	4	2	5	2	2
	Environmental impact	5	5	3	4	4	5	5	4	5	4	4	5	4	3	4	3
X_{14}	Severity	6	4	6	5	4	6	7	4	4	5	5	6	4	5	4	6
	Occurrence	5	4	3	4	5	3	5	4	3	4	4	5	3	3	5	4
	Detection	4	3	2	5	3	2	3	2	3	4	2	5	2	2	3	3
	Environmental impact	4	6	5	5	4	5	3	5	4	3	3	5	3	5	5	4
X_{15}	Severity	7	6	5	8	5	5	6	7	5	6	6	7	5	6	7	5
	Occurrence	5	3	4	4	6	3	3	4	5	3	4	4	6	3	3	4
	Detection	4	6	3	3	4	4	5	3	4	5	3	4	4	5	3	4
	Environmental impact	5	6	4	4	5	4	4	4	5	4	3	4	3	4	5	3

$$\bar{\bar{X}}_n = \frac{1}{P-1} X_{n*}^T X_{n*} = [b_{ij}]_{4\times4} \quad \ldots. (3)$$

Where X_{n^*} is another matrix,

$$X_{n*} = [\, c_{ij} \,]_{16\times4}, \; c_{ij} = a_{ij} - \bar{a}_j \quad \ldots (4)$$

Diagonal and off diagonal elements of the covariance matrix are the variance and covariance of the response variables, b_{jj} is the variance of j_{th} variable.

Standard deviation of j_{th} variable, $s_j = \sqrt{bjj}$ ……. … (5)

The standard deviation vector, $Sn = [S_j]_{4\times1}$ ……..…. (6)

Correlation Matrix

Correlation matrix corresponding to input data matrix is formed in the following way.

$\tilde{X}_n$ is the correlation matrix of the data matrix X_n,

$$\tilde{X}_n = [d_{ij}]_{4\times4} \quad \ldots\ldots\ldots\ldots (7)$$

$$d_{ij} = \frac{b_{ij}}{s_i \times s_j} \quad \ldots\ldots\ldots\ldots (8)$$

$$\frac{b_{jj}}{s_{j\times s_j}} = 1 \quad \ldots\ldots\ldots\ldots (9)$$

Hypothesis testing for mean value and mean vector

Hypothesis is the statement that has to be proven.

H_o and H_1 are the null and alternative hypothesis respectively.

$$H_o : \bar{a}_j = \bar{\mu}_j \quad \ldots. (10)$$

$$H_1 : \bar{a}_j \neq \bar{\mu}_j \quad \ldots (11)$$

$\bar{a}_j$ and $\bar{\mu}_j$ are mean value of the j_{th} response variable for the sample and population respectively.

Confidence interval or CI

θ is the statistic,

$$\theta = \frac{\bar{a}_j - \bar{\mu}_j}{\frac{s_j}{\sqrt{P}}} \quad \ldots. (12)$$

Where, s_j is the sample standard deviation of j_{th} response variable and P is the sample size.

CI will be,

$$-Z_{\alpha/2} \leq \theta \leq Z_{\alpha/2} \quad \ldots\ldots (13)$$

The critical value of $Z_{\alpha/2}$ will be taken from suitable statistical distribution table.

$$-Z_{\alpha/2} \leq \frac{\bar{a}_j - \bar{\mu}_j}{\frac{s_j}{\sqrt{P}}} \leq Z_{\alpha/2} \quad \ldots\ldots\ldots (14)$$

$$\bar{a}_j - \frac{Z_{\alpha/2}\, s_j}{\sqrt{P}} \leq \bar{\mu}_j \leq \bar{a}_j + \frac{Z_{\alpha/2}\, s_j}{\sqrt{P}} \quad \ldots\ldots (15)$$

Mean vector hypothesis test

H_{on} and H_{1n} are the null and alternative hypothesis of the input data matrix , n = 1,2,3, 4……14,15.

$$H_{on}: \bar{\bar{X}}_n = \bar{\mu}_n \quad \ldots. (16)$$

$$H_{1n}: \bar{\bar{X}}_n \neq \bar{\mu}_n \quad \ldots (17)$$

$\bar{\bar{X}}_n$ and $\bar{\mu}_n$ are the mean vector of sample size and population respectively.

CI will be,

$$\bar{\bar{X}}_n - \frac{Z_{\alpha/2}}{\sqrt{P}} . S_n \leq \bar{\mu}_n \leq \bar{\bar{X}}_n + \frac{Z_{\alpha/2}}{\sqrt{P}} . S_n \quad \ldots (18)$$

S_n is the standard deviation vector of the sample.

As P is the sample size = 16 which is less than 30 and non-directional hypothesis testing two tail t- distribution is suitable. α is the level of significance. $\alpha/2$ will be affected in each side of the confidence interval. $Z_{\alpha/2}$ is the critical value in the confidence interval and will be selected from t- distribution table with proper degree of freedom, degree freedom = sample size – 1. Assumed α = 0.1, $\alpha/2$ = 0.05 and degree of freedom = 16-1 = 15. From the t-distribution table $Z_{\alpha/2}$ = 2.13.

Ranking of the constraints

Failure mode and effects analysis (FMEA) is widely used in reliability studies, where severity (S), occurrence (O), and detectability (D) are combined to form the risk priority number (RPN) (Zandi *et al.*, 2020). The concept of (FMEA) was extended to the agricultural project risk management by

dividing severity, occurrence, detection and environmental impact. A hybrid model was developed by integrating multiple-criteria decision-making (MCDM) of TOPSIS with the analytic hierarchy process (AHP) and fuzzy set theory to provide decision support for selecting sustainable solutions to agricultural challenges (Keshavarzi et al., 2020; Rouyendegh & Savalan 2020). The fifteen constraints (alternatives) have been ranked with the help of Fuzzy AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method. The response variables (criteria) are as severity, occurrence, detection and environmental impact. The weight vector of these response variables is calculated by the help of Fuzzy AHP method whereas the rank of the constraints is found out using TOPSIS.

Determination of criteria weights using triangular Fuzzy numbers.

The criteria weights have been determined by the following steps.

Step 1. Determine fuzzy geometric mean value.

P is the number of criteria; each criterion is denoted by a triangular Fuzzy membership number as (l_i, m_i, u_i), where i = 1, 2, 3, ……., P. The geometric mean value of the criteria is denoted by (l_j, m_j, u_j) in triangular Fuzzy number, where j = 1, 2, 3, ……P.

$$(l_j, m_j, u_j) = (l_1 \times l_2 \times l_3 \times \ldots \times l_P)^{\frac{1}{P}}, (m_1 \times m_2 \times m_3 \times \ldots \times m_P)^{\frac{1}{P}}, (u_1 \times u_2 \times u_3 \times \ldots \times u_P)^{\frac{1}{P}} \quad \ldots\ldots (19)$$

Step 2. Determine fuzzy criteria weight.

The weight of the criteria is denoted by (l_{wj}, m_{wj}, u_{wj}) in triangular Fuzzy number.

$$(l_{wj}, m_{wj}, u_{wj}) = (l_j, m_j, u_j) \otimes \left(\frac{1}{\sum_{j=1}^{P} u_j}, \frac{1}{\sum_{j=1}^{P} m_j}, \frac{1}{\sum_{j=1}^{P} l_j}\right) \quad \ldots (20)$$

Step 3. Defuzzification of criteria weight.

The weight of the j_{th} criteria is denoted by w_j in numerical crest value then,

$$w_j = \frac{(l_{wj} + m_{wj} + u_{wj})}{3} \quad \ldots\ldots (21)$$

Step 4. Normalize criteria weight.

The weight in normalized crest value of the j_{th} criteria is $\overline{w}_j$.

$$\overline{w}_j = \frac{w_j}{\sum_{j=1}^{P} w_j} \quad \ldots\ldots (22)$$

Determination of performance score using TOPSIS

The following steps are followed in TOPSIS method.

Step 1. The decision support evaluation matrix $(y_{ij})_{q\times p}$ is formed with q number of alternatives and p number of criteria having as an element of row and column.

Step 2. The $(y_{ij})_{q\times p}$ matrix is normalized to create the normalized decision matrix $(t_{ij})_{q\times p}$, applying the method of normalization, $t_{ij} = \frac{y_{ij}}{\sqrt{\sum_{k=1}^{q} y_{kj}^2}}$, i = 1, 2…...q and j = 1, 2…. p.

Step 3. The weighted normalized decision matrix $(u_{ij})_{q\times p}$ is calculated with the elements of u_{ij} as, $u_{ij} = t_{ij} \times \overline{w}_j$, $\overline{w}_j$ is the normalized weight of j_{th} criteria such that $\sum_{j=1}^{p} \overline{w}_j = 1$.

Step 4. The best and worst value correspond to alternatives of criteria are denoted as and respectively. These values are selected as follows,

u_{bj} = max (u_{ij}), if j_{th} criteria have good impact towards the goal.

u_{bj} = min (u_{ij}), if j_{th} criteria have bad impact towards the goal.

u_{wj} = min (u_{ij}), if j_{th} criteria have good impact towards the goal.

u_{wj} = max (u_{ij}), if j_{th} criteria have bad impact towards the goal.

Step 5. Euclidean distance between best and i_{th} (target) alternatives is denoted by s_i^+ then,

$$s_i^+ = \sqrt{\sum_{j=1}^{p} (u_{ij} - u_{bj})^2}, \; i = 1,2,3\ldots\ldots q.$$

Euclidean distance between worst and (target) alternatives is denoted by s_i^- then,

$$s_i^- = \sqrt{\sum_{j=1}^{P}(u_{ij} - u_{wj})^2},\ i = 1,2,3\ldots\ldots q.$$

Step 6. The score of i_{th} (target) alternative is denoted by S_{ci}.

$$S_{ci} = \frac{s^-}{s^+ + s^-},\ 0 \le S_{ci} \le 1,\ i = 1,2,3\ldots\ldots q.$$

Step 7. Rank the alternatives accordingly to S_{ci}

In TOPSIS, alternatives are ranked according to their distance from the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS).

Ranking rule: A higher indicates that the alternative is closer to the ideal solution and therefore receives a better (higher) rank. A lower indicates lower importance/preference.

RESULTS AND DISCUSSIONS

Mean vector, correlation matrix and standard deviation vector are shown in Table 4. Summary of the statistical results are shown in Table 5. Null hypothesis test has been done to find the mean or average values of criteria of population for each constraint. Permissible maximum and minimum value of severity, occurrence, detection and impact of fifteen constraints are shown in Table 6.

Table 4. Mean vector, Correlation Matrix & Standard Deviation vector.

Mean Vector, $\bar{X}_n$	$[\bar{a}_j]_{4\times1}$	Correlation Matrix $\tilde{X}_n$	$[d_{ij}]_{4\times4}$				Standard Deviation Vector, Sn	$[S_j]_{4\times1}$
$\bar{X}_1$	8.00	$\tilde{X}_1$	1.00	0.15	-0.53	0.51	S_1	1.09
	6.00		0.15	1.00	-0.06	0.06		1.26
	4.00		-0.53	-0.06	1.00	0.29		0.96
	5.44		0.51	0.06	0.29	1.00		0.96
$\bar{X}_2$	5.00	$\tilde{X}_2$	1.00	0.23	-0.35	0.32	S_2	1.37
	6.00		0.23	1.00	0.97	0.07		1.26
	6.06		-0.35	0.97	1.00	-0.30		1.41
	4.81		0.32	0.07	-0.30	1.00		0.75
$\bar{X}_3$	7.00	$\tilde{X}_3$	1.00	-0.08	0.10	0.36	S_3	1.32
	6.00		-0.08	1.00	0.10	0.19		1.21
	4.00		0.10	0.10	1.00	0.31		1.03
	4.94		0.36	0.19	0.31	1.00		0.85
$\bar{X}_4$	9.00	$\tilde{X}_4$	1	-0.42	-0.14	0.00	S_4	0.89
	4.00		-0.42	1.00	0.58	0.27		0.89
	3.00		-0.14	0.58	1.00	0.08		1.03
	4.81		0.00	0.27	0.08	1.00		0.84
$\bar{X}_5$	5.00	$\tilde{X}_5$	1.00	0.06	0.30	0.30	S_5	1.15
	4.00		0.06	1.00	-0.27	-0.33		1.03
	3.00		0.30	0.27	1.00	0.58		0.96
	4.12		0.30	-0.33	0.58	1.00		0.96
$\bar{X}_6$	6.00	$\tilde{X}_6$	1.00	0.12	0.18	-0.08	S_6	1.15
	4.00		0.12	1.00	0.22	-0.17		0.96
	3.00		0.18	0.22	1.00	0.42		0.96
	4.38		-0.08	-0.17	0.42	1.00		0.81

Mean Vector, $\bar{X}_n$	$[\bar{a}_j]_{4\times1}$	Correlation Matrix $\tilde{X}_n$	$[d_{ij}]_{4\times4}$				Standard Deviation Vector, Sn	$[S_j]_{4\times1}$
$\bar{X}_7$	7.00	$\tilde{X}_7$	1.00	0.33	-0.51	0.00	S_7	1.03
	6.00		0.33	1.00	-0.31	0.00		0.96
	3.00		-0.51	-0.31	1.00	-0.11		0.89
	4.44		0.00	0.00	-0.11	1.00		0.73
$\bar{X}_8$	7.00	$\tilde{X}_8$	1.00	-0.33	-0.26	0.18	S_8	1.26
	4.00		-0.33	1.00	0.00	-0.32		0.96
	3.00		-0.26	0.00	1.00	0.45		0.82
	4.44		0.18	-0.32	0.45	1.00		0.89
$\bar{X}_9$	6.00	$\tilde{X}_9$	1.00	0.19	0.14	0.07	S_9	1.10
	5.00		0.19	1.00	-0.17	-0.23		0.96
	3.00		0.14	-0.17	1.00	0.72		0.82
	4.50		0.07	-0.23	0.72	1.00		0.89
$\bar{X}_{10}$	5.00	$\tilde{X}_{10}$	1.00	0.07	-0.20	0.21	S_{10}	1.21
	4.00		0.07	1.00	0.59	0.15		0.82
	4.00		-0.20	0.59	1.00	0.15		0.82
	4.50		0.21	0.15	0.15	1.00		1.03
$\bar{X}_{11}$	7.00	$\tilde{X}_{11}$	1.00	0.08	-0.11	-0.09	S_{11}	1.41
	6.00		0.08	1.00	-0.08	-0.28		1.09
	4.00		-0.11	-0.08	1.00	0.08		0.82
	4.69		-0.09	-0.28	0.08	1.00		1.08
$\bar{X}_{12}$	5.00	$\tilde{X}_{12}$	1.00	0.18	0.24	0.06	S_{12}	1.26
	4.00		0.18	1.00	-0.28	0.26		0.89
	4.00		0.24	-0.28	1.00	0.21		1.10
	4.31		0.06	0.26	0.21	1.00		0.87
$\bar{X}_{13}$	6.00	$\tilde{X}_{13}$	1.00	-0.53	0.33	-0.16	S_{13}	1.10
	5.00		-0.53	1.00	-0.37	-0.15		1.15
	3.00		033	-0.37	1.00	0.33		1.10
	4.19		-0.16	-0.15	0.33	1.00		0.75
$\bar{X}_{14}$	5.06	$\tilde{X}_{14}$	1.00	0.16	0.19	-0.09	S_{14}	1.00
	4.00		0.16	1.00	0.56	0.00		0.82
	3.00		0.19	0.56	1.00	0.13		1.03
	4.38		-0.09	0.00	0.13	1.00		0.96
$\bar{X}_{15}$	6.00	$\tilde{X}_{15}$	1.00	-0.27	-0.23	0.16	S_{15}	0.96
	4.00		-0.27	1.00	-0.29	-0.08		1.03
	4.00		-0.23	-0.29	1.00	0.36		0.89
	4.19		0.16	-0.08	0.36	1.00		0.84

Table 5. Summary of the statistical results.

Constraints No.	Sample mean value of response variables ($\bar{a}_j$) j = 1,2,3,4.				Sample standard deviation of response variables (s_j) j = 1,2,3,4.			
	Severity $\bar{a}_1$	Occurrence $\bar{a}_2$	Detection $\bar{a}_3$	Impact $\bar{a}_4$	Severity s_1	Occurrence s_2	Detection s_3	Impact s_4
A_1	8.00	6.00	4.00	5.44	1.09	1.26	0.96	0.96
A_2	5.00	6.00	6.06	4.81	1.37	1.26	1.41	0.75
A_3	7.00	6.00	4.00	4.94	1.32	1.21	1.03	0.85
A_4	9.00	4.00	3.00	4.81	0.89	0.89	1.03	0.84
A_5	5.00	4.00	3.00	4.12	1.15	1.03	0.96	0.96
A_6	6.00	4..00	3.00	4.38	1.15	0.96	0.96	0.81
A_7	7.00	6.00	3.00	4.44	1.03	0.96	0.89	0.73
A_8	7.00	4.00	3.00	4.44	1.26	0.96	0.82	0.89
A_9	6.00	5.00	3.00	4.50	1.10	0.96	0.82	0.89
A_{10}	5.00	4.00	4.00	4.50	1.21	0.82	0.82	1.03
A_{11}	7.00	6.00	4.00	4.69	1.41	1.09	0.82	1.08
A_{12}	5.00	4.00	4.00	4.31	1.26	0.89	1.10	0.87
A_{13}	6.00	5.00	3.00	4.19	1.10	1.15	1.10	0.75
A_{14}	5.06	4.00	3.00	4.38	1.00	0.82	1.03	0.96
A_{15}	6.00	4.00	4.00	4.19	0.96	1.03	0.89	0.84

Table 6. Hypothesis testing results.

Constraints No.	Null Hypothesis H_{on}: $\bar{a}_j = \bar{\mu}_j$	Population mean value ($\bar{\mu}_j$) of response variables for null hypothesis			
		Severity $\bar{\mu}_1$	Occurrence $\bar{\mu}_2$	Detection $\bar{\mu}_3$	Impact $\bar{\mu}_4$
A_1	H_{01}	$7.42 \le \bar{\mu}_1 \le 8.58$	$5.33 \le \bar{\mu}_2 \le 6.67$	$3.49 \le \bar{\mu}_3 \le 4.51$	$4.93 \le \bar{\mu}_4 \le 5.95$
A_2	H_{02}	$4.30 \le \bar{\mu}_1 \le 5.70$	$5.33 \le \bar{\mu}_2 \le 6.67$	$5.25 \le \bar{\mu}_3 \le 6.75$	$4.41 \le \bar{\mu}_4 \le 5.21$
A_3	H_{03}	$6.30 \le \bar{\mu}_1 \le 7.70$	$5.36 \le \bar{\mu}_2 \le 6.64$	$3.45 \le \bar{\mu}_3 \le 4.55$	$4.49 \le \bar{\mu}_4 \le 5.39$
A_4	H_{04}	$8.53 \le \bar{\mu}_1 \le 9.47$	$3.53 \le \bar{\mu}_2 \le 4.47$	$2.45 \le \bar{\mu}_3 \le 3.55$	$4.36 \le \bar{\mu}_4 \le 5.26$
A_5	H_{05}	$4.39 \le \bar{\mu}_1 \le 5.61$	$3.45 \le \bar{\mu}_2 \le 4.55$	$2.49 \le \bar{\mu}_3 \le 3.51$	$3.61 \le \bar{\mu}_4 \le 4.63$
A_6	H_{06}	$5.39 \le \bar{\mu}_1 \le 6.61$	$3.49 \le \bar{\mu}_2 \le 4.51$	$2.49 \le \bar{\mu}_3 \le 3.51$	$3.95 \le \bar{\mu}_4 \le 4.81$
A_7	H_{07}	$6.45 \le \bar{\mu}_1 \le 7.55$	$5.49 \le \bar{\mu}_2 \le 6.51$	$2.53 \le \bar{\mu}_3 \le 3.47$	$4.04 \le \bar{\mu}_4 \le 4.83$
A_8	H_{08}	$6.33 \le \bar{\mu}_1 \le 7.67$	$3.49 \le \bar{\mu}_2 \le 4.51$	$2.56 \le \bar{\mu}_3 \le 3.44$	$3.97 \le \bar{\mu}_4 \le 4.91$
A_9	H_{09}	$5.41 \le \bar{\mu}_1 \le 6.59$	$4.49 \le \bar{\mu}_2 \le 5.51$	$2.56 \le \bar{\mu}_3 \le 3.44$	$4.03 \le \bar{\mu}_4 \le 4.97$
A_{10}	H_{010}	$4.36 \le \bar{\mu}_1 \le 5.64$	$3.56 \le \bar{\mu}_2 \le 4.44$	$3.36 \le \bar{\mu}_3 \le 4.44$	$3.95 \le \bar{\mu}_4 \le 5.05$
A_{11}	H_{011}	$6.25 \le \bar{\mu}_1 \le 7.75$	$5.42 \le \bar{\mu}_2 \le 6.58$	$3.56 \le \bar{\mu}_3 \le 4.44$	$4.11 \le \bar{\mu}_4 \le 5.27$
A_{12}	H_{012}	$4.33 \le \bar{\mu}_1 \le 5.67$	$3.53 \le \bar{\mu}_2 \le 4.47$	$3.41 \le \bar{\mu}_3 \le 4.59$	$3.85 \le \bar{\mu}_4 \le 4.77$
A_{13}	H_{013}	$5.41 \le \bar{\mu}_1 \le 6.59$	$4.39 \le \bar{\mu}_2 \le 5.61$	$2.41 \le \bar{\mu}_3 \le 3.59$	$3.79 \le \bar{\mu}_4 \le 4.59$
A_{14}	H_{014}	$4.53 \le \bar{\mu}_1 \le 5.59$	$3.56 \le \bar{\mu}_2 \le 4.44$	$2.45 \le \bar{\mu}_3 \le 3.55$	$3.87 \le \bar{\mu}_4 \le 4.89$
A_{15}	H_{015}	$5.49 \le \bar{\mu}_1 \le 6.51$	$3.45 \le \bar{\mu}_2 \le 4.55$	$3.53 \le \bar{\mu}_3 \le 4.47$	$3.75 \le \bar{\mu}_4 \le 4.64$

Determination of criteria weights using Fuzzy-AHP.

Using Fuzzy-AHP the weights of the criteria have been determined following the various steps mentioned above.

Thus, the determined weights are shown in Table 7. Severity, occurrence, detection and impact are weighted as 34%, 31% ,13% and 22% respectively.

Application of TOPSIS for ranking of the constraints.

Decision support evaluation matrix of the TOPSIS method have been formed with fifteen constraints (alternatives) as rows and four response variables (criteria) as columns. Severity, occurrence, detection and environmental impact are the response variables and the value of these response variables for a particular constraint has been taken from the mean vector of that constraint. Table 8 and Table 9 show the decision and normalized decision matrix whereas weighted normalized matrix and TOPSIS result are shown in Table 10 and Table 11 respectively. TOPSIS result shows that the constraint-1 which is accessing quality seeds at affordable price becomes a top most serious constraint. Disease free good quality potato seeds are the most essential input for growing healthy and sustainable crops. Potato being a propagated clonally crop a rapid rate of perversive degeneration cause the potato seed to highly deteriorate after two or three generation for continuing amassing of viral and biotic diseases as a result most of the farmers in West Bengal depend on reliable outside source. Traditionally the farmers of West Bengal depend on Punjab as a reliable source of disease-free quality potato seeds which increases the cost of cultivation adding an extra financial burden.

Table 7. Determination of criteria weight

Pair- wise comparison of the criteria with triangular Fuzzy membership number.				
Criteria	Severity	Occurrence	Detection	Impact
Severity	(1,1,1)	(1,2,3)	(2,3,4)	(1,1,1)
Occurrence	(1/3, 1/2,1)	(1,1,1)	(1,2,3)	(1,2,3)
Detection	(1/4,1/3,1/2)	(1/3, 1/2,1)	(1,1,1)	(1/3, 1/2,1)
Impact	(1,1,1)	(1/3, 1/2,1)	(1,2,3)	(1,1,1)

	Weight of the criteria in triangular Fuzzy membership number. (l_{wj}, m_{wj}, u_{wj})		
Criteria		Criteria	
Severity	(1.189, 1.565, 1.861)	Severity	(0.346, 0.370, 0.324)
Occurrence	(1.074, 1.189, 1.732)	Occurrence	(0.313, 0.363, 0.277)
Detection	(0.408, 0.537, 0.841)	Detection	(0.119, 0.125, 0.146)
Impact	(0.759, 1.00, 1.316)	Impact	(0.220, 0.233, 0.229)

Weight of the criteria in numerical crest value (W_j). Defuzzification		Normalized weight of the criteria in numerical crest value ($\overline{W}_j$).	
Criteria		Criteria	
Severity	0.347	Severity	0.34
Occurrence	0.318	Occurrence	0.31
Detection	0.13	Detection	0.13
Impact	0.224	Impact	0.22

Table 8. Decision Matrix $(Y_{ij})_{15\times4}$

Alternatives	Criteria			
	Severity	Occurrence	Detection	Impact
A_1	8.00	6.00	4.00	5.44
A_2	5.00	6.00	6.06	4.81
A_3	7.00	6.00	4.00	4.94
A_4	9.00	4.00	3.00	4.81
A_5	5.00	4.00	3.00	4.12
A_6	6.00	4.00	3.00	4.38
A_7	7.00	6.00	3.00	4.44
A_8	7.00	4.00	3.00	4.44
A_9	6.00	5.00	3.00	4.50
A_{10}	5.00	4.00	4.00	4.50
A_{11}	7.00	6.00	4.00	4.69
A_{12}	5.00	4.00	4.00	4.31
A_{13}	6.00	5.00	3.00	4.19
A_{14}	5.06	4.00	3.00	4.38
A_{15}	6.00	4.00	4.00	4.19

Table 9. Normalized decision matrix $(t_{ij})_{15\times3}$

Alternatives	Criteria			
	Severity	Occurrence	Detection	Impact
A_1	0.324	0.317	0.280	0.308
A_2	0.202	0.317	0.424	0.273
A_3	0.283	0.317	0.280	0.280
A_4	0.364	0.211	0.210	0.273
A_5	0.202	0.211	0.210	0.234
A_6	0.243	0.211	0.210	0.248
A_7	0.283	0.317	0.210	0.252
A_8	0.283	0.211	0.210	0.252
A_9	0.243	0.264	0.210	0.255
A_{10}	0.202	0.211	0.280	0255
A_{11}	0.283	0.317	0.280	0.266
A_{12}	0.202	0.211	0.280	0.244
A_{13}	0.243	0.264	0.210	0.238
A_{14}	0.205	0.211	0.210	0.248
A_{15}	0.243	0.211	0.280	0.238
Weight $(\overline{W}_j)$	0.34	0.31	0.13	0.22
= , i = 1, 2…...15 and j = 1, 2,3,4.				

Table 10. Weighted normalized decision matrix $(u_{ij})_{15\times3}$

Alternatives	Criteria			
	Severity	Occurrence	Detection	Impact
A_1	0.110	0.0983	0.0363	0.0678
A_2	0.0688	0.0983	0.0551	0.0600
A_3	0.0963	0.0983	0.0363	0.0620
A_4	0.1238	0.0655	0.0273	0.0600
A_5	0.0688	0.0655	0.0273	0.0514
A_6	0.0826	0.0655	0.0273	0.0546
A_7	0.0963	0.0983	0.0273	0.0554
A_8	0.0963	0.0655	0.0273	0.0554
A_9	0.0826	0.0819	0.0273	0.0561
A_{10}	0.0688	0.0655	0.0363	0.0561
A_{11}	0.0963	0.0983	0.0363	0.0585
A_{12}	0.0688	0.0655	0.0363	0.0537
A_{13}	0.0826	0.0819	0.0273	0.0523
A_{14}	0.0696	0.0655	0.0273	0.0546
A_{15}	0.0826	0.0655	0.0363	0.0523
u_{bj}	0.0688	0.0655	0.0551	0.0513
u_{wj}	0.1238	0.0983	0.0273	0.0678

Table 11. TOPSIS result.

Sl. No.	Alternatives	s_i^-	s_i^+	s_{ci} (Score)	Rank
01	A_1	0.0290	0.0583	0.3320	15
02	A_2	0.0289	0.0339	0.4603	13
03	A_3	0.0561	0.0478	0.5400	9
04	A_4	0.0533	0.0623	0.4612	12
05	A_5	0.0458	0.0278	0.6225	5
06	A_6	0.0448	0.0312	0.5895	7
07	A_7	0.0431	0.0512	0.4572	14
08	A_8	0.0653	0.0393	0.6240	4
09	A_9	0.0341	0.0354	0.4907	10
10	A_{10}	0.0657	0.0193	0.7730	3
11	A_{11}	0.0433	0.0472	0.4782	11
12	A_{12}	0.0655	0.0189	0.7765	2
13	A_{13}	0.0471	0.0351	0.5729	8
14	A_{14}	0.1288	0.0280	0.8214	1
15	A_{15}	0.0374	0.0232	0.6167	6

The present study prioritised fifteen major constraints affecting potato cultivation and storage in four important potato-producing districts of West Bengal using a Fuzzy-AHP–TOPSIS framework. The Fuzzy-AHP results assigned the highest weight to severity (0.34), followed by occurrence (0.31), environmental impact (0.22) and detection (0.13). These weights indicate that the perceived seriousness of a constraint and the frequency with which it occurs are the dominant dimensions influencing farmers' overall assessment. Environmental consequences also received substantial importance, whereas detection received comparatively lower weight. Thus, the ranking obtained from TOPSIS reflects not only how frequently a constraint occurs but also its perceived seriousness and broader impact.

The TOPSIS results show substantial differences among the fifteen constraints. A14 (pest attack during storage) obtained the highest TOPSIS score of 0.8214 and was ranked 1st, indicating the most favourable or least critical position under the adopted ranking convention. Conversely, A1 (access to quality seeds at affordable prices) recorded the lowest score of 0.3320 and was ranked 15th, identifying it as the most critical constraint. The large difference between these two scores demonstrates that farmers do not perceive all constraints as equally important and that interventions should therefore be prioritised according to their relative criticality.

Access to quality seed as the most critical constraint

The most important finding is the 15th rank of A1, concerning access to quality seed at reasonable prices. Although the constraint is essentially an input-related problem, its consequences extend across the entire production cycle. Seed quality determines crop establishment, plant vigour, disease susceptibility, tuber development and final productivity. Moreover, the high frequency of this constraint reported by 366 out of 400 farmers (91.50%) in the survey, provides strong evidence that it is a widespread problem rather than a localised concern.

The high severity and occurrence associated with A1 are particularly important because these two criteria together account for 65% of the total Fuzzy-AHP weight. Therefore, even where detection is relatively easier, the high severity and frequent occurrence of the seed problem substantially influence its overall priority. The finding suggests that improving access to certified or high-quality seed at affordable prices should be considered a first-line intervention for improving potato productivity in the study area.

Market-price instability

A2, low and unpredictable prices during peak harvesting periods, was ranked 13th, with a TOPSIS score of 0.4603. Although its TOPSIS score is higher than that of A1, the constraint remains an important economic concern. About 69.25% of respondents identified unstable or low prices as a problem.

The problem is particularly relevant because potato production is seasonal and large quantities of tubers reach the market within a relatively short period. When supply exceeds immediate market demand, farm-gate prices may decline sharply. Farmers who lack adequate storage facilities or financial capacity to delay sales are consequently compelled to sell during periods of low prices. Thus, market-price instability is closely interconnected with the storage constraints identified in the study. Strengthening storage access, market information systems, farmer-producer organisations and alternative marketing channels could reduce farmers' dependence on distress sales.

Pest and disease management

A3, pest and disease control, obtained a TOPSIS score of 0.5400 and was ranked 9th. Its relatively high occurrence, identified by 71.25% of farmers, shows that biological stresses remain a significant production concern. Pest and disease attacks can reduce both yield and tuber quality and can increase expenditure on pesticides.

The moderate ranking of A3 should not be interpreted as indicating that pest and disease problems are unimportant. Rather, compared with constraints such as seed availability and market conditions, farmers appear to experience pest and disease management as a comparatively less dominant constraint in the overall decision structure. The comparatively high severity values observed across several blocks indicate that local climatic conditions, cropping practices and availability of plant-protection services may influence the perceived importance of this constraint.

Erratic rainfall and moisture stress

A4, unreliable rainfall causing moisture stress and yield-loss risk, received a TOPSIS score of 0.4612 and ranked 12th. However, its reported frequency of 82% makes it one of the most widely experienced constraints in the survey. This apparently contrasting result is important. High occurrence does not automatically result in the highest overall priority because TOPSIS simultaneously considers severity, occurrence, detection and environmental impact.

The block-wise responses show considerable variation in the perception of rainfall-related stress. This variation is expected because access to irrigation, soil characteristics, local rainfall patterns and farmers' ability to supplement rainfall through irrigation differ between blocks. Areas with comparatively inadequate irrigation infrastructure are likely to be more vulnerable to irregular rainfall. Consequently, climate-risk management should be combined with irrigation development rather than addressed through a single intervention.

Irrigation and farmer training

A5, inadequate irrigation infrastructure, was ranked 5th with a score of 0.6225. Its relatively low reported frequency (19.75%) suggests that irrigation infrastructure is not uniformly perceived as a major constraint across all surveyed locations. Nevertheless, where it exists, its consequences can be substantial, particularly during periods of inadequate rainfall.

Similarly, A6, insufficient farmer training centres, was ranked 7th, with a score of 0.5895. Its frequency was only 21.75%, indicating substantial spatial variation. The block-wise responses suggest that farmers' access to training and technical support differs between locations. Such variation is important because improved knowledge concerning seed selection, disease management, irrigation scheduling, fertiliser application, weed control and storage practices can reduce the severity of several other constraints simultaneously.

Cost and availability of agricultural inputs

A7, limited and costly access to pesticides and fertilisers at critical stages, received a score of 0.4572 and ranked 14th. Despite its relatively low TOPSIS position, its occurrence among 67.25% of farmers demonstrates that input accessibility is widespread.

The result suggests that farmers frequently encounter input-related difficulties, but the overall severity of these difficulties may be lower than that associated with quality seed. Nevertheless, timely availability is crucial because delayed application of fertilisers

or plant-protection chemicals can reduce their effectiveness and increase production risk. Input availability should therefore be considered together with extension services, credit access and seasonal supply planning.

Weed infestation, labour scarcity and soil management

A8, weed overgrowth, obtained a score of 0.6240 and ranked 4th. Although only 21.25% of farmers reported it as a major constraint, the relatively favourable TOPSIS position indicates that, among the constraints considered, it is less critical overall. Nevertheless, weed infestation can compete with potato plants for nutrients, water and sunlight and can increase labour and production costs.

A9, labour scarcity, ranked 10th, with a score of 0.4907, and was reported by 63.75% of respondents. The high occurrence indicates that labour availability is an important operational issue, even though its aggregate TOPSIS position is lower than several other constraints. Labour shortages may become particularly important during planting, intercultural operations and harvesting, when delays can directly influence yield and quality.

A10, soil nutrient management and technology, achieved a score of 0.7730 and ranked 3rd. This comparatively high TOPSIS score indicates a relatively favourable position, although the issue remains agronomically relevant. The finding suggests that, compared with the most critical constraints, farmers may have greater ability to manage soil nutrient-related problems through existing practices or advisory support.

Storage-related constraints

The storage-related findings provide an important dimension of the study. A11, inadequate modern cold-storage infrastructure, scored 0.4782 and ranked 11th, whereas A12, cold-storage charges, obtained 0.7765 and ranked 2nd. The difference between these two results is noteworthy. It suggests that although infrastructure availability is a concern, the relative economic burden associated with storage charges may be perceived differently across the surveyed locations.

The high score of A12 indicates a comparatively favourable position under the adopted TOPSIS convention. However, the fact that 77.25% of farmers reported cold-storage charges as a constraint demonstrates that the issue is widespread. This apparent difference between frequency and TOPSIS position again illustrates the importance of using a multi-criteria approach rather than ranking constraints solely according to the number of farmers reporting them.

A13, inadequate transport infrastructure, obtained a score of 0.5729 and ranked 8th. Transport facilities are particularly important because potatoes are bulky and perishable commodities, and transportation costs directly affect the profitability of farmers and traders. Poor rural roads and inadequate transport facilities can increase post-harvest losses, delay delivery and reduce farmers' access to distant markets and storage facilities.

Storage pest attack and cold-storage management

The most favourable constraint was A14, pest attack during storage, with a TOPSIS score of 0.8214 and 1st rank. Only 16.75% of farmers reported this problem, which is the lowest frequency among the fifteen constraints. This agreement between the low reported frequency and high TOPSIS score strengthens the interpretation that storage pest attack is comparatively less critical in the surveyed area.

A15, efficient cold-storage management and technology, received a score of 0.6167 and ranked 6th. The finding indicates that although modern management and technology remain relevant, farmers do not perceive them as the most urgent constraint compared with fundamental production problems such as seed availability.

Block-wise comparison

The block-wise variation is an important outcome because a single district-level intervention may not adequately address the specific needs of individual production clusters. Overall, the block-level findings demonstrate that the nature and intensity of potato constraints are spatially heterogeneous. Therefore, the TOPSIS-based overall ranking should be used as a regional priority framework, while block-level scores should guide the intervention.

CONCLUSION

The present study developed a systematic framework for prioritising major constraints affecting potato cultivation and storage in four major potato-producing districts of West Bengal. Fifteen constraints were identified through stakeholder consultations, focus group discussions and expert interactions and were evaluated using four criteria: severity, occurrence, detection and environmental impact. The application of Fuzzy-AHP assigned weights of 0.34, 0.31, 0.13 and 0.22, respectively, demonstrating that severity and occurrence were the two most influential criteria in the decision-making process.

The TOPSIS analysis revealed substantial differences in the relative priority of the identified constraints. Access to quality seed at an affordable price (A1) emerged as the most critical constraint, recording the lowest TOPSIS score of 0.3320 and the 15th position under the adopted ranking convention. Its importance is further supported by the fact that 91.50% of surveyed farmers reported this constraint. This finding establishes affordable access to quality seed as a fundamental intervention point for improving potato productivity and reducing production risk.

At the opposite end, pest attack during storage (A14) obtained the highest TOPSIS score of 0.8214 and ranked first, indicating that it was the least critical or most favourable constraint among the alternatives. Only 16.75% of farmers reported storage pest attack, further supporting its relatively lower priority compared with the other constraints.

The results also demonstrate that frequency alone cannot adequately determine the priority of agricultural constraints. For example, several constraints with relatively high frequencies did not necessarily obtain the lowest TOPSIS scores because the final ranking incorporates severity, occurrence, detection and environmental impact simultaneously. This demonstrates the usefulness of the Fuzzy-AHP–TOPSIS approach for complex agricultural decision-making where multiple and sometimes conflicting criteria must be considered.

The block-wise comparison further confirms that constraint intensity is spatially heterogeneous across the 16 surveyed blocks. Differences in irrigation availability, input accessibility, climatic exposure, farmer training, transportation, market access and storage infrastructure influence farmers' perceptions of individual constraints. Consequently, interventions should combine state- or district-level priorities with block-specific action plans.

Based on the findings, the following priorities are recommended:

1. Ensure timely availability of certified/ high-quality potato seed at affordable

prices, particularly before the planting season.

2. Strengthen seed distribution networks and institutional support to reduce farmers' dependence on costly or uncertain seed sources.
3. Improve irrigation infrastructure and water-management practices in blocks vulnerable to rainfall variability.
4. Strengthen market linkages, price information and collective marketing mechanisms to reduce the adverse effects of peak-season price fluctuations.
5. Improve access to farmer training and extension services, particularly concerning integrated pest management, nutrient management and climate-resilient production practices.
6. Expand and modernise cold-storage facilities while ensuring that storage services remain economically accessible to small and marginal farmers.
7. Improve rural transport and post-harvest logistics to reduce marketing delays and physical losses.
8. Promote block-specific interventions based on the local severity and occurrence profiles rather than applying identical solutions across all potato-growing areas.

In conclusion, the study establishes that the major challenge in the potato production system of the surveyed districts is not a single isolated problem but an interconnected set of input, climatic, economic, infrastructural and post-harvest constraints. Among these, affordable access to quality seed deserves the highest policy attention. The Fuzzy-AHP–TOPSIS framework provides a transparent and reproducible mechanism for converting farmers' perceptions into a structured priority order and can therefore support policymakers, extension agencies and other stakeholders in allocating scarce resources towards the most critical constraints. The incorporation of block-wise variation further enhances the practical value of the framework by enabling location-specific and priority-based strategies for sustainable potato production and storage in West Bengal.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICAL STATEMENT

This article does not contain any studies with animals. Responses received from human participants on purely voluntary basis during the survey.

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COMPARATIVE ECONOMICS OF CONVENTIONAL VERSUS CONSERVATION METHODS OF POTATO CULTIVATION: FINDINGS FROM ASSAM, INDIA

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ABSTRACT: This study was carried out to estimate the economics of potato cultivation under conventional and conservation agriculture in the Bishwanath Chariali district of Assam utilizing analytical tools like compound growth rates, cost concepts, break-even analysis, and Garrett's ranking technique. It was found that the conservation method generated 32.31 per cent higher net returns than the conventional method of potato cultivation. The results further revealed that the benefit-cost ratio was higher under the conservation method (1.94) than under the conventional method (1.47) of potato cultivation. Break-even production was 171.88 and 101.70 q/ha, against actual production of 330.58 and 289.10 q/ha, while break-even prices were Rs. 777.69/q and Rs. 589.25/q, respectively, indicating that break-even production and break-even price were substantially lower than the corresponding actual levels under both methods. Major problems faced under conservation agriculture were identified and prioritized in the study area. This study recommends that effective government measures need to be implemented through various programs and demonstrations, and encourages the farming community to adopt conservation practices.

KEYWORDS: Break-even analysis, Cost analysis, Conservation practice, Potato production, Trend analysis

INTRODUCTION

The fourth-largest cultivated food crop in the world is the potato, also known as the king of vegetables (*Solanum tuberosum L.*). The potato has a sizable impact on the nation's overall agricultural output. After China, India ranks second in the world for potato production (Rana and Anwer, 2018; Sahu *et al*., 2024). China and India are the world's leading potato producers, together accounting for nearly one-third of global potato production (FAOSTAT, 2023). Global potato production stood at 376 million tonnes (MT) in 2022–23, with China and India contributing 94 MT and 54 MT, respectively. Globally, potato production is essential for strengthening agricultural economies while promoting income generation and food security (Devi *et al*., 2025). Almost 85% of the crop is grown during short photoperiod winters (with roughly 10–11 hours of sunshine), and the crop duration is constrained to 90–100 days. The principal potato-growing states in India are Uttar Pradesh, Himachal Pradesh, West Bengal, Bihar, Gujarat, Madhya Pradesh, Punjab, Assam, Karnataka, Haryana, and Jharkhand. With a production of 191.73 lakh MT from 696.03 thousand ha, Uttar Pradesh is the leading potato-producing state in India, while Gujarat recorded the highest

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productivity at 29.66 MT/ha. During 2023–24, Uttar Pradesh, West Bengal, and Bihar together accounted for 65% of the country's total potato cultivation area and 71% of the national potato production (Agricultural Statistics at a Glance, 2024).

The majority of people in Assam state still rely primarily on agriculture for their income. Despite India's expanding potato production, productivity and sustainability remain constrained by region-specific agroecological conditions, particularly in Assam, where climatic variability, soil characteristics, and production constraints influence potato cultivation. In 2023–24, Assam recorded a potato production of 911.33 thousand tonnes from 106.47 thousand hectares under cultivation, accounting for 5% of the country's total potato cultivation area, with an average yield of 8,560 kg/ha (Agricultural Statistics at a Glance, 2024). In Assam, potato cultivation has long relied on conventional methods, yet many farmers are now transitioning to conservation agriculture. Conservation Agriculture (CA) was developed to improve the sustainability of agro-ecosystems by enhancing productivity, increasing farmers' income, and ensuring the efficient use of natural resources (Jat *et al*., 2021). Conservation agriculture is a farming technique that can prevent the loss of arable land and restore degraded areas by involving minimal or no soil disturbance for crop production. This practice reduces the cost of cultivation and saves labour time, energy, and cost. In contrast, conventional agriculture refers to the use of artificial chemical fertilisers, pesticides, herbicides, and other ongoing inputs for production. When the sowing/transplanting of the sali rice is delayed, leading to delayed harvesting, it is difficult to go for rabi crop cultivation, like potato cultivation under the conventional method. In that case, potato cultivation can be adopted with the help of conservation methods without any tillage. Thus, potato cultivation under a conservation method will reduce labour and total cultivation costs, resulting in lower potato production. Taking into account the above facts, the present study was an attempt to examine the comparative advantage of conservation agriculture over conventional agriculture with reference to cost, returns, and economic feasibility. Therefore, the study was conducted to analyse the comparative economics of the conservation method of potato cultivation vis-à-vis the conventional method and identify the problems of potato cultivation with special reference to the conservation method. The findings can support policymakers and farmers in strengthening the financial viability of potato farming in the region.

MATERIALS AND METHODS

Study area and data

This research was conducted from April 2022 to June 2022 utilizing both primary and secondary data in the Bishwanath Chariali district of Assam, as many farmers opted for the conservation method of potato cultivation over the conventional method. The potato varieties cultivated under each method were Kufri Pukhraj. Secondary information of Sonitpur district was gathered from the District Agriculture Office, Block Agriculture departments, and the official website of the Department of Agriculture, Assam. Primary data for the study were collected from respondents through personal interviews using pretested schedules.

Sampling design

A multistage stratified random sampling design was utilised to draw samples from the Bishwanath Chariali district, which was selected purposively. Under the Bishwanath Chariali district, two ADO circles were

selected, *i.e.*, Baghmara circle and Gingia circle, as the circles have the maximum potato area under conservation agriculture. Two villages from each circle were selected at random for the study. In the next stage, from each village, 10 farmers consisting of marginal (below 1 ha), small (1 to <2 ha), medium (2 to <10 ha), and large (10 ha and above) farmers cultivating potato under conventional agriculture and another 10 farmers practising conservation agriculture were selected randomly in the ratio of 4:3:2:1, respectively. Thus, a total of 80 farmers, 40 each practising conservation agriculture and conventional agriculture, were selected for the ultimate sample.

Analytical framework

Compound Growth rate

To determine the growth trends over time, the compound growth rate was used. The equation of compound growth rate can be written as:

$Y = ab^t$

Or, ln Y= ln a+ t ln b

Compound growth rate was estimated as

CAGR= Antilog (b – 1) x 100

Where, Y represents time series data, b regression coefficient and t is time period.

Cost concepts

The cost of cultivation was analysed by applying different cost concepts given by CACP. In the present study, the following cost concepts were used.

Cost A1: It includes value of hired human labour + value of hired and owned machine labour + value of manures and fertilizers (owned and purchased value of fertilizers) + value of purchased and owned seed + value of plant protection chemicals used + irrigation charges + interest on variable capital + depreciation on farm implements and machinery + land revenue charges + micronutrients.

Cost A_2: Cost A_1+ rent paid for leased land.

Cost B: Cost A_2+ rental value of owned land + interest on fixed capital.

Cost C: Cost B + value of owned human labour.

Return concepts

To estimate the farm's returns and profits, the following metrics were utilized in this study. The reference period for potato prices used in calculating returns was 2021-22.

Gross return (GR) = Total production × Total price.

Farm business income = Gross return - Cost A_1.

Family labour income = Gross return - Cost B.

Net return (NR) = Gross return (GR) - Total cost, or Cost C

Break-even analysis

Break-even analysis helps determine the economic feasibility of an enterprise. The break-even analysis helps to determine the break-even point at which the cost and revenue are equal, resulting in neither a profit nor a loss. In the present study, break-even production and break-even price were calculated.

$$\text{Break Even Production} = \frac{\text{Fixed cost}}{\text{Price per unit-Variable cost per unit}}$$

$$\text{Break Even Price} = \frac{\text{Total cost}}{\text{Total production}}$$

Garrett's ranking

This technique was utilised to categorize the problems encountered by farmers in potato cultivation under conservation agriculture in the study area.

$$P_{ij} = 100\left[\frac{R_{ij} - 0.5}{N_j}\right]$$

Where, P_{ij} = Garrett percentage position of the factor for the respondent, denotes the rank assigned to the i^{th} item by the j^{th} respondent,

and represents the total number of items ranked by the j^{th} respondent.

RESULTS AND DISCUSSION

Status of potato cultivation in Assam

The conservation method had an edge over the conventional method for various attributes of potato production, as it reduces the total cost of production and reduces time-consuming tillage operations. The area, production, and productivity of potatoes in Assam demonstrate that all three of these metrics have increased over time (Table 1), whereas, a nonsignificant growth trend was observed for the district during 2010-11 to 2020-21.

Potato cultivation across sample farm size groups

Table 2 presents the area, production, and productivity of potato across sample farm size groups. It was found that the area under conventional potato was more than the area under conservation potato. Similarly, production and productivity were higher for conventional potatoes than for conservation potatoes. Farmers from the study area are shifting towards conservation potato cultivation due to the lower cost of cultivation and less time-consuming tillage operations. The state government also played an important role in encouraging farmers to adopt conservation methods in potato cultivation. The district agricultural department has also brought many demonstrations and schemes for the farmers so that they can enhance their knowledge of conservation methods and potato cultivation practices.

Comparative economics of conventional v/s conservation method of potato cultivation

Table 3 illustrates the overall comparative economics of potato cultivation under the conservation method versus the conventional

Table 1. Trend estimates of growth pattern of potato in Assam

Year (2010-11 to 2020-21)	Area (in hectares)				Production (in tonnes)				Productivity (in kg/hectares)			
Potato in Assam	CAGR (%)	S.E.	C.I. at 95%		CAGR (%)	S.E.	C.I. at 95%		CAGR (%)	S.E.	C.I. at 95%	
			Lower	Upper			Lower	Upper			Lower	Upper
	1.55***	0.004	0.006	0.025	1.23**	0.004	0.003	0.021	-0.25^{NS}	0.004	-0.011	0.006
Potato in Sonitpur district	0.83^{NS}	0.007	-0.007	0.023	0.90^{NS}	0.010	-0.014	0.032	0.07^{NS}	0.005	-0.010	0.011

Note: CAGR- Compound annual growth rate, S.E.- Standard error, C.I.- Confidence interval.
*** and ** Significant at 1 and 5% levels, respectively.
Source: Authors calculations.

Table 2. Estimated potato cultivation across sample farm size groups (area: ha, production: q, productivity: q/ha)

Farm size	Conventional Potato				Conservation Potato			
	No. of farmers	Area	Production	Productivity	No. of farmers	Area	Production	Productivity
Marginal	16	13.32	3922.50	294.48	16	3.15	920.00	262.10
Small	12	22.36	6560.00	293.38	12	2.54	710.00	280.08
Medium	8	42.38	13286.00	313.49	8	1.89	532.50	282.49
Large	4	37.70	14500.00	384.62	4	0.91	292.50	321.43
All farms	40	115.76	38268.50	330.58	40	8.49	2454.50	289.10

Source: Authors calculations

Table 3. Comparative economics of conventional v/s conservation methods of potato cultivation (Rs/ha)

Sl. No.	Particulars	Conventional Potato					Conservation Potato				
		Marginal	Small	Medium	Large	Pooled	Marginal	Small	Medium	Large	Pooled
1	Total variable cost	114790.80	120067.80	123714.90	133239.59	125575.90	76007.09	80822.04	85350.63	91637.78	83154.76
2	Total fixed cost	120177.60	119677.70	127032.80	145664.84	131513.80	79159.36	84549.96	85509.38	96976.91	87198.66
3	Total cost	234968.30	239745.60	250747.70	278904.43	257089.70	155166.50	165372.00	170860.00	188614.70	170353.40
4	Cost A_1	90220.04	99569.65	109808.90	122306.01	110139.80	67898.27	75972.67	81864.59	87929.33	77406.04
5	Cost A_2	121377.30	130410.30	141940.80	122306.01	141827.70	67898.27	75972.67	81864.59	87929.33	77406.04
6	Cost B	207416.80	216159.00	233557.50	264556.19	238399.80	144094.20	157395.10	163991.00	181371.80	161449.60
7	Cost C	234968.30	239745.60	250747.70	278904.43	257089.70	155166.50	165372.00	170860.00	188614.70	170353.40
8	Gross return	337053.70	335920.10	358957.50	440389.90	378514.10	300104.50	320691.60	323451.10	368037.40	331019.50
9	Family business income	246833.70	236350.40	249148.60	318083.88	268374.30	232206.20	244718.90	241586.50	280108.10	253613.50
10	Family labour income	129636.90	119761.10	125400.00	175833.71	140114.30	156010.30	163296.50	159460.10	186665.60	169569.90
11	Net return	102085.40	96174.53	108209.80	161485.46	121424.40	144938.00	155319.60	152591.10	179422.70	160666.10
12	Gross return over total cost (Rs.)	1.43	1.40	1.43	1.57	1.47	1.93	1.93	1.89	1.95	1.94
13	Net return over total cost (Rs.)	0.43	0.40	0.43	0.57	0.47	0.93	0.93	0.89	0.95	0.94

Source: Authors calculations

method. It was observed that the total cost of cultivation was significantly lower under the conservation method (Rs. 170,353.40/ha) than under the conventional method (Rs. 257,089.70/ha) (t= 4.82, p< 0.001). Under the conventional method, the large-farm respondents cultivated potato on their own land, and consequently Cost A2 remained equal to Cost A1. The gross return under the conventional and conservation methods was found to be Rs. 378514.10 and Rs. 331019.50, respectively, indicating a significant difference between the two methods (t = 2.14, p = 0.035). These findings are well supported by the findings of Sujan *et al*. (2017). The net return under the conventional method was found to be Rs. 121424.40, while Rs. 160666.10 under the conservation method. Sinha and Singh (2019) also reported similar findings regarding potato production in Chhattisgarh. It was found that gross return over total cost was higher under the conservation method (1.94) than the conventional method (1.47) due to lower total cost involved under the conservation method. Figure 1 represents a comparison of net return over total cost and BC ratios between methods for visual impact. Raina *et al*. (2024) studied potato production in Himachal Pradesh and reported a BC ratio of 1.88. According to Singh *et al*. (2019), the return per rupee invested in potato cultivation was Rs. 3.42 for small farmers,

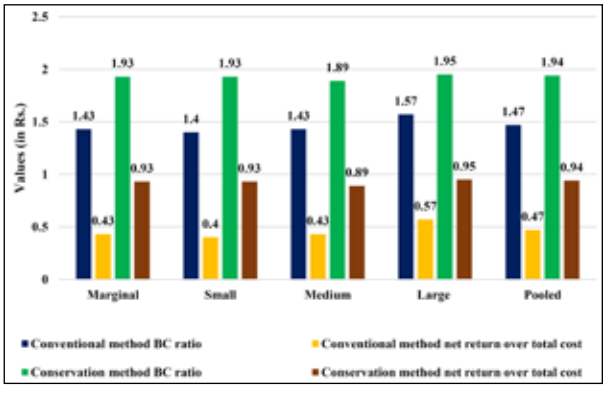


Fig. 1. Comparison of net returns and BC ratios between methods

Rs. 2.61 for medium farmers, and Rs. 2.21 for large farmers. Conservation agriculture generated higher net returns over total cost compared with conventional agriculture. The current study's cost concept estimation is consistent with the findings of Singh *et al*. (2020). The above analysis indicates an increasing trend of return per rupee with an increase in farm size for both conservation potato and conventional potato, except for small farms under the conventional method and medium farms under the conservation method. But the return per rupee for the conservation potato was more than that of the conventional potato. The returns from the cultivation of conservation and conventional potato indicate that the benefit gained from the conservation method was more compared to conventional potato, and it is economically more profitable.

Break-even analysis

Break-even production

Table 4 presents the break-even analysis of potato cultivation in monetary and physical terms across different farm categories. In the present study, the break-even production per hectare was calculated, and it was found to be 171.88 q/ha under the conventional method and 101.70 q/ha under the conservation method. The actual production under the conventional and conservation methods was 330.58 q/ha and 289.10 q/ha, respectively, which was more than the breakeven production. The margin of safety for production under the conventional method was 158.70 q/ha, while the per-ha safety in the conservation method stood at 187.40 q/ha. Break-even analysis provides farmers with a practical framework for optimizing production and managing costs, which indicates a positive margin of safety. These estimates can help farmers assess the minimum production or price required to cover total costs and can support production planning, cost control and price-risk assessment.

Break-even price

Break-even prices under the conventional and conservation methods were found to be Rs. 777.69 and Rs. 589.25 per quintal, respectively, which were lower than the actual price (Table 4). The actual price received under the conventional and conservation methods was found to be Rs. 1145 for both. The margin of safety for price under the conventional method was found to be Rs. 367.31 per quintal, and under the conservation method, it was Rs. 555.75 per quintal. Findings of Raina *et al*. (2024) also supported these findings. The average price received was significantly higher than the break-even price, which indicates that potato cultivation under both conventional

Table 4. Break-even output under conventional and conservation potato production

Particulars	Conventional Potato					Conservation Potato				
	Marginal	Small	Medium	Large	Pooled	Marginal	Small	Medium	Large	Pooled
Break-even production (q/ha)	159.16	162.66	169.29	182.40	171.88	92.58	98.72	101.45	112.77	101.70
Actual production (q/ha)	294.37	293.38	313.50	384.62	330.58	262.10	280.08	282.49	321.43	289.10
Margin of safety (q/ha)	135.21	130.72	144.21	202.22	158.70	169.52	181.36	181.04	208.66	187.40
Break-even price (Rs.)	798.20	817.18	799.83	725.14	777.69	592.01	590.44	604.83	586.79	589.25
Actual price (Rs.)	1145.00	1145.00	1145.00	1145.00	1145.00	1145.00	1145.00	1145.00	1145.00	1145.00
Margin of safety (Rs.)	346.8	327.82	345.17	419.86	367.31	552.99	554.56	540.17	558.21	555.75

Source: Authors calculations

and conservation methods is economically viable. It provides a basis for sound financial planning, appropriate pricing strategies, and realistic production planning.

Percentage change in conservation potato over conventional potato

Table 5 shows the percentage change in cost and returns of conservation potato cultivation over the conventional method of potato cultivation. It was found that the total cost under the conservation method of potato cultivation was 33.73 per cent less than the conventional method of potato cultivation. Similarly, gross return and yield under the conservation method of potato cultivation were found to be 12.54 and 16.08 per cent less than the conventional method of potato cultivation. But the net return was found to be higher under the conservation method by 32.31 per cent as compared to the conventional method of potato cultivation. Findings also revealed that yield was significantly higher under the conventional method (330.58 q/ ha) compared with the conservation method (277.40 q/ha) ($t = 3.21$, $p = 0.002$).

Table 5. Percentage change in cost and returns of conservation potato cultivation over conventional potato cultivation

Particulars	Conventional potato cultivation	Conservation potato cultivation	% change in conservation potato over conventional potato
Total cost (Rs./ ha)	257089.70	170353.40	-33.73
Gross return (Rs./ ha)	378514.10	331019.50	-12.54
Net return (Rs./ ha)	121424.40	160666.10	32.31
Yield per ha	330.58	289.10	-12.54

Source: Authors calculations

Table 6. Problems faced in potato cultivation with special reference to the conservation method

Sl. No.	Problems	Average Score	Rank
1.	Less availability of crop residues	71.12	I
2.	Difficulty in scaling up	62.42	II
3.	Incidence of animals	59.97	III
4.	Higher fencing cost	55.47	IV
5.	Shortage of labour at the early stage	55.20	V
6.	Infestation of pests and diseases	46.55	VI
7.	Environmental problems	36.65	VII
8.	Lack of capital	27.45	VIII
9.	Lack of proper technical knowledge	26.90	IX
10.	Farmers' perception of low crop yield	26.17	X

Source: Authors calculations

Problems faced in potato cultivation using the conservation method

Table 6 presents constraints faced under the conservation method. The major constraint faced under the conservation method was the limited availability of crop residues because the conservation method of cultivation demands a large requirement of crop residues, mainly paddy straw, rice husk, etc., for a small piece of land. Another major problem reported under the conservation method was the incidence of animals in the cultivated field. Bhan and Behera (2014) studied the problems associated with conservation practices, which are aligned with these findings. The shortage of labour at the early stage, as the conservation method involves a large number of operations at the initial stage, which leads to labour shortage for a period of time. Infestation of pests and diseases was ranked sixth, as the incidence of pests such as potato leafhopper, potato bug, and diseases such as late blight of potato was observed under the conservation method of potato cultivation. Another constraint found under the conservation method was environmental hazards, as the conservation method sometimes involves the burning of crop residues in the field for the next crop cultivation, which leads to the emission of harmful gases into the atmosphere, negatively impacting the environment.

The next minor constraint involved was the lack of capital because the conservation method involves a high amount of input cost, which leads to a constraint for marginal and small farmers in adopting the conservation method. The next constraint found was a lack of proper technical knowledge because there was a lack of awareness and knowledge dissemination regarding the conservation method among the marginal group of farmers. Lastly, farmers' perception of low crop yield was ranked last because, due to lack of knowledge and awareness, many farmers believed that the conservation method practice resulted in lower crop yield than the conventional method, so they preferred going with the conventional method of crop cultivation.

CONCLUSION

This study concludes that the area and productivity were found to be moderately high in the conventional method, as compared to the conservation method of potato cultivation. The net return generation was found to be moderately higher in the conservation method than in the conventional method of potato cultivation. Break-even production and break-even price were found to be lower than the actual production and price under the conventional and conservation methods. This study suggests that the government should take effective measures through various programmes and demonstrations to cover all the farmers, encouraging them to adopt the conservation method of crop cultivation, as it facilitates the adoption of double and multiple cropping by reducing the time, energy and cost. Similarly, non-government organisations like Farmer Producer Company should play an important role in helping the needy farmers through proper training and input supply at affordable prices. Therefore, needy farmers should be given proper skill development guidance and training, and support to make judicious decisions regarding resource utilisation to increase production.

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AUTHORS CONTRIBUTIONS

Kaustabh Kishor Das: Data collection, analysis of data; Riaz Abdul Halim, Nivedita Deka: Study conception and design, review; Saddam Hossen Majumder: Data analysis and review, interpretation of results, review, and manuscript finalization.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors.

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DRIVERS OF ICT UTILIZATION AMONG POTATO GROWERS IN GUJARAT: EVIDENCE FROM A BINARY LOGISTIC REGRESSION MODEL

Shruti Samadder[1], Sanjay P. Panday[2] and Sudhanand Prasad Lal[3*]

ABSTRACT: The adoption of Information and Communication Technology (ICT) in agriculture plays a critical role in enhancing farm productivity and improving decision-making. This study examines the extent of ICT utilization and its determinants among potato growers in Banaskantha district of Gujarat using a Binary Logit (BL) model. Primary data were collected from 150 farmers across three talukas, namely Dantiwada, Deesa, and Lakhani. The results indicate that mobile phones, television, and internet services are widely used by farmers, whereas Agricultural Information Services such as web portals and Kisan Call Centres remain underutilized. The Binary Logit analysis identifies income (p = 0.000, OR = 96.10), source of information (p = 0.066, OR = 1.461), attitude towards ICT (p = 0.039, OR = 1.203), and knowledge level (p = 0.001, OR = 2.306) as significant determinants influencing ICT adoption. The large odds ratio associated with income reflects the effect of categorical income measurement rather than a marginal increase in income, highlighting the importance of financial capacity in facilitating ICT adoption. Model diagnostics indicate a good fit, as confirmed by the Omnibus Test (χ^2 = 106.565, p < 0.001) and the Hosmer–Lemeshow test (χ^2 = 5.023, p = 0.755). The model achieved an overall classification accuracy of 84.0%, correctly predicting 88.4% of non-adopters and 78.1% of adopters. The findings suggest that strengthening rural ICT infrastructure, improving digital literacy, and enhancing affordability, along with reinforcing digital agricultural extension services, are essential for promoting ICT adoption and reducing the digital divide among farmers.

KEYWORDS: Digital Agriculture, ICT Tools, ICT Utilization, Binary Logit Model, Potato farmers.

INTRODUCTION

Information and Communication Technology (ICT) is increasingly transforming agriculture by improving farm productivity, decision-making, and resilience. Digital transformation in agriculture through ICT integrates tools such as mobile applications, Geographic Information Systems (GIS), Internet of Things (IoT) sensors, artificial intelligence (AI)-driven solutions, and e-market platforms to provide real-time information on crop management, pest control, weather forecasting, and market trends. These technologies enable precision farming, enhance knowledge access, and strengthen market linkages, thereby supporting sustainable agricultural development. Despite the substantial potential of ICT, its adoption in agriculture remains constrained by several challenges, including limited digital literacy, inadequate internet connectivity, cost constraints, and trust-related issues.

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While ICT-enabled solutions have demonstrated productivity gains of up to 20% in some regions through precision farming, real-time advisories, and improved pest management (Kumar *et al*., 2024), their effective utilization largely depends on farmers' socio-economic capacity and access to digital infrastructure. Gujarat is a major potato-producing state in India, contributing about 6.69% of the country's total potato production and ranking fourth after Uttar Pradesh (33.46%), West Bengal (24.12%), and Bihar (15.09%) (Singh & Dutt, 2024). Potato cultivation in Gujarat faces challenges related to climate variability, irrigation management, pest incidence, and market fluctuations. ICT interventions such as IoT-based irrigation systems can reduce water use by up to 30% (Obaideen *et al*., 2022), while AI-powered platforms like e-Krishi Mitra provide localized crop advisories to a large number of farmers. However, access to advanced ICT tools remains limited, as only about 35% of rural areas have reliable internet connectivity, and high costs restrict farmers' ability to adopt digital technologies (Panigrahy & Kalamkar, 2024). Bridging these gaps through targeted digital literacy initiatives and affordable technological solutions could potentially enhance productivity by 15–25%, positioning Gujarat as a leader in technology-driven agriculture (Samaddar *et al*., 2023). Addressing infrastructural and behavioural barriers is therefore essential for enabling farmers to effectively harness ICT and improve farm performance and market resilience. Although existing studies on agricultural technology adoption provide broad insights, crop-specific analyses remain limited. Potato farming, characterized by high input intensity and sensitivity to climatic and market risks, requires targeted digital interventions aligned with local conditions. Understanding ICT utilization patterns among potato growers is crucial for designing effective extension strategies and evidence-based policy interventions. Accordingly, the objectives of the study were to i) assess the extent of ICT utilization among potato growers ii) to identify the key socio-economic and behavioural determinants influencing ICT adoption among potato growers in Gujarat.

MATERIALS AND METHODS

The study was conducted in Banaskantha district, one of the leading potato-producing regions in Gujarat. Within Banaskantha, three talukas—Dantiwada, Deesa, and Lakhani—were purposively selected based on their high contribution to potato production. Given the heterogeneity in ICT adoption patterns among farmers, a random sampling approach was employed to ensure representation across different farming communities. A total of 150 potato growers were selected, with 10 respondents from each of the 15 villages across the three talukas: Dantiwada Taluka: Dantiwada, Deri, Dharni, Bhakarmoti, Bhakar Nani, Deesa Taluka: Juna Deesa, Vasana, Athamno Vas, Ugamno Vas, Vachlovas, Lakhani Taluka: Vasana, Dharanva Manki, Dera Agathala. The selection of villages was based on potato cultivation intensity and accessibility, ensuring diverse insights into ICT adoption patterns among farmers with varying socio-economic backgrounds. In order to gather primary data through in-person interviews, a structured survey questionnaire was created. Its validity, reliability, and clarity were checked through pre-testing. ICT access and usage patterns (ownership, frequency of use, purpose), demographic and socioeconomic variables (age, education, income, landholding, debt level), and farmers' attitudes, knowledge, and behavioural elements connected to ICT adoption were all collected through the survey. Participation

in extension activities and agricultural information sources were also examined. To acquire qualitative insights into the factors that encourage and hinder the adoption of ICT, focus groups and key informant interviews with progressive farmers, input dealers, and agricultural extension agents were also carried out. To systematically assess the extent of ICT adoption among potato farmers, a composite framework was developed to cover 14 widely used ICT tools in agriculture, including traditional ICT (Radio, Television), modern ICT devices (Mobile Phone, Laptop/ Desktop, Internet), social media and digital platforms (WhatsApp, Facebook, YouTube, Video Conference, e-mail), and agricultural information services (CD/DVD, E-Magazines, Kisan Call Centre, Web Portals). Respondents reported ownership, access, and usage frequency, which were categorized as high, moderate, or low based on frequency and purpose. Determinants of ICT adoption were examined, considering demographic factors (age, education level), economic variables (income, landholding, debt level), information sources and awareness (source of agricultural information, knowledge of ICT tools), behavioural and social factors (attitude toward technology, social participation, extension participation), and the innovation diffusion stage (innovator, early adopter, early majority, late majority, or laggard). These variables were hypothesized to influence ICT adoption likelihood based on respondents' socio--economic and behavioural profiles. For the Binary Logistic Regression analysis, the Extent of Utilization Pattern Index (EUPI) was converted into a dichotomous variable using the mean score as the cut-off point, classifying respondents as ICT adopters (1) and non-adopters (0). Binary Logistic Regression was employed to examine the factors influencing ICT adoption among potato growers, as it is appropriate for analyzing binary outcome variables. The model accounts for non-linear relationships between the dependent and independent variables and ensures that predicted probabilities of ICT adoption are bounded between 0 and 1 through the logistic function:

$$P\ (Y = 1 \mid X) = \frac{e^{\beta_0+\beta_1X_1+\ldots+\beta_nX_n}}{1 + e^{\beta_0+\beta_1X_1+\ldots+\beta_nX_n}}$$

The logistic regression model was specified as: $\log[P(Y=1)/(1-P(Y=1))] = \beta_0 + \beta_1X_1 + \beta_2X_2 + \ldots + \beta_nX_n$. Here, $P(Y=1 \mid X)$ denotes the probability that a respondent belongs to the higher ICT-utilization/adoption category; β_0 is the intercept; β_i represents the regression coefficient for the ith explanatory variable; and X_i represents the corresponding independent variable.

In this equation:

$P\ (Y = 1 \mid X)$ is the probability of the dependent variable Y being 1 given the independent variables X.

β_0 is the intercept.

β_0, β_1, ...β_n are the coefficients for the independent variables X_1, ...X_n.

where Xn represents independent variables (e.g., age, education, income, landholding, knowledge, attitude). The model outputs odds ratios (OR), where OR > 1 indicates a positive influence (e.g., higher education increases ICT adoption), OR < 1 suggests a negative impact (e.g., older farmers are less likely to adopt), and OR = 1 implies no effect (Hossain *et al*., 2024). Statistical significance is assessed using p-values (< 0.05 indicates a meaningful effect) and Wald statistics. Model fitness is evaluated using the Likelihood Ratio (LR) Test (Lal *et al.*, 2025), Pseudo R^2 (Nagelkerke R^2 range between 0 to1), and the Hosmer-Lemeshow test (p > 0.05 suggests a good fit). A well-fitting model should have a high classification accuracy of >70% (Davies *et al.*, 2024), correctly predicting ICT

adoption patterns. If the model does not fit well, modifications like including interaction terms or alternative regression approaches (e.g., Probit) may be considered. The Logit model thus provides critical insights into how socio-economic and behavioural factors shape ICT utilization, aiding policymakers in developing targeted interventions to enhance digital adoption in agriculture.

RESULTS AND DISCUSSION

The findings of this study provide empirical insights into the extent of ICT utilization among potato growers in Gujarat, along with the determinants influencing their adoption.

Table 1 exhibited the frequency distribution of ICT usage by respondents. Traditional ICT tools such as radio (65.34%) and television (70.00%) are frequently used on a daily basis, indicated their continued relevance in agricultural information dissemination. Mobile phones (78.00%) emerged as the most widely used ICT tool. However, a majority of respondents reported non-use of advanced ICT tools such as video conferencing (62.00% never used), e-mail (95.33% never used), CD/DVD (96.00% never used), e-magazines (90.66% never used), and web portals (98.00% never used), reflecting limited penetration of advanced digital platforms.

Figure 1 presented the aggregate ICT utilization index across four broad ICT categories. Traditional ICT recorded the highest utilization index (81.34%), followed by modern ICT (54.00%), media and digital platforms (28.00%), and agricultural information services

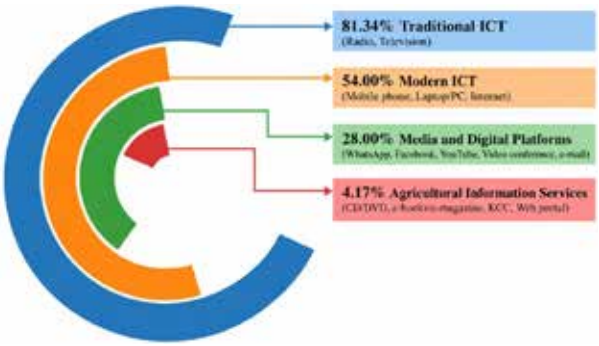


Fig. 1. Four Broad Spectrum of Utilization of ICT

Table 1. Extent of utilization of ICTs by the farmers

Sr. No.		ITCs	Daily		Weekly		Fortnight		Occasionally		Never	
			f	%	f	%	f	%	f	%	f	%
1	Traditional ICT	Radio	98	65.34	9	6.00	8	5.33	14	9.33	21	14
2		Television	105	70.00	16	10.67	8	5.33	4	2.67	17	11.33
3	Modern ICT	Mobile phones	117	78.00	14	9.33	9	6.00	6	4.00	4	2.67
4		Laptop/personal computer	0	0	0	0	8	5.33	4	2.67	138	92.00
5		Internet	74	49.33	15	10.00	6	4.00	3	2.00	52	34.67
6	Social Media And Digital Platform	WhatsApp	68	45.33	18	12.00	6	4.00	1	0.67	57	38.00
7		Facebook	24	16.00	9	6	1	0.67	50	33.33	66	44.00
8		You Tube	23	15.33	12	8.00	3	2.00	5	3.33	107	71.34
9		Video conference	0	0	3	2.00	39	26.00	15	10.00	93	62.00
10		e-mail	0	0	0	0	4	2.67	3	2.00	143	95.33
11	Agricultural Information Services	CD/DVD	0	0	0	0	0	0	6	4.00	144	96.00
12		e-books/e- magazine	0	0	0	0	4	2.67	9	6.00	137	91.33
13		Kisan Call Centre (KCC)	0	0	3	2.00	18	12.00	16	10.66	113	75.34
14		Web portal	0	0	0	0	0	0	3	2.00	147	98.00

(4.17%). The results indicated greater reliance on traditional and commonly accessible ICT tools, while specialized agricultural information services remained comparatively underutilized. Due to poor ICT utilization for Laptop/personal computer, Video conference, e-mail, CD/DVD, e-books/e- magazine, Kisan Call Centre (KCC) & Web portal none of the respondents fell in the high utilization category.

Extent of Utilization patterns of ICT tools

The majority of farmers were classified under low (57.33%) followed medium (42.67%) ICT utilization categories. No respondents were found in the high utilization category, indicating limited penetration of diverse and advanced ICT tools (Table 2). The mean utilization score of 18.126 (SD = 4.92) suggested low overall ICT engagement, with a majority of farmers lacking access or awareness of diverse ICT tools beyond mobile phones and traditional media.

As the classification in Table 2 revealed only two categories Low & Medium; so binary logit model was used instead of multinomial logistic model which predicted the probability of a categorical dependent variable with binary unordered choices based on 11 independent variables. Since no respondent was observed in the high-utilization category, the two observed categories, namely low and medium utilization, were used to construct the binary dependent variable. Respondents with EUPI scores ranging from 0 to 19 were coded as 0 (lower ICT utilization/non-adopter), whereas respondents with scores ranging from 20 to 38 were coded as 1 (higher ICT utilization/adopter)..

The classification accuracy of 84.0% (Table 3) indicates the model's robust predictive capability, effectively categorizing ICT users and non-users. The model correctly predicts 88.4% of non-users and 78.1% of users, supporting the reliability of the identified determinants. This highlights the necessity of targeted interventions to enhance digital access and ICT-driven agricultural extension in Gujarat. The Binary Logit regression model was employed to analyze the key factors influencing ICT adoption among farmers. The Omnibus Tests of Model Coefficients indicate a highly significant model fit (χ2= 106.565, p = 0.000), confirming that the selected independent variables significantly influence ICT adoption.

The model summary (Nagelkerke R^2 = 0.683) demonstrates that 68.3% of the variation in ICT utilization is explained by the independent variables, indicating a strong explanatory power of the model (Table 4). The Hosmer and Lemeshow test (χ2= 5.023, p = 0.755) confirms that the model is well-calibrated, as the non-significant p-value suggests a good fit (Shukla *et al.*, 2024). The Binary Logit regression analysis identifies four

Table 2. Distribution of respondents according to their utilization pattern of ICT tools

Sl. No.	Category	f	%
1	Low (0-19)	86	57.33
2	Medium (20-38)	64	42.67
3	High (39-56)	0	0.00
Total		150	100.00

$\bar{x}$=18.126; σ= 4.92

Table 3. Classification statistics of the Binary logistic regression model apropos EUPI

	Observed		Predicted		
			EUPI		% Correct
			0	1	
Step 1	EUPI	0	76	10	88.4
		1	14	50	78.1
	Overall Percentage				84.0

a. The cut value is .500; *EUPI: Extent of Utilization Pattern Index; 0 = lower ICT utilization/non-adopter and 1 = higher ICT utilization/adopter. (EUPI)

Table 4. Parameter Estimates of Binary Logistic Regression Analysis apropos EUPI

EUPI	B	S.E.	Wald	df	Sig.	Exp(B)	EXP (β)95% CI	
							LB	UB
Age	-.097	.088	1.224	1	.269	.907	.763	1.078
Education	.168	.297	.320	1	.572	1.183	.660	2.119
Laggard	.000	.000	.493	1	.483	1.000	1.000	1.000
Income	4.565	1.042	19.192	1	.000***	96.100	12.464	740.920
Source of information	.379	.206	3.378	1	.066*	1.461	.975	2.188
Landholding	.081	.148	.300	1	.584	1.084	.812	1.448
Debt	.437	.899	.237	1	.627	1.548	.266	9.010
Attitude	.185	.090	4.269	1	.039**	1.203	1.010	1.435
Knowledge	.836	.249	11.255	1	.001***	2.306	1.415	3.757
Extension Participation	-.020	.111	.033	1	.855	.980	.788	1.218
Social Participation	-.004	.026	.022	1	.883	.996	.946	1.049
Constant	-15.666	4.520	12.013	1	.001	.000		
-2 Log likelihood								98.141[a]
Cox & Snell R Square								.509
Nagelkerke R Square								.683

***, **, *, depict level of significant at 1%, 5%, 10% respectively.
LB = Lower Bound; Upper Bound.
a. Estimation terminated at iteration number 7 because parameter estimates changed by less than .001.
Variable(s): Age, Education, Income, Laggard, Source of information, Landholding, Debt, Attitude, Knowledge, Extension Participation, Social Participation.

significant variables influencing the extent of ICT utilization among potato farmers in Gujarat: Income, Source of Information, Attitude, and Knowledge. These factors play a crucial role in shaping farmers' adoption behaviours, as supported by the empirical findings. Income (p = 0.000, Exp(β) = 96.100, 95% C.I. = 12.464 – 740.920): Income is the most significant determinant at the 1% level, indicating that higher-income farmers are substantially more likely to utilize ICT tools. The odds ratio of 96.10 indicated that farmers belonging to higher income categories have substantially greater odds of ICT adoption compared to those in lower income categories. This large odds ratio reflects the effect of income measured in discrete categories rather than a marginal percentage increase in income, underscoring the role of financial capacity in enabling access to ICT tools such as smartphones, internet services, and digital agricultural advisory platforms. In Gujarat, where commercial potato farming (Patel *et al*., 2025) is capital-intensive, wealthier farmers are better positioned to invest in modern ICT tools for price forecasting, weather updates, and market linkages (Chetri *et al*., 2023). Additionally, prosperous farmers in Banaskantha, a leading potato-producing district (Banaskantha District, 2024), often have stronger ties with contract farming companies (e.g., McCain Foods) (Fernandes, 2013), which facilitate ICT-based agricultural advisory. Source of Information (p = 0.066, Exp(β) = 1.461, 95% C.I. = 0.975 – 2.188): Source of Information At the 10% significance level, the availability and accessibility of reliable information sources positively influence ICT adoption. Farmers with multiple information channels (e.g., Krishi Vigyan

Kendras (KVKs), agricultural universities, private advisory services) are 1.46 times more likely to engage with ICT tools (Pachamuthu, 2024). This aligns with the fact that Gujarat has a strong extension network, including Anand Agricultural University (AAU), Gujarat Agricultural University (GAU), and KVKs, which actively promote ICT-based advisories (Alvi *et al.*, 2021). However, limited awareness and fragmented access to agricultural digital platforms (Hackfort, 2020) (e.g., Kisan Suvidha, IFFCO Kisan App) among smallholder farmers highlight the need for better outreach strategies. Attitude ($p = 0.039$, $Exp(\beta) = 1.203$, 95% C.I. = 1.010 – 1.435): Attitude towards ICT is a significant determinant at the 5% level, with a positive impact on adoption behaviours. Farmers with a progressive mindset and openness to technological innovations are 1.2 times more likely to use ICT tools. This reflects Gujarat's entrepreneurial agricultural landscape, where progressive farmers in districts like Banaskantha and Sabarkantha are early adopters (Mahida & Cariappa, 2022) of digital marketing platforms for contract farming and e-NAM (National Agricultural Market) participation. However, resistance from conventional farmers, particularly older individuals with limited digital literacy, poses a challenge to widespread ICT adoption. Knowledge ($p = 0.001$, $Exp(\beta) = 2.306$, 95% C.I. = 1.415 – 3.757): Knowledge is highly significant at the 1% level, indicating that better-informed farmers are 2.3 times more likely to integrate ICT tools into their agricultural practices. Farmers with higher technical know-how can effectively navigate digital platforms for weather forecasting, market price tracking, pest control advisories, and input procurement. The presence of progressive farmer groups and agribusiness networks in Gujarat has facilitated knowledge dissemination. However, the digital divide, particularly among small and marginal farmers in remote villages, underscores the need for capacity-building programs and ICT literacy training to bridge the gap.

CONCLUSION

This study examined the extent of ICT utilization and its determinants among potato growers in Banaskantha district of Gujarat using a Binary Logistic Regression approach. The findings indicate that farmers predominantly rely on traditional ICT tools such as radio and television, along with mobile phones, while the adoption of advanced digital tools and web-based agricultural information services remains limited. The overall level of ICT utilization was low to moderate, with no respondents falling under the high utilization category, highlighting a persistent digital divide in the study area. The regression results reveal that income, access to information sources, attitude towards ICT, and knowledge significantly influence ICT adoption among potato growers. Farmers belonging to higher income categories exhibited substantially higher odds of ICT adoption, underscoring the importance of financial capacity in accessing digital tools and services. Positive attitudes toward technology and higher levels of ICT-related knowledge further enhanced the likelihood of adoption, while exposure to multiple and reliable information sources supported greater ICT use. The study provided empirical evidence on ICT utilization behaviour among potato growers in Gujarat and demonstrates the relevance of socio-economic and behavioural factors in shaping digital adoption. These findings offer valuable insights for policymakers and extension agencies in designing targeted digital extension strategies focused on improving affordability, strengthening information dissemination mechanisms, and enhancing

farmers' knowledge and attitudes toward ICT. Strengthening such interventions is essential for promoting inclusive digital transformation and improving decision-making in agriculture.

ETHICAL CONSIDERATIONS

Participants in the study took part voluntarily, giving informed consent before any data was collected. We maintained the confidentiality of both personal and financial information. Additionally, farmers were informed that the purpose of this study was to help create policy recommendations aimed at enhancing access to information and communication technologies (ICT) in agriculture.

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STATUS OF MECHANIZATION IN POTATO CULTIVATION

Gurkanwal Singh[1] and Baldev Dogra[1]

ABSTRACT: The mechanization of potato production is important for improving timeliness, labour productivity, resource-use efficiency and economic returns in India. India is the world's second-largest potato producer, with potato production expanding substantially over the past several decades. However, important operations such as planting, intercultural management and harvesting continue to involve considerable labour inputs, while adoption of specialized machinery remains uneven among regions and farm sizes. This review examines the status of mechanization in potato cultivation in India, covering land preparation, planting, intercultural operations, fertilizer and plant protection, harvesting and post-harvest handling. In addition to describing available machinery, the review synthesizes reported field capacity, planting accuracy, tuber damage, labour requirements, cost savings and operational limitations. The review also considers regional disparities, economic access through custom hiring, energy and environmental implications, and emerging precision, machine-vision and robotic technologies. The analysis indicates that mechanization has progressed from operation-specific tractorization toward integrated and precision systems, but fragmented holdings, high initial investment, limited technical skills, maintenance constraints and uneven access to machinery continue to restrict adoption. Greater emphasis on appropriately scaled machinery, custom hiring services and intelligent technologies is required for sustainable and inclusive mechanization of potato production in India.

INTRODUCTION

The potato (*Solanum tuberosum* L.) is an important food and commercial crop and a major component of the Indian horticultural economy. India has experienced a substantial long-term expansion in potato production, rising from roughly 1.3 million tonnes six decades ago to become the world's second-largest producer (Scott & Suárez, 2011). During 1949–1950, potato was cultivated on approximately 0.234 million hectares, producing 1.54 million metric tonnes with an average productivity of 6.58 t ha^{-1} (IndianPotato Research Team, 2026). By 2024–2025, official final estimates indicated production of about 58.57 million metric tonnes from approximately 2.2 million hectares, with average productivity of about 24.55–25 t ha^{-1} (DA&FW, 2024). By comparison, published estimates report 50.2 million tonnes from 2.17 million hectares at 23.10 t ha^{-1} in 2019 (Sood *et al*., 2022), over 51.3 million tonnes from 2.16 million hectares at 23.77 t ha^{-1} in 2019–2020 (Buckseth *et al*., 2022), and 53.58 million tonnes in 2022 (Khanal *et al*., 2023). This expansion has strengthened India's position as the world's second-largest potato producer (Khanal *et al*., 2023; Rana & Anwer, 2018) and demonstrates the increasing importance of efficient production systems.

Despite this increase in production, several potato production operations remain labour intensive, potato is reported to require

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about 600 man-h ha^{-1} for different operations (Mehta *et al*., 2018).

Planting, intercultural operations and harvesting require timely execution, while rising labour costs, labour shortages, fragmented landholdings and climatic uncertainty increase the need for mechanization. Mechanized solutions such as improved planters, tractor-operated harvesters, laser land levellers and precision application equipment can improve operational timeliness, planting uniformity, labour productivity and input-use efficiency (Mehta *et al*., 2018). However, the benefits and adoption of these technologies are not uniform across India because machinery suitability depends strongly on farm size, field geometry, access to capital, custom hiring services and technical support.

The present review therefore goes beyond a simple inventory of machines and examines potato mechanization as a production-chain system. The available technologies are discussed in relation to their field capacity, labour requirement, planting or harvesting performance, crop damage, cost and operational limitations. Regional differences in mechanization, the role of custom hiring, energy and environmental considerations, and emerging precision and intelligent technologies are also considered. The objective is to synthesize the current status of potato mechanization in India, identify the principal constraints to wider adoption, and indicate technology and research priorities for more efficient and sustainable potato production.

Review Methodology

A structured literature search was considered for the review of potato mechanization, covering scientific literature and Indian agricultural research sources. The search framework included databases such as Scopus, Web of Science, ScienceDirect, Google Scholar and Indian agricultural research repositories. The literature search was considered for the period 2000–2026, with combinations of terms including potato mechanization, potato planter, potato harvester, potato digging, custom hiring, mechanization adoption, precision potato production, machine vision and energy-use efficiency. Priority was given to studies reporting quantitative information on field performance, economics, labour requirements, crop damage, adoption constraints or energy and sustainability. This approach was used to complement the machinery descriptions in the original review with comparative and regional analysis.

Status of Potato Production and Mechanization in India

Potato mechanization in India has developed progressively with increasing tractorization and the introduction of specialized planting, harvesting and post-harvest equipment (Mehta *et al*., 2018). However, mechanization should not be considered a binary condition. It occurs along a continuum ranging from manual production to operation-specific mechanization, integrated mechanization, precision mechanization and autonomous or robotic systems. In the Indian context, this progression is strongly influenced by farm size, machinery cost, field geometry, access to custom hiring and the availability of skilled operators and repair services.

Mechanization level	Description	Dominant technologies	Current Indian context
Level 0: Manual	Complete reliance on human and draught-animal power for production operations.	Hand hoes, spades and traditional animal-drawn implements.	Confined mainly to highly marginalized, remote or difficult-to-mechanize areas.
Level 1: Partial mechanization	Tractorization concentrated mainly on high-draft primary and secondary tillage.	MB ploughs and rotavators; planting, weeding and harvesting remain partly manual.	Common where machinery access is limited and farm holdings are fragmented.
Level 2: Operation-specific mechanization	Individual core operations are mechanized without complete integration of the production chain.	Semi-automatic planters, digger elevators and boom sprayers.	Important stage for progressive small and medium farms.
Level 3: Integrated mechanization	Several operations from land preparation through harvesting and post-harvest handling are mechanically linked.	Automatic paired-row planters, harvesters and mechanized graders.	More feasible on relatively consolidated farms and through organized machinery access.
Level 4: Precision mechanization	Spatial information is integrated with machinery operation and input management.	GNSS guidance, variable-rate application and real-time machine monitoring.	Predominantly at research, institutional and advanced commercial stages.
Level 5: Autonomous/ robotic	Intelligent machines perform field operations with minimal direct operator intervention.	Autonomous tractors, machine-vision weeders and robotic harvesters.	Primarily prototype and research stage in India.

RESULTS AND DISCUSSION

Land Preparation

Efficient seedbed preparation is essential for ensuring optimal growth conditions for potatoes. The following equipment is commonly used in India:

Sub-soiler

Subsoil compaction is a significant agronomic challenge that adversely affects crop production (Shaheb *et al.*, 2021), particularly in mechanized farming systems that rely heavily on large machinery such as subsoiler (Fig. 1.) (Mileusnić *et al.*, 2022). In potato cultivation, compacted layers and tillage pans can restrict root and stolon development and affect tuber formation (Stalham *et al.*, 2007). Subsoiling is therefore used where compacted layers require mechanical loosening and deeper soil access is needed. Its suitability should, however, be considered in relation to soil condition, working depth, draft requirement and the



Fig. 1. Subsoiler

subsequent seedbed preparation operation (Abisuwa *et al*., 2023; Ghosh & Daigh, 2020).

Rotavator/Rotary Tiller

The rotavator (Fig. 2.) is recognized for its numerous advantages, including the generation of negative draft, which makes it an ideal attachment for power tillers (Tupkari *et al*., 2021). Tractor-operated rotary tillers, or rotavators, play a crucial role in the mechanization of potato cultivation by efficiently preparing seedbeds in both, while also incorporating straw and green manuring. These implements consist of a steel frame, a rotary shaft with L-type blades made from hardened medium carbon or alloy steel (Mahapatra *et al*., 2020), and a power transmission system driven by the tractor's PTO. The rotavator's design allows for uniform soil pulverization, enhancing seedbed quality. Reported capacities are around 0.25 ha per hour, with rotavator operation typically reported as cheaper than multi-pass conventional tillage in AICRP trials (2017); the exact saving per hectare varies by soil, region and depth, so the figure should be treated as an indicative range rather than a fixed rupee value.



Fig. 2. Rotavator/rotary tiller

Tractor-Operated Laser Land Leveller

Laser land levelling is a transformative precision agricultural technology that significantly enhances soil preparation for potato cultivation. This method utilizes laser-guided equipment (Fig. 3.) to achieve a highly accurate levelling of the soil surface, with a precision of ±2 cm (Sahu *et al*., 2023), which is crucial for establishing optimal field conditions. By ensuring a uniform slope and contour, laser land levelling facilitates efficient irrigation and drainage, leading to improved water management and reduced runoff (Jat *et al*., 2006). Beyond potato specifically, documented gains from laser-levelled fields include visible water savings and yield improvements when irrigation and *rabi*-season crops are combined with proper levelling (Ahmad & Sharma, 2023). Published field studies in rice–wheat systems of western



Fig. 3. Laser land leveller

Uttar Pradesh report irrigation-water savings around 20–35% and yield gains of 10–20% with laser levelling; the magnitude of these gains in potato systems depends strongly on preceding irrigation practice and soil texture, so application to potato should be drawn from this body of work as a directional indication. The precise levelling achieved through this method not only enhances the effectiveness of irrigation systems but also minimizes soil compaction, thereby promoting healthier root development and maximizing yield potential (Ahmad *et al*., 2024). As potato production increasingly relies on mechanization, the adoption of laser land levelling stands out as a key practice that contributes to sustainable agricultural practices and improved economic returns for farmers.

Reversible Mould Board Plough

The mouldboard plough (MB plough) as shown in Fig. 4. is a traditional but important implement for primary tillage in potato cultivation. It turns and inverts the soil, assists in breaking compacted layers, buries crop residues and incorporates organic matter (Piccoli *et al*., 2022; Gatkal *et al*., 2024). Reversible mouldboard ploughs are particularly relevant where repeated passes and directional field movement need to be minimized. However, their use should be balanced against draft requirement, fuel consumption and the possibility of repeated intensive tillage contributing to soil degradation. Recent research on improved tillage systems therefore emphasizes matching plough geometry, working depth and operating conditions with soil properties and the requirements of the potato seedbed. Properly selected primary tillage followed by appropriate secondary tillage can provide a suitable soil structure for tuber development and reduce unnecessary field passes.

Potato Planting

Mechanized potato planting significantly reduces labour requirements and improves planting precision (Zhou *et al*., 2022). Various planting machines include:

Semi-Automatic Planters

Belt Cup Type

Belt Type planter (Fig. 5.) plants potatoes to the desire depth and plant spacing. Ridges of the desired size and shape are automatically are formed over the potatoes. These have provision of fertilizer application. The functioning of most potato planters is based on transport and placement of the



Fig. 4. Reversible mould board plough



Fig. 5. Belt-cup type semi-automatic potato planter

seed potatoes by a cup-belt. The capacity of this process is rather low and planting accuracy has to stay at acceptable levels. The main limitations are set by the speed of the cup-belt, the number and positioning of the cups. Inherent structural limitations within the cup-belt metering mechanism have been identified as the main source of inaccurate planting distances (Buitenwerf *et al*., 2006).

Revolving Magazine Type

A revolving magazine-type potato planter (Fig. 6.) is a specialized agricultural implement designed to enhance the efficiency and precision of potato planting. This planter features a rotating drum or magazine equipped with compartments that systematically release seed potatoes into the soil. The design ensures uniform spacing and depth, which are crucial for optimal crop growth.

In their comprehensive review, Zhou *et al*. (2022) discuss various potato planting technologies, highlighting the significance of seed metering devices in achieving precise planting. They categorize these devices into types such as cup, spoon, belt, and pneumatic, each with unique mechanisms to handle seed potatoes. The revolving magazine-type planter aligns with these designs, aiming to improve planting accuracy and efficiency.

The precision offered by such planters not only enhances planting efficiency but also contributes to increased crop yields by ensuring consistent seed placement. As agricultural technology advances, the development and refinement of these planting mechanisms continue to play a pivotal role in modernizing potato cultivation practices.

Automatic Potato Planters

Picker Wheel Type

Picker wheel type automatic potato planter (Fig. 7) consisted of a hopper, two picker wheels for picking the tubers,seed tubes, furrow openers, three bottom ridger to form two ridges, a fertilizer metering system, and a frame. The hopper for potatoes is made of MS sheet. It is rectangular in shape at the top with sides sloping towards bottom. At the bottom of the hopper, there are agitators to improve the delivery of potato tubers to feeder. The rear wall of the hopper has window and a gate for feed regulation. The agitators and the screw conveyors ensure



Fig. 6. Revolving magazine-type semi-automatic potato planter



Fig. 7. Picker-wheel type automatic potato planter

proper feed of the tubers to the picker unit. The picker units of the planter are set in motion from ground wheel of 52 cm diameter (adjustable). The spacing between adjacent plants can be varied by suitably modifying the gear ratio. The planter has fertilizer distributors for the application of fertilizer during planting (Verma *et al.*, 2015)

Vertical Belt Paired-Row Automatic Potato Planter

The vertical belt paired row automatic potato planter (Fig. 8.) is a tractor operated planter having dimensions (LxHxW) of 1820 mm, 1700 mm and 1860 mm, respectively. It consists of two vertical rubber belts fitted with metal cups in paired rows for picking potato tubers. Arrangement of cups on the belt is in zig-zag manner. Number of cups per belt is 40. The machine is having two shovel type furrow openers. Planter is equipped with multi-speed gears to adjust the seed spacing using chain and sprocket. There is provision to adjust the row spacing from 609-711 mm, whereas, plant to plant spacing varies between 220-280 mm. Power to the metering mechanism is provided through ground wheel having diameter of 640 mm and power transmission gear ratio is 9:2. The planter also has provision to spread fertilizer on both the sides. Three persons are required to operate the machine (Verma *et al.*, 2015).



Fig. 8. Vertical-belt paired-row automatic potato planter

Performance evaluation of a tractor operated vertical belt paired row automatic potato planter was conducted by (Verma *et al.*, 2015) and it was compared with picker wheel type automatic potato planter as control. Field capacity of the paired row planter was 0.24 ha h−1 at an average forward speed of 2.5 km/h. Top width, slant height and bottom width of the bed formed were found to be 30 cm, 20 cm and 40 cm, respectively. Average depth of planting from ridge top was 21.2 cm for vertical belt paired row automatic potato planter, whereas, it was 20.8 cm in case of picker wheel type automatic potato planter. Missing, doubling and seed damage for paired row planter was 3.3, 1.5 and 1.5 % respectively, whereas, in case of picker wheel type automatic planter it was 5.0, 18 and 10.0 %, respectively. Tuber to tuber placement for both the machines was 20 cm. Germination count for paired row planter was 4.25 per meter length, whereas, in case of picker wheel type automatic potato planter it was 7.3 per meter length. This may be due to more doubling in case of picker wheel type automatic potato planter. The field capacity of both the machines was 0.24 - 0.25 ha h^{-1}

Sugarcane-Cum-Potato Planter for Mechanisation of Simultaneous Planting of Sugarcane and Potato

Sugarcane and potato are the two major cash crops cultivated in the Indo-Gangetic plains of South Asia. Growing potato as intercrop with sugarcane has a synergistic effect on sugarcane, resulting in increased economic returns to farmers. In order to mechanise simultaneous planting of sugarcane and potato for intercropping, a new planting machinery named as sugarcane-cum-potato planter (Fig. 9.) was designed and developed



Fig. 9. ICAR-IISR sugarcane-cum-potato planter

at ICAR-Indian Institute of Sugarcane Research, Lucknow, India. It was equipped with furrowers for opening of furrow and ridge making in between furrows, sett cutting unit for cane planting, potato seed tuber metering mechanism for potato planting, covering unit to cover planted sugarcane setts and potato and insecticide application unit. The designed equipment planted two rows of sugarcane in furrows and two rows of potato on ridges simultaneously in single pass. Picking and dropping of seed potato were automatic, whereas sugarcane seed stalk feeding for sett cutting was manual. Field testing of the developed planter was conducted at IISR farm in sandy loam soil. The effective field capacity of planter was 0.127 ha h^{-1}. Average soil cover on sugarcane setts was 45 mm. Average depth of seed potato tuber placement on the ridges was 40 mm, and average tuber to tuber spacing was 192 mm. Developed machine-planted sugarcane at furrow spacing of 750 mm with average overlapping of 68 mm between the setts. The cost of planting operation with developed equipment was rupees 3160 ha^{-1} as against rupees 13,600 ha^{-1} in conventional planting. Saving in cost of planting operation was about 76% and labour about 90% with the developed planter as compared to conventional planting. Irrigation water use efficiency, yield attributes and total yield increased significantly in potato–sugarcane intercropping as compared to relay cropping of potato and sugarcane. Benefit/cost ratio in mechanised intercropping of potato and sugarcane with the developed planter was 2.57:1 followed by conventional manual intercropping (2.26:1) and manual potato–sugarcane relay cropping (1.84:1). (Gupta *et al*., 2017)

Intercultural Operations and Weed Management

Effective intercultural operations enhance crop growth and reduce manual labour.

Self-Propelled Power Weeder

Inter-row weed control in potato requires machinery that can operate between ridges without damaging developing plants or disturbing the ridge excessively. Self-propelled power weeders can provide mechanical weed control while reducing dependence on manual hoeing and, where appropriate, herbicide use. Adjustable working width and suitable operating depth are important because the safe operating zone changes with crop stage and row spacing. Studies on power weeders and precision weed-management technologies indicate that improved control can be achieved by matching machine configuration and operational parameters with crop geometry (Tewari *et al*., 2014; Vijayakumar *et al*., 2023; Lahre & Satpathy, 2024).

Spring Tyne Cultivator

The spring tyne cultivator (Fig. 10) is an essential tool in potato cultivation, particularly during the intercultural operations phase, where it plays a vital role in soil preparation, weed control, and soil aeration (Anonymous(b) 2020). This implement



Fig. 10. Spring Tyne Cultivator

features flexible tines that can penetrate the soil without causing excessive disturbance, making it ideal for use in potato fields where maintaining soil structure is crucial for root development. The spring action of the tines allows them to adapt to varying soil conditions, effectively breaking up compacted layers while minimizing damage to the potato tubers below the surface.

By using a spring tyne cultivator, farmers can efficiently manage weeds that compete with potato plants for resources, thereby reducing the reliance on chemical herbicides and promoting environmentally friendly practices (Bàrberi, 2024). Additionally, the cultivator helps improve soil aeration and moisture retention, which are critical for healthy potato growth. Its ability to operate in different soil types and conditions makes it a versatile tool for farmers, enhancing productivity and ensuring a more uniform crop. Overall, the spring tyne cultivator is a valuable asset in modern potato farming, contributing to higher yields and sustainable agricultural practices.

Fertilizer Application and Plant Protection

Mechanized equipment ensures uniform application of fertilizers and chemicals, reducing wastage and improving efficiency.

Tractor-Operated Fertilizer Broadcaster

The tractor-operated fertilizer broadcaster (Fig. 11.) is a vital piece of equipment in potato cultivation, designed to enhance the efficiency and effectiveness of fertilizer application. This implement allows for the precise and uniform distribution of fertilizers across potato fields, ensuring that crops receive the necessary nutrients for optimal growth and yield. By utilizing a tractor for operation, the broadcaster can cover large areas quickly, significantly reducing the time and labour required compared to manual application methods (Manda *et al*., 2018).

The integration of a tractor-operated fertilizer broadcaster in potato farming not only enhances productivity but also supports the overall health of the soil and crop. By ensuring that potatoes receive the right nutrients at the right time, farmers can achieve higher yields and better-quality produce, ultimately leading to improved economic returns and sustainable agricultural practices(Mia *et al*., 2024).



Fig. 11. Tractor-operated fertilizer broadcaster

Tractor-Operated Boom Sprayer

The tractor-operated boom sprayer (Fig. 12.) is an essential tool in modern potato cultivation, designed to enhance the efficiency and effectiveness of pesticide and fertilizer application. This implement features a long boom equipped with multiple nozzles that can cover a wide swath of the field in a single pass (Sanchavat *et al*. 2020), ensuring uniform distribution of chemicals over the potato crop. By utilizing a tractor for operation, farmers can achieve high-speed application, significantly reducing the time and labour involved compared to manual spraying methods (Ahmad *et al*. 2021).

One of the key advantages of the tractor-operated boom sprayer is its ability to adjust the spray height and pressure (Kumar 2023), allowing for precise targeting of the crop while minimizing drift and ensuring that the chemicals reach the intended areas. This precision is particularly important in potato farming, where the risk of diseases and pests can significantly impact yield and quality (Ahmad and Sharma 2023). The sprayer can be calibrated to apply various types of solutions, including herbicides, fungicides, and insecticides, making it a versatile tool for integrated pest management (Ozkan and Smith 2018).

Moreover, the use of a boom sprayer contributes to sustainable agricultural practices by promoting efficient use of inputs and reducing the environmental impact of chemical applications (Yamamoto *et al*. 2023). By ensuring that the right amount of product is applied at the right time, farmers can enhance crop health and yield while minimizing waste and potential harm to beneficial organisms. Overall, the tractor-operated boom sprayer is a valuable asset in potato farming, enabling farmers to maintain healthy crops and achieve optimal production outcomes (Kumar *et al*. 2021).

Harvesting

Mechanized harvesting reduces time and minimizes damage to potato tubers.

Potato Digger Elevator

The potato digger elevator (Fig. 13.) is a specialized agricultural implement designed to enhance the efficiency and effectiveness of potato harvesting (Kumar & Tripathi, 2017). This machine plays a crucial role in the mechanization of potato production, allowing farmers to efficiently extract tubers from the soil while minimizing damage to the crop. The potato digger operates by using a series of digging blades or shares that



Fig. 12. Tractor-operated boom sprayer



Fig. 13. A view of Potato Digger Elevator

penetrate the soil, loosening the potatoes and bringing them to the surface (Tikuneh, 2022). Comparative Indian field trials consistently show that tractor-mounted digger-elevators reduce total man-hours per hectare by a large margin over manual harvesting, with reported digging efficiencies typically in the 90–98% range and total tuber damage usually held below 5% under optimized settings (Kumar & Tripathi, 2017; Tikuneh, 2022).

One of the key advantages of the potato digger elevator is its ability to minimize tuber bruising and damage during the harvesting process, which is critical for maintaining the quality of the potatoes. By ensuring that the potatoes are handled gently and efficiently, farmers can improve their marketability and reduce post-harvest losses. Additionally, the machine can be adjusted to accommodate different soil types and conditions, making it versatile for various farming environments.

Overall, the potato digger elevator is an invaluable tool in modern potato farming, contributing to higher productivity, improved crop quality, and more sustainable agricultural practices by streamlining the harvesting process and reducing labour costs (Kaur *et al*. 2023).

Potato Harvester

The potato harvester (Fig. 14.) is a vital piece of machinery in modern agriculture, specifically designed to streamline the harvesting process of potatoes while maximizing efficiency and minimizing crop damage. This implement is engineered to dig, lift, and separate potatoes from the soil in a single operation, significantly reducing the time and labour required compared to traditional manual harvesting methods. A potato harvester consists of a series of digging blades or shares that penetrate the soil to loosen the tubers. Once the potatoes are unearthed, they are conveyed onto a series of belts or chains that gently transport them to a collection area (Gulati and Singh 2021). The integration of potato harvesters into farming operations not only boosts productivity but also supports sustainable agricultural practices by reducing labour costs and improving the overall efficiency of the harvesting process (Sahara *et al*. 2024).



Fig. 14. Potato harvester

Potato Combine

The potato combine is an advanced agricultural machine that integrates multiple harvesting functions into a single operation, significantly enhancing the efficiency of potato harvesting (Wang *et al*., 2024). Unlike traditional harvesters that may require separate machines for digging, lifting, and cleaning, the potato combine performs all these tasks simultaneously, streamlining the harvesting process and reducing the time and labour involved. One of the standout features of modern potato combines is their integrated storage capacity for harvested potatoes. This storage compartment allows for temporary holding of the tubers directly within the machine, enabling continuous operation without the need for frequent unloading. This feature is particularly beneficial for large-scale operations, as it reduces downtime and allows farmers to cover more ground in a shorter period (Wang *et al*., 2024). Exact field-capacity and damage values for Indian conditions are not yet well

established across soil types and varieties, so they should be drawn from local prototype-trial reports rather than from cross-condition extrapolations.

The adoption of potato combines with storage capabilities not only boosts productivity but also supports sustainable agricultural practices by reducing labour costs and improving the overall efficiency of the harvesting process. By enabling farmers to harvest their crops more quickly and effectively, potato combines play a crucial role in enhancing yield, reducing post-harvest losses, and ultimately increasing profitability in potato production.

Post-Harvest Technology

Mechanization in processing and storage is critical for value addition and reducing post-harvest losses.

Grading and Sizing Machines

Potato graders (Fig. 15.) are specialized machines designed to sort and classify harvested potatoes based on size, shape, and quality. These machines play a crucial role in the post-harvest processing of potatoes, ensuring that only the best quality tubers are prepared for market or storage. By automating the grading process, potato graders significantly enhance efficiency and accuracy compared to manual sorting methods (Widodo *et al*. 2013).



Fig. 15. Potato grader

Typically, a potato grader consists of a series of conveyor belts, screens, and sorting mechanisms that work together to separate potatoes into different categories. The grading process often begins with the potatoes being fed onto a conveyor belt, where they are subjected to various sorting criteria. The machine may use a combination of mechanical and optical sensors to assess the size and quality of each tuber. For instance, adjustable screens can allow smaller potatoes to fall through while larger ones continue along the conveyor for further inspection (Ghanbarian *et al*. 2009).

In summary, potato graders are essential tools in the post-harvest handling of potatoes, contributing to improved product quality, increased efficiency, and reduced labour costs. By ensuring that only the best potatoes make it to market, these machines play a vital role in the overall success of potato production and distribution.

Comparative Performance of Potato Machinery

A major limitation of a purely descriptive machinery review is that it does not show which technologies provide the greatest practical advantage. The available studies in the manuscript provide useful quantitative indicators such as field capacity, planting accuracy, tuber damage, labour requirement and operating cost. These parameters are summarized below to facilitate comparison. The values represent reported or synthesized performance values already available in the reviewed material and should be interpreted in relation to machine configuration and field conditions.

Operation	Machine/ technology	Power source	Field capacity (ha h^{-1})	Labour requirement	Accuracy/ damage	Labour saving (%)	Cost saving (%)	Source
Land preparation	Rotavator	60-hp tractor	0.25	1 operator	High pulverization	~60	25–30	(AICRP on FIM, 2017)
Planting	Picker-wheel planter	45-hp tractor	0.24–0.25	2 operators	10.0% seed damage; 5.0% missing	~85	~65	(Verma *et al.*, 2015)
Planting	Vertical-belt paired-row planter	45-hp tractor	0.24	3 operators	1.5% seed damage; 3.3% missing	~80	~60	(Verma *et al.*, 2015)
Planting	Sugarcane-cum-potato planter	60-hp tractor	0.127	2 operators	40 mm depth; 192 mm spacing	90	76	(Gupta *et al.*, 2017)
Harvesting	Digger elevator	45-hp tractor	0.15–0.25	1 operator + manual collectors	97.9% digging efficiency; 4.19% total damage	50–65	45–54	(Kumar & Tripathi, 2017; Tikuneh, 2022)
Harvesting	Combine harvester	>75-hp tractor	0.30–0.45	1–2 operators	<3% total damage under optimized conditions	>90	>60	(Wang *et al.*, 2024)

The comparison indicates that planting and harvesting are particularly important mechanization bottlenecks. The vertical-belt paired-row planter offers substantially lower seed damage than the picker-wheel system in the reported evaluation, while the digger elevator can achieve high digging efficiency but still requires manual collection. Combine harvesters provide the highest level of integration but require high investment, adequate tractor power and sufficiently large, contiguous fields. Thus, the technically highest-capacity machine is not necessarily the most appropriate machine for every Indian farm.

Economic Feasibility and Machinery Access

The economic feasibility of potato mechanization depends not only on machine performance but also on annual utilization. Specialized machines such as automatic planters and combine harvesters have high fixed costs, including depreciation and interest, and may remain underutilized outside the short potato production window. This makes individual ownership difficult for smallholders. Custom Hiring Centres, Farmer Producer Organizations and cooperative ownership can improve machinery access by spreading fixed costs over a larger number of users. Published Indian field comparisons

consistently show that the manual harvesting cost of potato exceeds the mechanical digger cost by roughly half to two-thirds in a single-pass digger-elevator operation, with overall cost reductions in the range commonly reported by Indian digger trials versus manual hoe harvesting (Kumar & Tripathi, 2017; Tikuneh, 2022); the exact rupee per hectare depends on region, season, machine type, custom-hire rate, field capacity and the short harvesting window, so these economic figures should always be interpreted with locality-specific adjustment.

Energy, Environmental and Sustainability Implications

Mechanization changes the energy profile of potato production. Reported energy-use assessments on a per-hectare basis for potato indicate substantial variation between traditional and highly mechanized commercial systems; in traditional systems, total energy input is dominated by seed material and fertilizer, while irrigation, mechanized seedbed preparation, plant protection and harvesting are the major direct fossil-fuel components. Sustainable mechanization should focus on reducing unnecessary field passes, avoiding excessive soil compaction, improving irrigation efficiency and progressively introducing low-draft and electrically powered technologies where technically feasible. Potato-system energy shares for seed material, fertilizer, irrigation and mechanization should be drawn from source-specific assessments (Lohan *et al.*, 2023) rather than from generalized national averages, because the underlying values vary markedly with soil type, water source, machine choice and input intensity.

Emerging Technologies: Precision Agriculture, AI and Robotics

The next stage of potato mechanization is likely to involve the integration of positioning, sensing, machine vision and automation. GNSS-based guidance can improve row-following and reduce overlap during field operations. Machine-vision grading can identify size and visible defects, while variable-rate application can use spatial information to reduce unnecessary input application. AI-based weed detection offers a pathway toward selective intra-row weed control, whereas robotic harvesting remains a more difficult challenge because tubers are concealed below the soil and harvesting involves simultaneous soil separation and crop handling. For Indian conditions, low-cost retrofitting of existing tractors and implements with sensors and guidance systems may provide a more realistic transition toward intelligent mechanization than immediate replacement by fully autonomous machines.

Technology	Current development stage	Major benefit	Limitation in Indian conditions	Future research need
GNSS autosteer	High	Improved row spacing and reduced overlap	RTK and system cost for small farms	Low-cost localized RTK and retrofit systems
Machine-vision grading	High	Automated identification of size and visible defects	Capital cost and electricity requirement	Low-cost edge-computing optical graders

Technology	Current development stage	Major benefit	Limitation in Indian conditions	Future research need
Variable-rate application	Medium	Spatially targeted fertilizer and chemical application	Limited high-resolution spatial data	Sensor fusion and field-scale mapping
AI weed detection	Medium	Selective intra-row weed management	Variable field illumination and weed morphology	Robust models for Indian crops and weeds
Robotic harvesting	Low	Large labour reduction and controlled handling	Subsoil tuber detection and complex field conditions	Integrated sensing, digging and soft handling systems

Current Challenges in Potato Mechanization

Potato mechanization has considerable potential to improve timeliness, labour productivity and operational efficiency, but adoption is constrained by interacting technical, economic and institutional factors.

High Initial Investment Costs: Specialized planters, harvesters, graders and precision equipment require substantial capital. The cost is particularly restrictive when a machine is used for only a short seasonal period.

Fragmented Landholdings and Field Geometry: Large tractor-operated equipment is difficult to operate economically in small and irregular plots. Machinery therefore needs to be scaled to local farm sizes and field conditions.

Limited Technical Knowledge and Skilled Operators: Increasingly sophisticated machines require correct adjustment, calibration and maintenance. Lack of trained operators can reduce field performance and increase downtime.

Maintenance, Spare Parts and Repair Infrastructure: Limited access to specialized spare parts and trained technicians can become critical during short planting and harvesting windows.

Seed and Crop Variability: Seed-tuber size and shape influence the performance of metering systems. More consistent seed grading and adaptive metering technologies can improve planting accuracy.

Limited Machinery Access and Utilization: Low annual utilization makes individual ownership uneconomic for many specialized machines. Custom Hiring Centres, cooperatives and Farmer Producer Organizations can improve access and utilization.

Regional Disparities: Mechanization is not uniform across states. Higher-capacity systems are more feasible in consolidated production regions, while eastern and highly fragmented areas require compact, affordable machinery.

FUTURE PROSPECTS

Future mechanization should emphasize machines that are technically effective but also economically compatible with Indian farm sizes. Small-sized planters, diggers and harvesters are particularly important for fragmented holdings.

Custom Hiring Centres should be expanded and strengthened so that farmers can access specialized potato machinery without bearing the full fixed cost of ownership. Cooperative and Farmer Producer Organization models can improve annual machine utilization.

Precision guidance, machine monitoring, variable-rate application and machine vision should be developed as intermediate technologies that can be retrofitted to existing tractors and implements.

Research on low-cost pneumatic or adaptive metering systems can improve planting performance across variable seed-tuber sizes and reduce seed damage.

Intelligent harvesting systems should focus on controlling conveyor speed, soil separation and tuber handling to reduce bruising while minimizing manual collection.

Post-harvest machine vision and optical grading can improve quality-based sorting beyond simple size classification and can support decentralized processing and packing.

Electrification of low-draft implements and improved energy management can contribute to lower emissions and operating costs, particularly where suitable charging infrastructure is available.

Development of autonomous and robotic potato machinery should continue at the research level, with emphasis on robust sensing, field safety, soil-tuber detection and operation in heterogeneous Indian field conditions.

CONCLUSION

Potato mechanization in India is progressing from conventional tractorization toward operation-specific, integrated and precision systems, but the level of adoption remains highly variable among operations and regions. The most important mechanization opportunities occur in planting and harvesting, where appropriate machinery can substantially reduce labour requirements and improve timeliness. The vertical-belt paired-row planter, sugarcane-cum-potato planter and digger-elevator technologies demonstrate the practical benefits of mechanization, while high-capacity combines and intelligent systems remain more appropriate for larger and better-organized production systems. Wider adoption will require machinery matched to farm size, improved custom-hiring access, skilled operators, maintenance support and technologies that reduce crop damage and operating costs. Future research should therefore emphasize compact machinery for fragmented farms, precision guidance, machine vision, intelligent input application, improved harvesting systems and sustainable energy use. Mechanization should ultimately be evaluated not only by machine capacity but by its technical, economic and environmental suitability for Indian potato production systems.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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ROGUING IN SEED POTATO PRODUCTION IN INDIA: PRINCIPLES, PRACTICES AND PROSPECTS

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ABSTRACT: Roguing, the systematic removal of diseased, off-type, and volunteer plants, is a critical component of the Seed Plot Technique (SPT) for maintaining the health and genetic purity of seed potato. Potato is vegetatively propagated, pathogens particularly viruses accumulate rapidly over generations, resulting in seed degeneration and substantial yield losses. Effective roguing reduces primary inoculum sources, restricts secondary virus spread, delays degeneration, and ensures compliance with seed certification standard. Although roguing is labor-intensive and requires skilled personnel, it remains one of the most economical and reliable practices for sustaining seed health under Indian conditions. This review synthesizes principles, timing, operational steps, influencing factors, and precautionary measures associated with roguing in seed potato production. Emphasis is placed on its role within the Indian Seed Plot Technique, challenges arising from changing climate and vector dynamics, and the need for integration with modern diagnostic and digital tools. Strengthening roguing practices through training, supervision, and technology-assisted monitoring will be essential for sustaining seed potato productivity and profitability in India.

KEYWORDS: Seed Potato; Seed Plot Technique; Roguing; Seed Health; Seed Degeneration; Productivity

INTRODUCTION

Potato (*Solanum tuberosum* L.) is the third most important food crop globally after wheat and rice, serving as a crucial source of calories and income for millions of farmers across the world. Its remarkable productivity per unit area and time has made it an indispensable component of food and nutritional security, particularly in developing countries (FAO, 2021). However, unlike most cereals, potato is vegetatively propagated through tubers, which facilitates the perpetuation and accumulation of viruses, viroids, bacteria, fungi and nematodes associated with seed tubers across successive generations. Among these, viruses are particularly important because systemic viral infections are readily carried over through infected seed tubers and subsequently spread within crops by insect vectors. This progressive build-up of diseases, especially viral infections, results in seed degeneration, ultimately leading to substantial yield and quality losses (Forbes, 2020a; Lacomme *et al*., 2017). In many developing potato-producing regions of South and Southeast Asia and sub-Saharan Africa, farmers rely substantially on farm-saved, locally exchanged or informally sourced seed, which may vary considerably in physiological and phytosanitary quality. Use of unhealthy seed tubers can result in poor crop establishment, increased disease incidence and substantial yield losses (Buckseth *et al.,* 2024). Because seed is one of the largest inputs in potato cultivation,

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maintaining healthy planting material is important for both crop productivity and farm profitability (Sadawarti *et al*., 2023). The use of disease-free seed alone can improve productivity by 15-20% under field conditions (Naik and Buckseth, 2018). The degeneration of potato tubers is mainly due to viruses transmitted through seed tubers and insect vectors majorly aphids and white fly. The continuous presence of vectors throughout the growing season, coupled with the emergence of new pathogens like Potato yellow vein virus and Tobacco streak virus, has made disease management increasingly difficult (Lacomme *et al.,* 2017; Singh and Sharma, 2018). In India, this challenge was addressed through the development of the Seed Plot Technique (SPT) by the ICAR-Central Potato Research Institute (ICAR-CPRI), Shimla, in 1965. The SPT exploits the low-aphid period (October-January) in the Indo-Gangetic plains, incorporating timely dehaulming, chemical vector control, and roguing to minimize disease spread (Sikka *et al*., 1978; Sharma *et al.,* 2021). Within the Seed Plot Technique, timely removal of diseased, off-type and volunteer plants from the standing crop is one of the most important and cost-effective roguing practices for maintaining seed health and varietal purity. When executed properly and at the right crop stages, roguing substantially reduces the primary inoculum and restricts the secondary spread of viruses within and between seed generations. It complements chemical vector control and other cultural measures, forming an integral component of the integrated seed health management strategy in potato. However, its success depends heavily on the skill and vigilance of the roguing personnel and the distinct expression of disease symptoms, which can be obscured by mild or latent infections, environmental conditions, and mixed virus complexes (Singh and Sharma, 2018).

In recent years, the efficiency of roguing has been challenged by changing climatic conditions, extended vector activity, overlapping crop cycles, and the emergence of symptomless carriers. These developments have renewed interest in strengthening visual diagnosis with modern diagnostic tools, training programs, and digital phenotyping techniques to enhance accuracy and timeliness. Understanding the biological, operational, and environmental factors influencing roguing efficacy is thus essential for sustaining the health and productivity of India's seed potato system.

ROGUING

Roguing is a vital field operation in seed potato production systems, designed to maintain both genetic purity and phytosanitary quality of the crop. It involves the systematic inspection and removal of diseased, off-type, or volunteer plants from seed potato fields to prevent pathogen spread and ensure that only healthy plants contribute to the next generation of seed tubers (Sadawarti *et al.,* 2023; Forbes, 2020). Since potato (*Solanum tuberosum* L.) is vegetatively propagated, it is particularly prone to the accumulation of pathogens especially viruses over successive generations, resulting in seed degeneration (Lacomme *et al.,* 2017). Roguing interrupts this cycle by eliminating visible sources of infection before viruses can be transmitted to healthy plants.

In most potato-growing regions, particularly in developing countries, farmers depend on farm-saved or informally exchanged seed due to high costs or limited availability of certified seed (NAAS, 2021; Venkataslam *et al.,* 2017). Even when healthy seed is planted, crops remain vulnerable to infection by viruliferous insect vectors such as aphids (*Myzus persicae*), whiteflies (*Bemisia tabaci*), and leafhoppers, which transmit

viruses including Potato virus Y (PVY), Potato leafroll virus (PLRV), and Potato virus X (PVX) during the growing season (Singh and Sharma, 2018). These infections persist in tubers and can cause severe degeneration and yield losses in subsequent generations if infected plants are not promptly removed (Forbes, 2020a). Roguing operations are carried out at multiple crop stages before flowering, during full canopy development, and prior to haulm destruction to eliminate infected or off-type plants before they contaminate the seed lot. Removed plants are destroyed or buried deeply to prevent further infection (Sadawarti *et al.,* 2023).

The success of roguing depends on accurate visual identification of diseased or abnormal plants. Virus-infected plants may show symptoms on different parts of the plant. On leaves, symptoms commonly include mosaic, mottling, chlorotic patches, vein clearing, curling, crinkling and deformation. At the whole-plant level, infected plants may exhibit stunting, reduced vigour, shortened internodes, abnormal architecture and premature senescence. Depending on the virus and cultivar, symptoms may be mild, severe or completely absent (Singh and Sharma, 2018). Symptoms should, however, be interpreted carefully because nutrient deficiencies, herbicide injury, insect damage, drought, frost and other abiotic stresses may produce symptoms resembling viral infection (Fig. 1). However, mild or latent infections, such as those caused by Potato virus S (PVS) or mixed virus complexes, may exhibit subtle or no visible symptoms, complicating visual diagnosis (Lacomme *et al.,* 2017). Therefore, roguing should be conducted when the crop is healthy, weed-free, and actively growing so that symptoms are clearly expressed (Singh *et al.,* 2019).

For effective disease management, roguing should begin early and be repeated at



Fig. 1. Symptomatic potato plants exhibiting different types of foliar abnormalities; (a) herbicide injury characterized by chlorotic streaks and leaf distortion; (b) nutrient deficiency symptoms showing generalized chlorosis; (c) mild mosaic with light green mottling; (d) leaf curling with distortion and reduced leaf expansion; (e) mottling with irregular chlorotic patches; and (f) severe mosaic showing pronounced chlorosis, leaf crinkling, and deformation.

appropriate crop stages, with particular emphasis on completing critical seed-health operations before aphid populations reach damaging levels. Under the Indian Seed Plot Technique, a population of approximately 20 aphids per 100 compound leaves has traditionally been used as a critical level for initiating haulm termination, although vector pressure should be monitored locally because aphid abundance varies with region and season (Sikka *et al.,* 1978). Certain modern diagnostic tools, such as enzyme-linked immunosorbent assay (ELISA), immunostrip-based assays and polymerase chain reaction (PCR), can be used for the detection of virus infections in symptomless or doubtful plants. These tools can complement the traditional roguing system by supporting confirmation of suspected infections and improving the accuracy of seed-health assessment (Forbes, 2020; Singh and Sharma, 2018). Integration of these diagnostic tools with systematic rouging enhances the production of virus-

free, genetically pure seed stocks and sustains long-term productivity of potato seed systems (Naik and Buckseth, 2018).

Importance of Roguing in Healthy Seed Potato Production

The health status of seed potato plants is the cornerstone of a sustainable and productive potato seed system. Since potatoes are propagated vegetatively through tubers, systemic infections particularly those caused by viruses can be perpetuated from one generation to the next (Hooker, 1980; Salazar, 1996). Once infected seed tubers are planted, the resulting plants become primary sources of inoculum, initiating a disease cycle that accelerates the process of seed degeneration (Thomas-Sharma *et al.,* 2016). Degeneration is characterized by a progressive decline in yield and quality due to the accumulation of pathogens over successive generations (Singh *et al*., 2020). Without proper control, viral and other systemic diseases can spread rapidly within a few seasons through insect vectors, mechanical contact, or volunteer plants, leading to significant economic losses (Radcliffe & Ragsdale, 2002; International Potato Center, 2022). The intensity of roguing is particularly high in early-generation seed stages (e.g., pre-breeder and breeder seed), where maintaining genetic and pathological purity is crucial. However, at the farmer level, roguing is often neglected due to the perceived loss of plant population and consequent yield reduction (Khurana *et al.,* 2005). Therefore, roguing not only maintains genetic and phytosanitary purity but also ensures higher net returns through improved tuber quality and market value.

Role and Training of Roguers

Effective roguing depends largely on the skill, vigilance, and consistency of personnel performing the operation. Roguers (Fig. 2) must be well trained to accurately recognize disease symptoms, varietal deviations, and abnormal plant growth under field conditions (Hossain *et al.,* 2015). Training programs organized by research institutions and extension agencies, including ICAR-Central Potato Research Institute, are essential for improving disease recognition and operational efficiency. To minimize mechanical transmission of pathogens, roguers should use appropriate protective gear such as smooth rain pants, rubber boots, disposable gloves, and disinfectant sprays for tool sanitation (Food and Agriculture Organization, 2010). Roguing should preferably be conducted under the supervision of an experienced field inspector to ensure uniform standards in seed health management (International Potato Center, 2022).



Fig. 2. Roguers performing roguing to maintain seed health

Identification and Classification of Rogue Plants

Accurate identification of rogue plants requires familiarity with disease symptoms and varietal characteristics (Figure 3). Roguing should be performed when the crop is healthy, well irrigated, and free from stress, as nutrient deficiency or environmental injury can mask disease symptoms (Venkataslam *et al.,* 2017). Morning hours or periods of diffused light



Fig. 3. Classification of Rogue Plants

are preferred, as bright sunlight or dew may obscure mosaic or chlorotic patterns. Diseased plants, mother and daughter tubers along with their stolon's should be completely removed during the tuber initiation stage to prevent further spread (Salazar, 1996). Rogue plants are broadly classified into three categories (FAO, 2010):

1. Volunteer plants arising from tubers left in the soil from previous crops, often emerging earlier than the main crop and acting as primary sources of infection or varietal admixture (Khurana *et al*., 2005; Thomas-Sharma *et al*., 2016).
2. Atypical or off-type plants differing in morphology or phenology from the target variety, identifiable by variations in leaf shape, pigmentation, stem color, or flowering, particularly at 45-50 days after planting.
3. Diseased plants exhibiting viral (mosaic, leaf curl, crinkling), bacterial (wilt, blackleg), or fungal (early or late blight) symptoms (Hooker, 1980).

Timing and Frequency of Roguing in Seed Potato Production

Timely and systematic roguing is essential for maintaining seed potato health and varietal purity. Infected plants act as foci for disease dissemination, particularly for aphid-transmitted viruses spread by *Myzus persicae* and *Aphis gossypii* (Radcliffe & Ragsdale, 2002). Delayed removal of diseased plants, often practiced to avoid yield loss, undermines roguing objectives by allowing secondary spread of infection (Khurana *et al*., 2005). Field inspection should begin approximately two weeks after crop emergence, when systemic disease symptoms become visible (Salazar, 1996). Roguing must include removal of both above-ground parts and underground seed tubers prevent resprouting from infected tubers (Singh *et al*., 2019). Disease symptoms are most clearly expressed under moderate light conditions, typically during early morning or late afternoon. Roguing is best conducted between 9:00-11:00 AM or 3:00–5:00 PM, with roguers moving opposite to the sun to enhance symptom visibility (CPRI, 2018).

Under Indian conditions, three rounds of roguing are recommended for seed production (Sadawarti *et al*., 2023; Singh *et al*., 2019):

1. First roguing (40-45 days after planting): Removal of visibly diseased, weak, or off-type plants before canopy closure. In hill regions, where crop duration is longer, roguing is typically carried out at 45-50, 70-75, and 85-90 days after planting.
2. Second roguing (55-60 days after planting): Conducted during peak vegetative growth when viral symptoms are most distinct.
3. Third roguing (70-75 days after planting): Performed prior to dehaulming to eliminate late-infected plants that may serve as inoculum sources.

Operational Steps in Roguing

Roguing should commence as soon as infected or off-type plants are visible. Suspected plants must be carefully dug out using hand tools to remove the entire plant, including

the mother tuber, stolons, and newly formed tubers, as manual pulling may leave infected tissues in the soil (FAO, 2010; Singh *et al.,* 2019). Rogued plants should be immediately removed from the field and placed in sealed bags to prevent virus acquisition by aphids. Disposal should involve deep burial (~60 cm) or burning at designated sites away from seed plots to eliminate residual inoculum (FAO, 2010; Cortbaoui, 1984). Mechanical transmission is particularly relevant for viruses such as Potato virus X (PVX), Potato virus S (PVS), Potato virus M (PVM) and Potato virus Y (PVY), which can be transmitted through contact with infected plant sap. Mechanical spread may occur through handling, field operations, cutting implements and contact between plants. In contrast, viruses such as Potato leafroll virus (PLRV) are not considered mechanically transmitted and are primarily managed through control of their insect vectors. Therefore, sanitation of hands, tools and equipment is particularly important where mechanically transmissible viruses are present (Sharma *et al*., 2021).

Factors Affecting the Roguing Process

The effectiveness of roguing is strongly influenced by crop, environmental, and operational conditions, which collectively determine symptom visibility and removal efficiency. Several agronomic and environmental factors influence the accuracy and efficiency of roguing in seed potato fields. Proper management of these factors is essential for effective identification and removal of diseased or off-type plants and for maintaining the genetic and phytosanitary purity of seed crops.

Crop Uniformity: Uniform crop growth facilitates the detection of diseased, off-type and abnormal plants because deviations in plant vigour, colour, architecture and phenology become easier to recognize. Uniformity begins with the use of healthy and properly graded seed tubers of appropriate physiological age. Good land preparation, uniform planting depth and spacing, proper earthing-up, balanced nutrient management, timely irrigation, effective weed management and appropriate pest and disease control also contribute to uniform crop establishment and growth. Uneven emergence or excessive variation in plant vigour can make visual identification of rogue plants difficult and may result in missed infections (Sharma et al., 2021; Khurana and Pandey, 2008)

Moisture Conditions: Adequate soil moisture enhances symptom expression, making leaf mosaic, curling, or chlorosis more apparent. Excessively dry conditions cause leaves to droop, wilting of the plants, masking characteristic viral symptoms.

Light Conditions: Diffused light, such as during early morning hours or cloudy weather, provides optimal conditions for detecting subtle foliar color variations (FAO, 2010). Direct sunlight creates shadows that may obscure symptoms. Roguers should preferably work with their backs to the sun so that their shadow falls on the plants, improving visual clarity.

Wind: Strong winds cause constant leaf movement, making it difficult to observe mild distortions or discoloration. Roguing should therefore be conducted during calm weather conditions (Sharma *et al.,* 2021).

Dirt, Residues, and Foliage Damage: Soil particles, pesticide residues, or dust on foliage can obscure disease symptoms and lead to misidentification. Roguing should be avoided immediately after spraying or earthing-up until foliage is clean (Khurana and Pandey, 2008). Similarly, mechanical injury, insect feeding, or phytotoxic effects may mimic disease symptoms, requiring trained personnel to distinguish abiotic stress from true infections.

Weed Infestation: Weeds hinder visual inspection and contribute to non-uniform crop growth. They may also serve as alternate hosts for insect vectors, increasing disease risk (Spooner *et al.,* 2014). Timely weeding and judicious herbicide use are therefore essential for accurate roguing.

Collectively, these factors underscore the importance of conducting roguing under optimal field conditions to maximize accuracy and operational efficiency.

Precautionary Measures for Effective Roguing

Effective roguing requires technical expertise, proper timing, and strict adherence to phytosanitary precautions to prevent vector-borne and contact transmission of viral diseases (Sharma *et al.,* 2021).

1. ***Skilled and Supervised Roguers:*** Roguing should preferably be carried out under the supervision of an experienced seed production supervisor, plant pathologist, seed technologist or other trained technical personnel. In certified seed production, roguing should also be coordinated with the requirements of the designated seed certification authority and field inspection procedures. Roguing should be performed by trained personnel for the proper identification of diseased plants, volunteer plants, varietal off-types and plants showing symptoms caused by abiotic stresses that may resemble viral diseases (FAO, 2010).
2. ***Integration with Vector Control:*** Roguing should be synchronized with integrated pest management strategies. Insecticides recommended under the Seed Plot Technique should be applied two to three days before roguing to reduce vector activity (Khurana and Pandey, 2008).
3. ***Minimizing Contact Transmission:*** Roguers should avoid unnecessary contact with healthy plants and perform roguing before canopy closure to reduce mechanical virus spread (Sharma *et al.,* 2021).
4. ***Sanitation and Field Operations:*** Tools, hands, and footwear should be disinfected regularly. Intercultural operations should be mechanized where possible to reduce physical transmission of pathogens (FAO, 2009).
5. ***Safe Disposal of Rogued Plants:*** Infected plants and tubers must be removed from the field and destroyed by deep burial or burning to eliminate residual inoculum (Cortbaoui, 1984).
6. ***Environmental Considerations:*** Moderate soil moisture and calm weather are ideal for roguing. Extreme wetness, drought, or high winds reduce symptom visibility and operational efficiency (FAO, 2009).
7. ***Early and Regular Roguing:*** Early roguing soon after plant emergence is critical for preventing virus spread. The guiding principle remains: "When in doubt, take it out" (Sharma *et al.,* 2021).
8. ***Field Allocation and Accountability:*** Assigning specific field sections to individual roguers improves coverage, accountability, and efficiency (Khurana and Pandey, 2008).
9. ***Role in Seed Quality Assurance:*** Roguing is a cornerstone of the seed plot technique and plays a decisive role in maintaining varietal purity and seed health, ensuring compliance with certification standards and long-term seed system sustainability (Sharma *et al.,* 2021).

For ease of reference and to facilitate comparison across operational stages, the key elements of roguing in seed potato production are presented in Table 1. The table

Table 1. Roguing in seed potato production under the Seed Plot Technique

Aspects	Description
Purpose of roguing	Removal of diseased, off-type and volunteer plants to maintain genetic purity and phytosanitary quality
Rationale	Vegetative propagation leads to accumulation of systemic pathogens causing seed degeneration
Major target pathogen	Potato viruses (PVY, PLRV, PVX, PVS, PVA, PVM)
Key vectors	Aphids (major vectors); whiteflies and other sucking insects may contribute to virus transmission
Integration with SPT	Combined with low-aphid period cultivation, vector control and dehaulming
Stages of roguing (plains)	40-45, 55-60 and 70-75 days after planting
Stages of roguing (hills)	45-50, 70-75 and 85-90 days after planting
Identification criteria	Mosaic, leaf curl, crinkling, chlorosis, stunting, off-type growth
Classification of rogues	Diseased plants, off-types and volunteer plants
Operational steps	Identification → uprooting → removal → destruction
Disposal method	Deep burial (>60 cm) or burning away from seed fields
Factors affecting efficiency	Crop uniformity, moisture, light, wind, weeds, foliage cleanliness
Precautionary measures	Skilled roguers, tool disinfection, synchronization with vector control
Diagnostic support	ELISA, immunostrips and PCR
Impact on seed quality	Reduced virus incidence, delayed degeneration, certification compliance
Future strengthening	Digital detection, mobile advisories, drone monitoring and training
Overall Impact	Healthier seed crop, reduced virus incidence and degeneration, improved crop performance, higher yield potential and better economic returns

summarizes the rationale, implementation framework, and expected outcomes of roguing within the Seed Plot Technique, emphasizing its role in controlling virus spread and delaying seed degeneration.

WAY FORWARD

Effective roguing reduces sources of inoculum, limits secondary virus spread, delays seed degeneration and supports compliance with seed certification standards. Although labour-intensive and dependent on skilled field personnel, roguing remains one of the most practical and economical approaches for maintaining seed health under Indian conditions. This review discusses the principles, timing, identification criteria, operational procedures, influencing factors and precautionary measures associated with roguing, with particular emphasis on its integration with the Indian Seed Plot Technique. The review also highlights the emerging challenges posed by changing vector dynamics and climate variability and the opportunities for strengthening roguing through improved training, vector surveillance, modern diagnostics and digital technologies.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by any of the authors

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EMERGING NON-THERMAL APPROACHES IN POTATO PROCESSING: OPPORTUNITIES AND CHALLENGES

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ABSTRACT: Non-thermal processing techniques are emerging as innovative methods in the potato processing industry, offering opportunities to improve product quality at a commercial scale. These approaches enhance the stability of processed potatoes by reducing microbial load, preserving physico-chemical properties, and minimizing nutrient degradation during processing. Techniques such as high-pressure processing, pulsed electric fields, cold plasma, and irradiation have demonstrated potential in maintaining the sensory, nutritional, and functional attributes of potato products. While each method offers distinct advantages, limitations related to cost, equipment availability, and process optimization remain. This review highlights recent developments in non-thermal processing of potatoes, emphasizing their applications, benefits, and challenges. The integration of these technologies in potato processing can ensure improved safety, extended shelf life, and retention of nutritional quality in various potato-based products.

KEYWORDS: Non-thermal, pulsed electric field, ohmic heating, potato frying, high pressure processing

INTRODUCTION

Non-thermal processing technologies such as pulsed electric field (PEF), ohmic heating, irradiation, plasma treatment, high pressure processing (HP), and supercritical fluid extraction techniques have recently emerged as significant alternatives to traditional physical and chemical preservation methods for thermal processing of potatoes, particularly concerning their nutritive and organoleptic characteristics (Allai *et al*., 2023).

The use of these technologies, whether individually or in conjunction with other natural additives, can greatly enhance the shelf stability of fresh-cut potatoes as well as potato-based processed products. Below, a brief description of the various non-thermal processing techniques specifically employed for potato processing is provided.

Ultrasound

Ultrasound is a non-thermal food processing technique that effectively preserves food without inducing spoilage (Drouso *et al*., 2024). The method relies primarily on the cavitation phenomenon, which involves the formation, oscillation, and collapse of microbubbles in liquids (Chemat *et al*., 2011). High-frequency ultrasound waves, typically exceeding 20 kHz, are applied at intensities ranging from 10 to 1000 W/cm^2, while lower frequency applications are usually in the range of 18–100 kHz. The power intensity of an ultrasonic probe is defined as the output power (W) divided by the beam area (cm^2).

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Enzyme inactivation occurs through the induction of cell membrane leakage, which helps reduce enzymatic browning in fresh-cut potatoes (Amaral *et al*., 2017). Additionally, ultrasound treatment aids in maintaining wound healing and membrane integrity in fresh-cut produce (Qiao *et al*., 2021).

Ultrasound (US), especially high-intensity power ultrasound, has garnered significant interest as a technology for process intensification in potato processing due to its ability to enhance mass transfer, disrupt cellular structures, and accelerate dehydration along with other physicochemical processes through acoustic cavitation. Previous research has shown that ultrasound-assisted osmotic dehydration (UAOD) can lead to increased moisture loss and soluble-solids transfer within potato tissues, effectively reducing the pre-treatment duration prior to subsequent drying operations (Goula *et al*., 2017). More recent investigations have validated that ultrasound can offer valuable processing advantages in potato products. For instance, Cheng *et al.* (2023) found that ultrasound pre-treatment markedly improved the drying rate and decreased the drying time of potato slices during subsequent microwave-vacuum drying. Nonetheless, the effectiveness was highly contingent on the treatment medium; ultrasound-assisted osmotic dehydration utilizing a concentrated sucrose solution did not necessarily enhance drying performance, indicating that ultrasound's benefits cannot be viewed in isolation from the surrounding process conditions. Likewise, recent studies on ultrasound-assisted frying revealed a reduction in oil absorption and enhancements in the quality characteristics of potato chips, with an optimized dual-stage ultrasound treatment achieving a reduction in oil content by approximately 32% (Alikhani Chamgordani *et al*., 2024). Furthermore, Yuan *et al*. (2025) recently demonstrated that ultrasonic-assisted ethanol pre-treatment facilitated the formation of microchannels in potato slices, improved mass transfer during osmotic dehydration, and enhanced the quality of CO_2-puffed dried potato products. These results suggest that the most significant potential of ultrasound may reside in its capacity to intensify existing unit operations rather than to supplant traditional potato-processing technologies.

Despite the encouraging results observed in laboratory and pilot-scale studies, the commercial application of ultrasound-assisted potato processing has not yet been widely adopted as an independent industrial technology. The primary challenge lies in the difficulty of replicating the acoustic conditions achieved in small laboratory reactors within high-throughput continuous systems. In larger processing volumes, acoustic energy is not evenly distributed due to factors such as attenuation, reflection, interference, and variations in acoustic impedance, which can lead to inconsistencies in cavitation intensity. As a result, merely increasing the reactor size or ultrasonic power does not guarantee a corresponding rise in treatment capacity. Furthermore, the treatment response is influenced by several factors, including potato size, tissue structure, moisture content, temperature, solid-to-liquid ratio, ultrasound frequency, amplitude, and exposure duration. Recent engineering reviews have highlighted reactor design, cavitation uniformity, transducer configuration, and continuous-flow operation as significant obstacles to scaling up for industrial use (Cárcel *et al*., 2024). Research is currently underway to explore advanced multi-transducer and large-area reactor designs to address these challenges; however, their effectiveness in continuous industrial potato-processing settings still needs to be validated.

Another significant limitation pertains to the complexity of equipment and the

required capital investment. Industrial ultrasound systems necessitate high-power generators, transducers or sonotrodes, reactors, temperature-control systems, and process-monitoring equipment. When dealing with large throughput, multiple transducers or several treatment stages may be essential to achieve adequately uniform acoustic exposure, which in turn raises capital costs and maintenance demands. Additionally, transducer degradation, fouling, and a decline in acoustic efficiency can further escalate maintenance expenses. Recent reviews have highlighted that the high cost of equipment, matrix-dependent acoustic propagation, the absence of standardized processing protocols, and challenges in ensuring uniform treatment are key factors hindering the widespread adoption of ultrasound in food processing (Tarafdarf *et al*., 2024; Gallo *et al*., 2025). Furthermore, the lack of standardized criteria for reporting ultrasonic power, acoustic intensity, energy density, and the actual energy delivered to the food matrix complicates comparisons between studies and poses challenges for industrial process design.

A further critical limitation is the complexity of the equipment and the associated capital investment. Industrial ultrasound systems demand high-power generators, transducers or sonotrodes, reactors, temperature-control systems, and process-monitoring equipment. For large throughput, it may be necessary to employ several transducers or multiple treatment stages to achieve sufficiently uniform acoustic exposure, which increases both capital costs and maintenance requirements. Moreover, issues such as transducer degradation, fouling, and a reduction in acoustic efficiency can lead to higher maintenance costs. Recent reviews have pointed out that the high cost of equipment, matrix-dependent acoustic propagation, the lack of standardized processing protocols, and the difficulties in maintaining uniform treatment are among the main factors that limit the large-scale implementation of ultrasound in food processing (Tarafdarf *et al*., 2024; Gallo *et al*., 2025). The absence of standardized criteria for reporting ultrasonic power, acoustic intensity, energy density, and the actual energy delivered to the food matrix also complicates the comparison of studies and hinders the design of industrial processes.

Another notable limitation is the complexity of the equipment and the significant capital investment required. Industrial ultrasound systems require high-power generators, transducers or sonotrodes, reactors, temperature-control systems, and process-monitoring equipment. In scenarios involving large throughput, multiple transducers or several treatment stages may be necessary to ensure sufficiently uniform acoustic exposure, which in turn raises capital costs and maintenance obligations. Additionally, transducer degradation, fouling, and a decrease in acoustic efficiency can further increase maintenance costs. Recent reviews have underscored that the high cost of equipment, matrix-dependent acoustic propagation, the lack of standardized processing protocols, and the challenges in achieving uniform treatment are among the primary factors that restrict the large-scale adoption of ultrasound in food processing (Tarafdarf *et al*., 2024; Gallo *et al*., 2025). Furthermore, the lack of standardized criteria for reporting ultrasonic power, acoustic intensity, energy density, and the actual energy delivered to the food matrix complicates the comparison between studies and poses challenges for the design of industrial processes.

The economic viability of ultrasound cannot be assessed merely by labeling the technology as energy efficient. While ultrasound has the potential to decrease processing time and possibly lower

energy usage in subsequent operations, a comprehensive economic evaluation must take into account the costs associated with equipment acquisition, installation, electricity usage, cooling, maintenance, transducer replacement, cleaning and sanitation, labor, and integration with current processing systems. Recent analyses have highlighted that the economic benefits of ultrasound are significantly dependent on the specific process, and that favorable laboratory outcomes do not necessarily lead to a positive return on investment when applied at an industrial level (Gallo *et al.*, 2025). Furthermore, high-intensity systems may demand more electrical input compared to the low-intensity laboratory systems often described as "low-energy" technologies. Consequently, future studies on potatoes should provide detailed information on specific energy consumption (kWh kg^{-1}), processing capacity (kg h^{-1} or t h^{-1}), equipment costs, operating expenses, product yield, and payback period, rather than focusing solely on treatment duration and product quality outcomes.

The relatively low economic value associated with bulk raw potatoes is a significant factor to consider. Justifying a dedicated ultrasound installation may prove challenging when the technology offers only slight enhancements in color, texture, or drying time. The economic rationale becomes more compelling for high-throughput and higher-value products, such as French fries, potato chips, dehydrated potato products, and specialty potato ingredients, where even minor improvements in yield, oil absorption, processing duration, or product quality can lead to a notable financial impact. This indicates that the commercial application should be assessed on a product-specific and line-specific basis, rather than presuming that ultrasound will be economically beneficial for all potato products.

Crucially, recent literature suggests that ultrasound should not be dismissed as a technology lacking industrial potential. High-power ultrasound has already proven commercially viable in certain food-processing applications, especially where it can be integrated into existing processes and yield measurable enhancements in throughput, separation, or product functionality. Nevertheless, potato processing introduces additional complexities due to the heterogeneous nature of potato tissue and the extremely high throughputs necessary for commodity products. Consequently, current research advocates for a more cautious perspective: ultrasound is technically promising but commercially specific in its applications, with its most immediate potential lying in its integration with established processes such as osmotic dehydration, drying, frying, or extraction, rather than serving as a complete substitute for traditional processing.

As a result, future investigations should progress from laboratory optimization to pilot and demonstration-scale techno-economic evaluations. Research should analyse both ultrasound-assisted and conventional processing on a standardized mass basis, documenting throughput, specific energy consumption, water and chemical needs, product yield, quality retention, capital expenditures, operating costs, and projected payback periods. Additionally, long-term continuous operation should be assessed to evaluate transducer stability, cleaning requirements, and treatment uniformity. This information is crucial for assessing whether the quality and process-intensification advantages noted in laboratory studies can deliver sufficient economic benefits to warrant industrial investment. Based on the current evidence, ultrasound should be regarded as a promising emerging technology for process

intensification in specific potato applications, although it has not yet achieved status as a universally accepted commercial-scale potato processing technology (Cárcel *et al*., 2024; Tarafdarf *et al*., 2024; Gallo *et al*., 2025).

Pulsed electric field (PEF)

In the processing of potatoes, pulsed electric field (PEF) treatment is typically applied prior to the cutting stage, which follows peeling (Leong *et al*., 2022; Botero-Uribe *et al*., 2017) (Figure 1). PEF induces the formation of temporary pores in the cell membranes, leading to a reduction in turgor pressure and a partial loss of structural integrity. This contributes to enhanced tissue rigidity and firmness. The pros and cons of using PEF during processing of potatoes is given in Table 1.

PEF-induced electroporation enhances membrane permeability and leads to a decrease in intracellular water and turgor pressure, which typically results in diminished firmness and cutting resistance of fresh potato tissue. PEF-induced electroporation enhances membrane permeability and leads to a decrease in intracellular water and turgor pressure, which typically results in diminished firmness and cutting resistance of fresh potato tissue.



Fig.1. Application of PEF to potatoes during processing

Nevertheless, during later stages of dehydration or frying, the created porous microstructure aids in moisture movement and may help in forming a firmer and crispier outer layer following significant water loss (Lee *et al*., 2024; Katsouli *et al*., 2024).

The application of PEF above the electroporation threshold leads to the formation of pores in potato cell membranes, which enhances membrane permeability and results in a reduction of intracellular turgor pressure. As a result, fresh potato tissue that has undergone PEF treatment typically becomes softer and more flexible, which diminishes its resistance to mechanical forces such as cutting, thus lowering the likelihood of fracture and breakage during slicing (Golberg *et al*., 2016; Moens *et al*., 2021; Katsouli *et al*., 2024). The degree of softening is influenced by factors such as electric-field strength, the number of pulses, specific energy input, and the structural properties of the potato tissue. Recent research has demonstrated that an increase in PEF intensity and pulse count can significantly decrease the firmness of fresh-

Table 1. Pros and cons of using PEF for potato processing

Pros	References	Cons	References
It can function at reduced temperatures, which helps to retain the heat-sensitive nutrients throughout the processing.	Arshad *et al.* (2020)	High capital expenditure may limit adoption; however, reduced cutting losses, improved yield, faster mass transfer and lower oil/energy use can offset investment in high-throughput potato processing.	Arshad *et al.* (2020)
The organoleptic quality characteristics of the product are being preserved.	Arshad *et al.* (2020)		Arshad *et al.* (2020)
The activities of enzymes were significantly regulated.	Poojary *et al.* (2016)		
In the processing of potatoes, particularly in the production of chips, the crispiness is preserved while minimizing oil absorption..	Leong *et al.* (2022) Zhang *et al.* (2021 & 2022).		

cut potato tissue due to ongoing disruption of cellular membranes (Katsouli *et al*., 2024). Nevertheless, this initial softening should not be mistaken for the texture of the final fried, dried, or cooked product. During further processing, the membrane permeabilization induced by PEF aids in the migration of water and solutes and modifies the microstructure of the tissue, while the removal of moisture, transformation of starch, and formation of crust can greatly alter the final mechanical characteristics. Therefore, PEF should not be characterized as universally enhancing tissue rigidity or firmness; its immediate effect on fresh potato tissue is predominantly softening, while the ultimate texture is contingent upon the conditions of subsequent processing and the intensity of treatment (Leong *et al*., 2022; Katsouli *et al*., 2024).

Furthermore, exposure of potato slices to PEF promotes the development of a porous tissue structure, facilitating more efficient water removal. This modification improves the frying process and reduces oil uptake in potato products (Leong *et al.,* 2022; Zhang *et al.,* 2021, 2022).

The oil absorption of potato slices was significantly reduced to 20% following PEF treatment at 5 kV/cm, which was attributed to modifications in tissue porosity and microstructure (Zhang *et al.,* 2022). When PEF treatment was combined with drying at 60°C, the maximum cutting forces related to firmness were improved, particularly at PEF intensities of 1–1.5 kV/cm (Iaccheri *et al.,* 2022). Abduh *et al.* (2019) reported that physico-chemical properties, including thermal stability and starch gelatinization behavior, remained largely unchanged in shredded potatoes subjected to PEF treatment.

Furthermore, PEF treatment applied prior to frying markedly reduced acrylamide concentration to 10 ng/g fresh weight, with only trace amounts detectable (Zhang *et al.,* 2021). Moreover, it has been observed that PEF treatment prior to frying significantly decreases the formation of acrylamide in potato products, suggesting a potentially advantageous food-safety aspect when suitable treatment conditions are utilized (Zhang *et al*., 2021).

PEF treatment also has the capacity to alter starch digestibility and the textural attributes of French fries made from steam-peeled potato tubers (Leong *et al*., 2022).

From a nutritional standpoint, a decrease in starch digestibility may be viewed as advantageous if it correlates with increased resistant starch formation or a reduced predicted glycemic response; however, excessive alterations to starch structure could affect desirable cooking and textural qualities.

Consequently, the nutritional impact of PEF should be assessed in conjunction with product texture and sensory quality, rather than being regarded as inherently beneficial or harmful.

PEF treatment can also affect the texture of the final fried product. While electroporation typically softens fresh potato tissue by disrupting cell membranes and lowering cellular turgor pressure, the end result may present a harder and crispier outer crust. This noticeable difference arises from the interplay between PEF-induced structural modifications and the frying process. Electroporation enhances membrane permeability, allowing intracellular water to migrate towards the surface. During frying, this increased water migration and evaporation hastens the dehydration of the outer layer, leading to the development of a relatively dry and mechanically robust crust. Consequently, the changes in porosity and mass transfer induced by PEF may contribute to the heightened hardness and crispness of the crust post-frying

(Leong *et al*., 2022; Zhang *et al*., 2022). Such an enhancement can be advantageous when it leads to improved crispness and structural integrity; however, excessive hardness may be perceived negatively from a sensory standpoint. Therefore, the impact of PEF on texture should be evaluated in the context of treatment intensity, moisture loss, frying conditions, and the desired attributes of the final product.

The economic evaluation detailed in Table 1 reveals that the primary constraint to the commercial application of PEF in potato processing is the relatively high initial capital investment required for pulse generators, treatment chambers, fluid-handling systems, control units, and their integration with existing processing lines (Arshad *et al*., 2020). This constraint is particularly significant for potatoes, as the raw material possesses a relatively low unit value, making it challenging to accommodate a substantial additional processing cost unless the technology yields considerable enhancements in throughput, yield, or product quality. Nevertheless, the economic viability of PEF should not be assessed solely based on its capital expenditure. PEF has the potential to diminish the mechanical resistance of potato tissue, which in turn reduces cutting forces and minimizes breakage and processing losses; it can also improve mass transfer during subsequent dehydration and frying processes, potentially leading to reduced oil absorption and processing duration. These operational advantages can help mitigate the initial investment by increasing the yield of usable products, enhancing line efficiency, and decreasing downstream processing needs (Arshad *et al*., 2020; Leong *et al*., 2022; Katsouli *et al*., 2024).

The economic benefits are anticipated to be more pronounced in high-throughput processing facilities that manufacture French fries, potato chips, and other value-added items compared to smaller operations. When throughput levels are sufficiently elevated, even minor decreases in raw material losses, frying oil usage, processing duration, or energy demands can lead to substantial annual savings. Furthermore, enhanced product consistency and decreased breakage may yield indirect economic advantages through increased saleable yield and more uniform product quality. Commercial suppliers of PEF technology have reported the installation of over 100 PEF systems worldwide, including uses for potato chips and French fries; however, these figures reflect industry-reported deployments and should not be construed as independent proof of profitability for every potato processing facility. Consequently, the commercial viability of PEF should ultimately be determined through a plant-specific techno-economic analysis that takes into account capital expenditures, operating costs, throughput, specific energy consumption, yield enhancements, reductions in oil or energy usage, maintenance needs, and payback periods. For low-margin potato products, PEF is most likely to be economically feasible when incorporated into large-scale, continuous processing lines where multiple operational advantages are achieved simultaneously, rather than being applied as a standalone treatment step.

High hydrostatic pressure (HHP)

The application of high hydrostatic pressure (HHP), ranging from 100 to 1000 MPa, to foods at low temperatures for specific durations, typically between 1 and 20 minutes, has been shown to effectively inactivate or prevent enzymatic browning in fruits and vegetables. In addition, HHP inhibits microbial growth, thereby enhancing the shelf stability of treated products. A mixture

of water and ethanol, possessing suitable physico-chemical properties, was employed as a non-toxic pressure-transmitting medium to facilitate uniform pressure transmission to the potato samples. The potatoes were placed in a hyperbaric vessel (Tsikrika *et al.*, 2021), and HHP was applied in either vertical or horizontal orientations. The pros and cons of using HHP were provided in Table 2.

Polyphenol oxidase (PPO) activity was assessed following high hydrostatic pressure (HHP) processing of both peeled and unpeeled potatoes. It was observed that treatment at 600 MPa resulted in higher residual PPO activity compared to treatment at 400 MPa. Moreover, HHP treatment at 400 MPa for 6 minutes effectively suppressed microbial growth; however, it did not significantly reduce enzymatic browning in freshly cut potato sticks. This treatment was also associated with a decrease in the lightness parameter (L*) on a scale ranging from black to white (Procaccini *et al.*, 2021).

The commercial significance of High-Pressure Processing (HPP) in the processing of potatoes goes beyond merely preserving color and inactivating enzymes. A primary application of HPP is the microbial stabilization and extension of shelf life for minimally processed, fresh-cut, refrigerated, and ready-to-eat potato products. HPP can significantly diminish microbial populations while maintaining numerous nutritional and functional properties, as the processing occurs at relatively low temperatures. In the case of minimally processed potatoes, HPP at 600 MPa has been shown to delay microbial growth during refrigerated storage and completely inhibit Enterobacteriaceae, while largely preserving total phenolic content and antioxidant activity (Tsikrika *et al.*, 2021). Additionally, HPP can affect texture by altering cellular structures, water distribution, and matrix components, which in turn influences firmness, hardness, and cohesiveness; however, these effects are highly dependent on factors such as

Table 2. Pros and cons of using high hydrostatic pressure for potato processing

Pros	References	Cons	References
It has the ability to eliminate microbes while maintaining the quality of food, without sacrificing organoleptic acceptability or nutritional value.	Argyri *et al.* (2018)	The installation requires additional investment.	Balasubramaniam *et al.* (2015)
This technique preserves the freshness, color, and texture, particularly for fresh, ready-to-eat, or minimally processed potato products.	Nguyen *et al.* (2010)	This method demands a significant amount of energy and requires substantial power for its functioning.	Balasubramaniam *et al.* (2015)
Improves microbial safety and refrigerated shelf life of minimally processed and ready-to-eat potato products; may also enable packaged-product processing, preserve bioactive compounds, modify texture and starch functionality, and reduce reliance on chemical preservatives.	Tsikrika *et al.* (2021); Gokul Nath *et al.* (2023); Colussi *et al.* (2020); Balasubramaniam *et al.* (2015)	Not all products were appropriate for their intended application due to post-treatment effects such as alterations in color, texture, and so forth.	Gokul Nath *et al.* (2023)
		The packed material must possess a high resistance capacity when subjected to high-pressure treatment.	Marangoni Júnior *et al.* (2019)
		High capital investment for pressure vessels, pumps, intensifiers, packaging and process integration can restrict economic feasibility, particularly for low-value bulk potatoes.	Balasubramaniam *et al.* (2015)

pressure level, treatment duration, cultivar, moisture content, and subsequent processing conditions (Gokul Nath *et al*., 2023). Moreover, the pressure-induced alterations in starch structure and functionality can impact gelatinization, pasting behavior, and starch digestibility, thus providing opportunities for the development of potato products with modified nutritional profiles (Colussi *et al*., 2020). HPP has also been studied for its impact on bioactive compounds, with research indicating retention of total phenolics and antioxidant activity, alterations in individual phenolic compounds, and reductions in the glycoalkaloids α-chaconine and α-solanine (Tsikrika *et al*., 2021).

From a commercial standpoint, HPP presents several additional benefits, such as decreased reliance on chemical preservatives, enhanced microbial safety, prolonged refrigerated shelf life, and the capability to process packaged products, which helps to reduce post-process contamination (Balasubramaniam *et al*., 2015; Tsikrika *et al*., 2021). These advantages are especially pertinent for high-end fresh-cut and ready-to-eat potato items, rather than for low-value bulk potatoes. However, the commercial application of HPP necessitates significant investment in high-pressure vessels, pumps, intensifiers, process controls, water handling systems, and pressure-resistant packaging. Additionally, the costs associated with high-pressure cycles and equipment maintenance can add to operational expenses (Balasubramaniam *et al*., 2015; Marangoni Júnior *et al*., 2019). Consequently, HPP is unlikely to be economically viable for low-margin potato products that are only aimed at color or enzyme control. Its commercial viability is more pronounced in scenarios where microbial safety, extended shelf life, premium quality, packaged processing, and functional or nutritional enhancements offer enough added value to justify the capital and operational expenditures. Therefore, future techno-economic evaluations should take into account throughput, energy usage, cost per kilogram, packaging needs, shelf-life extension, yield enhancement, and product price premiums when assessing the feasibility of HPP for potato processing.

Ohmic heating

Electrical current is conducted through foods that contain polar compounds, which aid in the flow of electricity. Fresh-cut potatoes, due to their relatively high-water content and ionic components, demonstrate adequate electrical conductivity for ohmic processing (Mari *et al*., 2024). This conductivity facilitates the movement of ions in the aqueous phase, while the electrical resistance within the food transforms electrical energy into heat, leading to rapid and relatively uniform volumetric heating (Zareifard *et al*., 2003). The effectiveness of ohmic heating is significantly determined by the product's electrical conductivity, which is influenced by the concentration of ionic compounds such as acids, bases, and salts (Alkanan *et al*., 2021). Conversely, non-polar components like oils and fats have minimal impact on electrical conductivity. The primary benefits and drawbacks of ohmic heating in potato processing are illustrated in Figure 2.

Consequently, the commercial viability of ohmic heating is expected to be more significant for continuous, high-throughput, and value-added potato applications compared to low-margin bulk processing. A comprehensive economic evaluation should take into account capital investment, operational and electricity expenses, throughput, energy usage per kilogram of product, electrode longevity, maintenance needs, product yield, and possible reductions in processing time and water consumption.

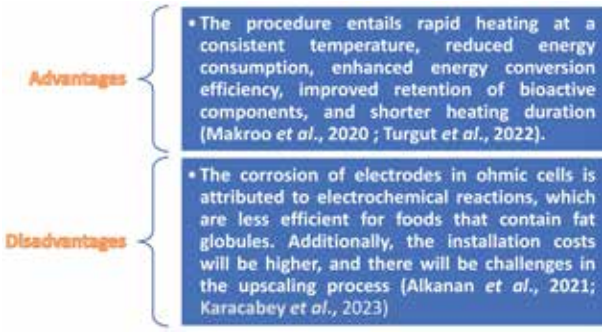


Fig.2. Advantages and disadvantages of using ohmic heating during potato processing

Currently, there is a scarcity of potato-specific techno-economic data at the industrial scale, and improvements observed in laboratory settings regarding nutrient retention or extraction efficiency alone cannot confirm commercial feasibility. Therefore, pilot and industrial-scale research that combines process performance, energy efficiency, product quality, equipment dependability, and cost per unit of processed potato is essential to assess the practical applicability of ohmic heating in large-scale potato processing.

Osmotic dehydration

Osmotic dehydration involves immersing solid food in a concentrated hypertonic solution, leading to water loss from the food and the concurrent transfer of osmo-active solutes into the tissue (Goula *et al*., 2017; Ahmed *et al*., 2016; Rózek *et al*., 2010). The extent of solute diffusion into the product is influenced by several critical factors, including immersion time, nature of the food tissue, temperature, solution concentration, and agitation (González-Pérez *et al*., 2021). The concentration of the osmotic solution is particularly crucial, as sub-critical concentrations can result in water absorption rather than dehydration (Goula *et al*., 2017).

In the realm of commercial food processing, osmotic dehydration (OD) is primarily utilized as a partial dehydration or pre-treatment phase, rather than serving as a complete substitute for drying. Its applications are documented in the processing of fruits and vegetables, the production of snacks and convenience foods, ingredient manufacturing, and in products that undergo subsequent air drying, frying, freezing, or other preservation methods. For potatoes, OD is especially pertinent to fresh-cut and minimally processed items and can be incorporated prior to drying or frying to decrease moisture content, alter water activity, and affect mass transfer during later processing stages. However, publicly accessible data typically does not specify the annual processing capacity directly linked to OD, as industrial facilities usually integrate OD with other unit operations and report total product throughput instead of OD-specific capacity. Consequently, the commercial viability should be assessed based on throughput, osmotic solution consumption and recovery, residence time, water removal per unit of solution, labor, energy consumption, and the requirements for downstream drying or frying, rather than presuming a distinct OD industry capacity. The primary commercial benefit of OD lies in its ability to remove water without a phase change, thus minimizing the latent heat demand associated with evaporation. Recent studies suggest that OD can eliminate roughly 30–40% of water, subsequently decreasing the load, energy needs, and residence time of air, vacuum, or other drying systems (Asghari *et al*., 2024). Therefore, this technology is most economically viable as a hybrid pre-treatment in high-throughput processing lines rather than as an independent dehydration technique.

In comparison to traditional solar drying, osmotic dehydration (OD) offers significantly enhanced process control, as dehydration

takes place under regulated conditions of solution concentration, temperature, agitation, and processing duration. In contrast, solar drying is heavily influenced by weather variability and is more prone to issues such as contamination, extended drying times, and degradation of quality.

When compared to hot-air drying, OD functions at relatively lower temperatures and extracts moisture without necessitating its vaporization. This characteristic leads to a decrease in thermal energy requirements and minimizes heat-related damage to color, flavor, texture, and sensitive nutrients (Asghari *et al*., 2024; Ramya and Jain, 2017). Furthermore, OD can alleviate the moisture burden on subsequent hot-air drying processes, which may result in reduced drying times and increased dryer capacity, all while lowering energy usage.

However, it is important to note that OD typically does not achieve adequate moisture reduction for complete stability at ambient temperatures, thus necessitating an additional drying or preservation phase. Challenges such as prolonged processing durations, solute absorption, management and regeneration of osmotic solutions, microbial control of the solution, and wastewater production continue to pose significant obstacles to widespread adoption (Asghari *et al*., 2024). Therefore, the commercial benefits of OD over traditional drying methods should not be viewed merely as a replacement for existing dryers; rather, its primary advantage lies in mitigating the intensity and costs associated with subsequent drying processes while enhancing product quality. Consequently, the industrial application for potatoes should be underpinned by a techno-economic evaluation that considers capital investment, solution recycling, energy consumption, throughput, labor, savings from downstream drying, product yield, and the market value related to quality.

In commercial practice, osmotic dehydration is widely used to reduce the water content of potatoes, thereby inhibiting microbial growth and prolonging shelf life, especially for fresh-cut potatoes destined for further processing such as drying or frying. Moreover, the spent osmotic solution can be repurposed for applications in beverage production (Ahmed *et al*., 2016). The various osmotic agents employed in potato processing is shown in Figure 3.

Freeze drying

Freeze-drying presents promising applications in the processing of potatoes, where the preservation of quality, rehydration efficiency, and bioactive compounds offers sufficient added value to warrant its relatively high processing costs. In contrast to traditional hot-air drying, this method removes water through sublimation under vacuum, which can mitigate thermal and oxidative degradation while creating a porous

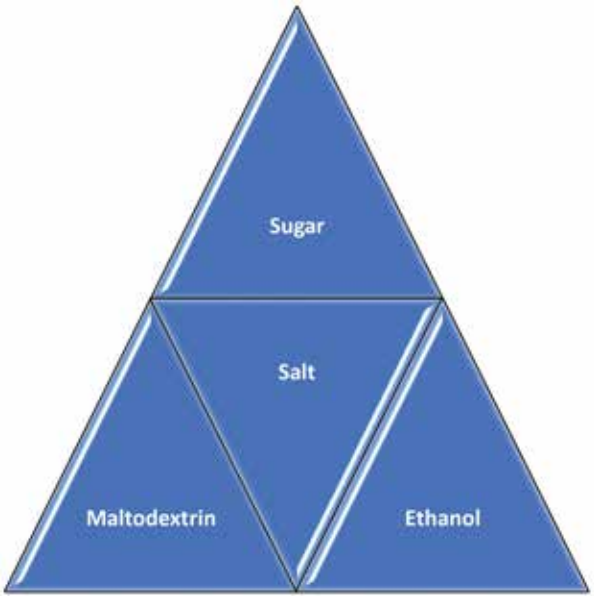


Fig.3. Various osmotic agents used in potato processing

structure that enhances rapid rehydration. This is especially beneficial for high-value potato products, including instant potato flakes or granules, dehydrated specialty potatoes, functional potato ingredients, and items designed for long-term storage. Research has indicated superior retention of heat-sensitive nutrients, polyphenols, color, structural integrity, and rehydration properties when compared to harsher thermal drying methods (Larder *et al*., 2018; Busler *et al*., 2017). Nevertheless, these quality benefits must be weighed against the significant drawbacks of freeze-drying, such as the substantial capital investment required for vacuum chambers and refrigeration systems, extended processing durations, high electricity usage, and the necessity for controlled freezing and vacuum conditions. As a result, freeze-drying is typically more economically viable for premium, nutrient-sensitive, or specialty potato products rather than for low-value bulk potatoes, for which hot-air or other continuous drying techniques may offer lower processing expenses. Therefore, industrial implementation should be assessed based on specific energy consumption, drying duration, throughput, product yield, equipment utilization, and enhancement of product value, rather than solely on nutritional retention. Hybrid methods, such as osmotic or convective pre-treatment followed by freeze-drying, could further decrease drying load and energy demands, thereby improving the economic viability of the process.

Irradiation

Food products can be subjected to irradiation using low-wavelength ultraviolet (UV) light, which is effective in disinfecting air, water, packaging materials, and solid surfaces (Teoh *et al*., 2016). Exposure to UV radiation at a wavelength of 254 nm can damage the nucleic acids of microorganisms, thereby reducing microbial contamination (Teoh *et al*., 2016). The primary advantage of irradiation lies in its ability to replace chemical treatments, improving overall product quality, particularly in terms of food safety. As a non-thermal processing method, UV irradiation minimizes nutrient degradation in potatoes (Xie *et al*., 2017). In commercial practice, irradiation has been employed to reduce microbial load on the surface of fresh-cut potato slices, thereby extending their shelf life. However, a limitation of UV-C irradiation is its shallow penetration depth, which primarily affects surface layers and may be less effective for dense or irregularly shaped products (Pandiselvam *et al*., 2022). Teoh *et al*. (2016) reported that immersing potato slices in calcium chloride and ascorbic acid, followed by UV-C exposure at 6.84 kJ/m², was the most effective treatment for reducing enzymatic activities, including POD, PAL, and PPO. Moreover, the total phenolic content in treated slices remained higher during storage compared to untreated samples or those exposed to UV-C alone. The study concluded that combining chemical treatment with UV-C irradiation can enhance the shelf life of fresh-cut potatoes by inhibiting enzymatic activities.

Irradiation holds significant promise in the processing of potatoes, particularly for microbial decontamination, sprout suppression, and extending shelf life. However, its effectiveness is highly contingent upon the type of radiation used and the specific product targeted. For fresh-cut potatoes, UV-C irradiation serves as an effective surface treatment, as it can diminish microbial contamination without significantly raising the product's temperature, thereby potentially reducing reliance on chemical sanitizers (Teoh *et al*., 2016; Pandiselvam *et*

al., 2022). Nonetheless, the limited penetration of UV-C limits its efficacy in bulk or irregularly shaped potatoes, necessitating careful consideration of uniform exposure, slice thickness, surface geometry, and dose control for practical application. Combination treatments, such as UV-C paired with calcium chloride or ascorbic acid, may offer enhanced control over enzymatic browning and quality degradation compared to UV-C used in isolation (Teoh *et al*., 2016). Therefore, UV-C is best suited for continuously conveyed fresh-cut potato surfaces, sanitation of packaging or equipment, and other scenarios where direct exposure can be guaranteed, rather than serving as a universal solution for whole potatoes.

From an economic and industrial standpoint, UV-C systems present an appealing option due to their relatively brief treatment durations, minimal chemical requirements, and compatibility with continuous processing lines.

However, the commercial viability of these systems hinges on factors such as lamp replacement and maintenance, energy consumption, safety measures for workers, the cleanliness of lamp surfaces, and the necessity to ensure sufficient irradiation of all product surfaces. In the case of potatoes, the financial benefits may be most pronounced when UV-C technology can decrease the need for sanitizers, reduce microbial spoilage, and minimize product losses, all while prolonging refrigerated shelf life.

Conversely, traditional chemical sanitation methods may prove to be more cost-effective in situations where achieving complete surface coverage is challenging or when processing volumes are limited. Thus, the optimal implementation of UV-C technology in industrial settings must take into account various factors, including UV-C dosage, exposure distance, conveyor speed, product loading, surface properties, microbial reduction, quality preservation, energy usage, and treatment costs per kilogram.

It is crucial to view UV-C as a specialized surface decontamination method rather than a substitute for all conventional preservation techniques. Further pilot and commercial-scale research that incorporates aspects such as microbial safety, product quality, energy consumption, equipment costs, throughput, and shelf-life extension is essential to determine its economic feasibility for large-scale potato processing.

Plasma treatment

Plasma technology can be effectively utilized as a novel method for the targeted inactivation of microorganisms. Plasma is a state of ionized gas characterized by the presence of electric fields, ultraviolet photons, charged particles, and reactive nitrogen and oxygen species (Wu *et al*., 2022). Plasma is generated when electrical energy is applied across two electrodes with a high potential difference, leading to gas ionization as free electrons collide with gas molecules (Laroque *et al*., 2022).

Various methods have been employed to generate plasma in food processing, including plasma jet (PJ), corona discharge (CD), dielectric barrier discharge (DBD), microwave (MW), and radiofrequency (RF) systems (Laroque *et al*., 2022; Sakudo *et al*., 2020). The primary antimicrobial agents responsible for plasma-induced inactivation are reactive oxygen species (ROS) and reactive nitrogen species (RNS), which can damage microbial DNA, proteins, and cell membranes (Wu *et al*., 2022; Li *et al*., 2019; Misra *et al*., 2014).

The key advantages of plasma treatment include lower operational costs, reduced treatment times, and minimal energy

requirements (Sarangapani *et al*., 2018). In large-scale commercial applications, plasma treatment can be used for surface sterilization of fresh-cut potatoes, effectively preventing enzymatic browning and microbial contamination. An indirect form of plasma treatment, known as plasma-processed air (PPA), involves remote exposure of the sample to plasma generated by a discharge device. This approach has been shown to reduce enzymatic activity, particularly polyphenol oxidase (PPO) and peroxidase (POD), by 77% and 89%, respectively, within 10 minutes of treatment (Busler *et al*., 2017).

The use of plasma treatment in the commercial sector for potatoes is still in its early stages, and there is a lack of publicly available evidence to pinpoint significant potato-processing companies that utilize cold plasma with specified annual production capacities. This differentiation is crucial, as most documented applications are confined to laboratory or pilot scales, rather than reflecting established industrial potato-processing practices (Rajan *et al*., 2023). Nonetheless, plasma technology presents various potential applications pertinent to the potato sector, such as the surface decontamination of fresh-cut potatoes, the reduction of enzymatic browning, the prolongation of refrigerated shelf life, the sanitation of food-contact surfaces, and pre-treatment prior to drying. Furthermore, plasma-activated water may serve as an alternative treatment medium for fresh-cut potatoes; recent studies have shown enhanced antimicrobial and anti-browning effects, as well as an extension of the shelf life of fresh-cut potatoes when organic-acid-enhanced plasma-activated water was utilized (2026). Additionally, cold filamentary microplasma has been specifically explored as a pre-treatment method for potato drying, where optimized treatment improved the drying rate and decreased the drying duration to approximately 130 minutes without significant alterations in starch and sugar levels (2020).

From an industrial standpoint, plasma treatment presents a compelling option for continuous fresh-cut potato production lines, as it necessitates minimal or no process water or chemical sanitizers and can be seamlessly integrated with conveyors or enclosed treatment chambers. A recently designed continuous industrial-scale cold-plasma system for fresh produce utilizes modular plasma units, showcasing the feasibility of engineering systems that are suitable for integration and scaling up (2024). Nevertheless, the commercial economics specific to potatoes are not yet sufficiently established. The capital investment required for plasma generators, treatment chambers, gas supply or air-handling systems, controls, shielding, and maintenance must be weighed against potential savings in water usage, chemical sanitizers, drying time, product losses, and energy consumption. Additionally, treatment uniformity is a critical factor, as the effectiveness of plasma treatment is influenced by exposure geometry, treatment duration, gas composition, moisture levels, microbial load, and product characteristics. Consequently, instead of asserting that specific potato companies have established commercial applications, plasma should be regarded as a promising emerging technology, with its industrial viability needing validation through pilot-scale potato trials, continuous throughput studies, regulatory evaluations, and techno-economic analyses.

Supercritical CO_2 extraction

The potato peel, a by-product of the potato processing industry, remains largely underutilized despite being rich in phenolic compounds. Traditionally, organic solvents have been employed to extract these

bioactive compounds; however, a major limitation of such methods is the potential presence of residual chemicals, which may compromise food safety. Recently, novel extraction techniques have been developed that eliminate the use of harmful solvents, thereby producing phenolic extracts free from chemical residues and enhancing their applicability in food systems.

De Andrade Lima *et al.* (2021) employed the central composite design of experiments to optimize the extraction of phenolic compounds from potato peels. Their study successfully identified key phenolics, including chlorogenic acid (CGA) and caffeic acid (CFA), achieving a significant antioxidant activity of 73%. The authors reported that the optimal extraction conditions comprised 20% methanol, a temperature of 80°C, a pressure of 350 bar, and a flow rate of 18 g/min. These findings highlight the potential of potato peel as a valuable source of natural antioxidants and underscore the efficacy of advanced, solvent-free extraction methods.

CONCLUSIONS

Non-thermal and innovative processing technologies present significant opportunities to enhance the quality, safety, nutritional content, and shelf life of potato products, while also mitigating some of the drawbacks associated with traditional thermal processing. The studies reviewed suggest that pulsed electric field (PEF) technology can enhance tissue permeability, mass transfer, cutting efficiency, and subsequent frying characteristics; high-pressure processing (HPP) can achieve microbial stabilization and extend shelf life while preserving essential nutritional and bioactive components; and osmotic dehydration can lower moisture levels and the energy demands of subsequent drying processes. Freeze-drying excels in retaining heat-sensitive compounds and improving rehydration properties, while UV-C and plasma treatments show potential for surface decontamination, controlling enzymatic browning, and preserving fresh-cut potatoes. Together, these findings illustrate that the primary advantage of emerging technologies lies not only in preservation but also in enhancing process efficiency and facilitating the creation of higher-value potato products.

Nevertheless, the evidence reviewed indicates that performance observed at the laboratory scale does not automatically equate to commercial viability. Significant barriers persist for various technologies, including high capital investment, energy demands, consistency in processes, equipment upkeep, packaging needs, limited penetration of treatments, and a lack of validation at the industrial scale. Consequently, future investigations should prioritize pilot and commercial-scale experiments, standardized processing parameters, techno-economic and life-cycle evaluations, energy efficiency improvements, and the incorporation of complementary technologies into continuous potato-processing systems. Special emphasis should be placed on the cost per kilogram of product, throughput rates, specific energy usage, enhancements in yield, prolongation of shelf life, and consumer acceptance. The field is likely to progress most effectively through interdisciplinary research that merges processing efficiency with economic and environmental assessments, facilitating the selection of technology based on product type and processing goals. Therefore, instead of pinpointing a single universally superior non-thermal technology, the evidence advocates for a product-specific and process-integrated strategy to achieve economically viable and sustainable potato processing.

CONFLICT OF INTERESTS

The author declare that they have no conflict of interest

ETHICAL STATEMENT

This article does not contain any studies with human participants or animals performed by the author

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POTATO LATE BLIGHT CAUSED BY *PHYTOPHTHORA INFESTANS*: BIOLOGY, EPIDEMIOLOGY, CLIMATE CHANGE, AND SUSTAINABLE MANAGEMENT STRATEGIES

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ABSTRACT: Potato late blight, caused by *Phytophthora infestans*, remains one of the most destructive diseases affecting global potato production, resulting in substantial yield and economic losses. This review summarizes the pathogen's biology, disease cycle, epidemiology, host–pathogen interactions, and current diagnostic approaches, along with major management strategies, including cultural practices, host resistance, biological control, botanical extracts, chemical control, disease forecasting, and integrated disease management. It also highlights the impacts of climate change on disease distribution and severity, as well as recent advances in molecular breeding, genome editing, and precision agriculture. Overall, sustainable management of potato late blight requires integrating resistant cultivars, environmentally friendly control measures, disease forecasting, and judicious fungicide use. Continued research on durable resistance, climate-smart management, and emerging biotechnological tools will be essential to enhance potato resilience and ensure future food security.

KEYWORDS: Potato; *Phytophthora infestans*; Integrated disease management; Host plant resistance; Climate change; Biological control.

INTRODUCTION

Potato plays a vital role in ensuring food security, particularly in developing countries, where it is one of the four major staple crops that collectively provide approximately 50% of the world's dietary energy alongside rice, wheat, and maize (Wijesinha-Bettoni & Mouillé, 2019). It is a nutritionally important crop that contributes significantly to global food and nutritional security (Singh *et al*., 2020). Potato tubers are rich sources of essential minerals, including potassium, phosphorus, magnesium, sodium, and calcium, as well as vitamins, particularly vitamin C and several B-complex vitamins (Varga & Đurović, 2023). China accounts for the largest potato cultivation area globally, followed by other major producers such as India. The global potato processing industry was valued at approximately USD 41 billion in 2023 and is projected to exceed USD 60 billion by 2031, reflecting the increasing demand for processed potato products worldwide (Hu *et al*., 2025). However, potato productivity and tuber quality are severely constrained by numerous insect pests and diseases, among which late blight, caused by *Phytophthora infestans*, is the most destructive, resulting in annual economic losses of billions of dollars worldwide (Chakrabarti et al., 2022).

Late blight, caused by the oomycete *Phytophthora infestans* (Mont.) de Bary, is

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one of the most destructive and extensively studied diseases of potato, capable of causing yield losses of up to 100% under favorable environmental conditions (Mizubuti & Fry, 2006; Tsedaley, 2014; Lal *et al*., 2018). The disease is historically significant for causing the Irish Potato Famine during the 1840s, which resulted in catastrophic crop failures, widespread famine, a decline of more than 20% in Ireland's population due to starvation, and mass migration (Yoshida *et al*., 2013; Majeed *et al*., 2017). More than 175 years later, late blight remains one of the most economically important plant diseases worldwide, with *P. infestans* causing annual losses exceeding US$10 billion through yield reduction and disease management costs (Lal *et al*., 2018; Rhouma *et al*., 2024). Rising global food demand, climate change, the emergence of more virulent pathogen genotypes, and fungicide-resistant populations have intensified the need for sustainable late blight management strategies (Dong & Zhou, 2022; Wang *et al*., 2025). The pathogen reproduces rapidly through asexual spores under cool and humid conditions because its infection cycle is highly dependent on moisture (Melhus, 1915; Fry, 2008). Under high humidity, *P. infestans* can complete its asexual infection cycle in approximately four days, with cool temperatures (10–15°C) promoting rapid zoospore germination and warmer temperatures (20–25°C) favoring direct germ tube penetration (Fry, 2008).

Effective management of late blight requires an integrated approach that combines resistant cultivars, cultural practices, disease forecasting systems, biological control agents, and judicious fungicide applications (Dong & Zhou, 2022; Bourki *et al*., 2026). Recent advances in pathogen biology, molecular diagnostics, host resistance breeding, and precision agriculture have further expanded opportunities for developing sustainable and environmentally sound disease management strategies (Bourki *et al*., 2026). This review provides a comprehensive overview of potato late blight, covering its causal organism, epidemiology, symptomatology, disease cycle, host–pathogen interactions, diagnostic approaches, and integrated management strategies. It also highlights recent advances, current challenges, and future research directions for achieving sustainable management of this economically important disease.

Causal Organism

Phytophthora infestans is an obligate biotrophic oomycete belonging to the kingdom Stramenopila. Although it is commonly referred to as a fungus because of its filamentous growth habit and disease symptoms, it is phylogenetically distinct from true fungi and is more closely related to brown algae and diatoms (Judelson, 2014). The pathogen produces coenocytic, multinucleate, and predominantly aseptate hyphae, with hyaline, lemon-shaped, papillate sporangia borne singly on the tips of branched sporangiophores. It is heterothallic, requiring two compatible mating types (A1 and A2) for sexual reproduction (Raza *et al*., 2022; Mugao, 2023).

During its life cycle, *P. infestans* differentiates hyphae into sporangia that facilitate dispersal and host infection through protein kinase-mediated phosphorylation pathways (Judelson & Ah-Fong, 2010). The pathogen reproduces both asexually through sporangia, zoospores, and mycelium and sexually through oospores, enabling survival under diverse environmental conditions (Andrivon, 1995). Between cropping seasons, it survives primarily in infected seed tubers, volunteer potato plants, cull piles, and, where both mating types coexist, persistent soil-borne oospores, which serve as the primary

inoculum for new epidemics (Andrivon, 1995; Johnson, 2010; Hu *et al*., 2022). Under favorable environmental conditions, these survival structures initiate disease outbreaks, with airborne sporangia driving rapid secondary spread and repeated infection cycles (Wang *et al*., 2025).

The population biology of *P. infestans* is characterized by frequent migration, genetic recombination, and natural selection, resulting in rapid shifts in pathogen populations across time and geographic regions (Fry, 2016). Its genome has evolved through transposable elements, horizontal gene transfer, gene family expansion, and transcriptional and epigenetic regulation, enabling dynamic gene expression during development and host infection (Judelson, 2014). Although potato and tomato are the primary hosts, *P. infestans* can also infect other members of the Solanaceae, including wild species such as *Solanum dulcamara*, *S. sarrachoides*, and petunia, which may act as reservoirs of inoculum between cropping seasons (Leesutthiphonchai *et al*., 2018).

Infection process

Most *Phytophthora infestans* infections are initiated by asexual sporangia, which germinate either directly or by releasing motile zoospores depending on temperature. At temperatures above 15°C, sporangia germinate directly to infect host tissues, whereas at lower temperatures they release 10–12 motile zoospores that swim in water films, encyst, and initiate infection (Ghorbani *et al*., 2004). Following encystment, germ tubes penetrate host tissues through appressoria, stomata, wounds, or other natural openings (Leesutthiphonchai *et al*., 2018). Successful infection is facilitated by the formation of specialized structures, including appressoria, which enable host penetration (Avrova *et al*., 2008). After penetration, the pathogen develops intercellular hyphae and haustoria to acquire nutrients from living host cells while secreting effector proteins and small RNAs that suppress plant immune responses and promote colonization (Leesutthiphonchai *et al*., 2018; Singh *et al*., 2026). As the infection progresses, new sporangia are produced, host tissues become necrotic, and secondary disease cycles are initiated (Leesutthiphonchai *et al*., 2018). Between growing seasons, the pathogen survives primarily as mycelium in infected tubers, providing an important source of primary inoculum for subsequent epidemics (Ghorbani *et al*., 2004).

The pathogenicity of *P. infestans* varies among physiological races because of differences in virulence and gene expression. Highly aggressive strains exhibit rapid mycelial growth and enhanced expression of genes involved in carbon metabolism, amino acid biosynthesis, glycolysis, and cell wall degradation, leading to faster host colonization and disease development (Deng *et al*., 2025). Sexual reproduction is regulated by coordinated expression of genes associated with epigenetic regulation and RXLR effectors, with Avrblb2 contributing to both virulence and oospore formation (Tzelepis *et al*., 2020).

Potato responds to *P. infestans* infection by activating multiple defense mechanisms. During incompatible interactions, rapid oxidative and nitrosative bursts increase peroxynitrite ($ONOO^-$) production, resulting in RNA, mRNA, and protein nitration that contributes to programmed cell death and restricts pathogen spread (Izbiańska *et al*., 2018). The pathogen, however, suppresses host immunity through secreted effectors such as Pi08174, which interfere with defense-related pathways and enhance virulence (Zheng *et al*., 2025). Infection also induces dynamic changes in host DNA methylation that regulate defense-related gene expression,

with epigenetic reprogramming influencing disease progression (Tian *et al*., 2025). Resistance is primarily mediated through the hypersensitive response (HR), in which rapid localized cell death limits pathogen growth, while callose deposition and phenolic compound accumulation strengthen cell walls and further restrict pathogen invasion (Vleeshouwers *et al*., 2000).

Recent advances in genome editing have opened new opportunities for improving late blight resistance. CRISPR/Cas9-mediated disruption of the susceptibility gene *StDND2* significantly reduced disease severity, demonstrating the potential of susceptibility gene editing for developing durable resistance against *P. infestans* (Bibi *et al*., 2026).

Disease symptoms of late blight

***Leaves*:** Initial symptoms of late blight appear as small (2–10 mm), circular, pale- to dark-green, water-soaked lesions, typically developing at the leaf margins and tips. Under cool and humid conditions, lesions may occur anywhere on the leaf surface, enlarge rapidly, turn dark brown to black, and coalesce, resulting in extensive blighting and rapid leaf death (Lal *et al*., 2018; Al Harethi *et al*., 2023; Bagchi et al., 2024). A characteristic diagnostic feature is the presence of white sporulation on the abaxial (lower) surface of infected leaves under humid conditions (Tsedaley, 2014; Al Harethi *et al*., 2023).

***Stems and petioles*:** Water-soaked lesions on stems and petioles enlarge rapidly into dark brown to black lesions that may develop before or after leaf symptoms. As the disease progresses, these lesions weaken the affected tissues, often causing stem collapse, and serve as important sources of secondary inoculum for further disease spread (Ghorbani *et al*., 2004; Arora *et al*., 2014; Kumar *et al*., 2018).

***Tubers*:** Tuber infection occurs when sporangia are washed from infected foliage into the soil and reach developing tubers. Infected tubers develop irregular, slightly sunken, brown to reddish-brown or purplish lesions on the surface, which extend into the underlying tissues as reddish-brown, granular rot, reducing both tuber quality and storability (Arora *et al*., 2014; Adolf *et al*., 2020). Representative symptoms of late blight on leaves, stems, and tubers are shown in Fig. 1.

Epidemiology

The development of potato late blight is strongly influenced by environmental conditions. The disease is favored by cool, humid weather, with temperatures of 10–20°C, prolonged leaf wetness, fog, and heavy dew promoting infection. Sporangial production is greatest at 15–20°C, whereas lower temperatures (10–13°C) stimulate zoospore release, while dry conditions and temperatures above 24°C suppress disease



Fig. 1. Symptoms of potato late blight caused by Phytophthora infestans: (A) leaf symptoms, (B) stem symptoms, and (C) tuber symptoms. Images adapted from (A–B) ©Eric Anderson, Crop Science, and (C) ©Anna L. Snowdon, CABI.

development (Dey *et al*., 2014). Leaf wetness duration, soil moisture, and irrigation management further influence sporulation, pathogen dispersal, infection efficiency, disease severity, and epidemic development (Café-Filho *et al*., 2019).

The dispersal of *P. infestans* occurs primarily through airborne sporangia and water-mediated movement, with seasonal and environmental conditions playing a crucial role in epidemic initiation and spread (Mohaimin *et al*., 2023; Bregant *et al*., 2024). Disease gradient studies have shown that infested organic potato fields can act as important mid-season inoculum sources, facilitating pathogen spread to neighboring conventional fields (Zwankhuizen *et al*., 1998).

Host susceptibility also contributes to epidemic development, with potato plants becoming increasingly susceptible to late blight as they age (Abuley & Hansen, 2021). In addition, climate change is expected to alter the distribution and severity of late blight by modifying temperature, humidity, and rainfall patterns, emphasizing the need for adaptive disease management strategies (Bagchi *et al*., 2024).

Sustainable management practices

Integrated disease management

Sustainable management of potato late blight relies on an integrated disease management (IDM) approach that combines cultural practices, host resistance, biological control, disease forecasting, and judicious fungicide use to achieve effective and durable disease suppression (Dong & Zhou, 2022; Maurya *et al*., 2025). The integration of multiple complementary strategies reduces disease pressure, delays fungicide resistance, and promotes environmentally sustainable potato production.

Host resistance forms the foundation of IDM. Advancing this genetic approach, the ICAR-Central Potato Research Institute (ICAR-CPRI) has actively developed next-generation cultivars like *Kufri Ratan*, which incorporates robust resistance to *Phytophthora infestans* with high-yielding traits to anchor sustainable regional IDM frameworks (Singh *et al*., 2026). The incorporation of resistance genes from wild potato relatives into commercial cultivars has improved durable resistance, although weather conditions and inoculum pressure often exert a greater influence on disease development than cultivar resistance alone, emphasizing the need to combine resistant cultivars with other management practices (Lamichhane *et al*., 2024; Meno *et al*., 2025). Disease forecasting models based on weather variables, such as BLITECAST and JHULSACAST, further enhance IDM by optimizing the timing and efficiency of fungicide applications (Lamichhane *et al*., 2024).

Several studies have demonstrated the benefits of integrating resistant cultivars with fungicides and other cultural practices. Combining resistant cultivars with fungicide applications significantly reduced late blight severity, increased potato yield, and reduced fungicide dependence, whereas the additional benefits of mulching varied with environmental conditions (Demis Gedlu *et al*., 2022; Kilonzi *et al*., 2024; Phungula *et al*., 2025). Similarly, integrating farmyard manure, poultry manure, *Trichoderma harzianum*, and fungicide application reduced late blight severity from 49.05% in the untreated control to 5.35% while increasing tuber yield from 211.68 to 449.40 g plant^{-1} (Bansal *et al*., 2022). Strip cropping with grass or maize also reduced disease severity, with grass strips increasing potato yield by 31–33% compared with monoculture (Homulle *et al*., 2024).

Successful implementation of IDM also depends on farmer knowledge and technological innovation. Farmer training and extension services improve the effective use of fungicides and integrated management practices (Tadiye *et al*., 2026). In addition, eco-friendly approaches, including plant extracts, essential oils, biological control agents, RNA interference, and nanoencapsulation, represent promising alternatives for sustainable late blight management (Hari *et al*., 2025). Decision-support tools such as the Taguchi optimization approach further facilitate IDM by identifying cultivar selection as a key factor influencing disease management and optimizing integrated control strategies (Ritchie *et al*., 2025).

Host plant resistance

Host plant resistance is one of the most sustainable strategies for managing potato late blight because it reduces reliance on fungicides while providing long-term disease suppression (Paluchowska *et al*., 2022; Dechen Angmo *et al*., 2023). Integrating conventional and molecular breeding approaches has accelerated the development of durable resistant cultivars. Advanced technologies, including marker-assisted selection, somatic hybridization, gene pyramiding, and CRISPR-based genome editing, have facilitated the incorporation of multiple late blight resistance (*Rpi*) genes, resulting in broader and more durable resistance against *Phytophthora infestans* (Berindean *et al*., 2024; Sahito *et al*., 2026). The successful development of potato populations carrying stacked *Rpi* genes further demonstrates the potential of gene pyramiding to enhance resistance durability (Keijzer *et al*., 2021).

Field evaluations have confirmed the effectiveness of resistant cultivars in suppressing late blight while maintaining high productivity. A resistant potato clone (C2-5) carrying multiple resistance genes sustained only 0.4–0.5% foliage damage and produced 59.5 t ha^{-1} without fungicide application (Islam *et al*., 2022). Similarly, resistant cultivars maintained less than 1% disease severity compared with 60–78% in susceptible cultivars grown without fungicide treatment (Kilonzi *et al*., 2024). Maincrop cultivars combining moderate-to-high late blight resistance with yields of up to 49 t ha^{-1} and starch contents exceeding 19% demonstrate that disease resistance can be successfully integrated with desirable agronomic traits (Asakaviciute *et al*., 2025). In addition, the climate-resilient cultivar INIA 333–CHUGAYNA exhibited frost tolerance, field resistance to late blight, high yield, and reduced fungicide requirements, highlighting the importance of resistant cultivars for climate-resilient potato production (Cabrera *et al*., 2025). Examples of potato cultivars and genotypes exhibiting resistance to late blight across different countries are summarized in Table 1.

Cultural management

Cultural practices play a fundamental role in integrated late blight management by reducing the survival, reproduction, dispersal, and infection of *Phytophthora infestans*, thereby lowering primary inoculum and disease pressure (Tsedaley, 2014; Lal *et al*., 2018; Rhouma *et al*., 2024; Maurya *et al*., 2025). Effective sanitation measures include crop rotation, destruction of cull piles and volunteer potato plants, removal of infected plants and crop debris, and vine desiccation before harvest to minimize pathogen survival between growing seasons (Demissie, 2019; Lal *et al*., 2018).

Agronomic practices such as proper irrigation management to reduce leaf wetness, adequate plant spacing to improve air circulation, and the use of certified disease-free seed tubers further limit disease

Table 1. Comparative Performance of Potato Cultivars and Genotypes Resistant to Late Blight (*Phytophthora infestans*) in Different Countries

Cultivars/Genotypes	Country/Region	Peak Foliar Disease Severity (%)	Average Potato Yield (t/ha)	Research Source
'Goda', 'Rasa'	Lithuania	3.0%-35.0%	38.5-45.2 t/ha	Asakaviciute *et al.*, 2025
'CIP-Matilde'	Peru	<5.0%	32.0-37.5 t/ha	Gastelo *et al.*, 2024
'Unica'	Kenya	12.5%	28.4 t/ha	Kilonzi *et al.*, 2024
BARI Alu 77 BARI Alu 53	Bangladesh	8.0%-14.5%	30.0-34.8 t/ha	Islam *et al.*, 2022
Regional Genotypes (High Altitude)	Ethiopia	18.0%-62.0%	12.1-24.5 t/ha	Biri *et al.*, 2026
'Bioimpuls' Selections	Netherlands	<2.0%	35.0-41.0 t/ha	Keijzer *et al.*, 2022
'Bionica' / 'Toluca'	Denmark	0.0%-10.0%	38.0-44.0 t/ha	Abuley & Hansen, 2022
Selected Phenotypes	Estonia	15.0%-40.0%	26.0-33.0 t/ha	Agho *et al.*, 2023
'Cooperation-88' (C88)	China	<8.0%	30.0-45.0 t/ha	YAAS, 2024
'Khumal Ujjwal'	Nepal	11.0%-15.0%	13.9-18.5 t/ha	NARC, 2023
'Kufri Himalini'	India	16.21 %	45 t/ha	Chakraborty *et al.*, 2022
'Atlantic' (with RB gene)	United States	4.0%-8.5%	42.0-48.0 t/ha	USDA-ARS, 2024

development (Sahu, 2012; Demissie, 2019). Adjusting planting dates can also reduce disease pressure; Chulda *et al*. (2021) reported that late planting enabled potato crops to escape periods of peak late blight infection where climatic conditions were suitable. Nitrogen management is equally important, as excessive nitrogen application (320 kg ha^{-1}) increased late blight severity and reduced yield compared with a moderate application rate of 160 kg ha^{-1} under intermediate disease pressure (Juárez *et al*., 1999). In addition, mulching reduces late blight by minimizing rain splash, thereby limiting the dispersal of *P. infestans* sporangia and reducing primary inoculum (Waheed *et al*., 2023). Proper postharvest storage of healthy tubers further minimizes the carryover of inoculum to subsequent cropping seasons (Sahu, 2012).

Biological management

Biological control is a promising and environmentally sustainable approach for managing potato late blight because beneficial microorganisms suppress *Phytophthora infestans* through antagonism, competition, mycoparasitism, antimicrobial metabolite production, and induction of plant defense responses (Goutam *et al*., 2018; Wang & Long, 2023). The effectiveness of biological control can be further enhanced by combining agents with different modes of action and integrating them with other disease management practices within an integrated pest management (IPM) framework (Wang & Long, 2023).

Numerous microbial biocontrol agents have demonstrated efficacy against late blight. Species of *Trichoderma*, *Bacillus*, *Pseudomonas*, *Streptomyces*, *Pythium oligandrum*, *Glomus*, *Xenorhabdus*, and *Chaetomium*, as well as chitosan hydrochloride, significantly reduced disease severity and, in many cases, promoted potato growth and yield (Wharton *et al*., 2012; Yao *et al*., 2015; Slininger *et al*., 2007; Daaboub *et al*., 2022; Jin *et al*., 2023; Soytong & Ratanacherdchai, 2023; Põldmets *et al*., 2025). For example, *Trichoderma harzianum* and *Bacillus subtilis* effectively reduced seed-piece decay (Wharton *et al*., 2012), *Trichoderma* isolate HNA14 significantly suppressed late blight while enhancing plant growth (Yao *et al*., 2015), and combining *Streptomyces* with

biochar provided greater disease suppression than either treatment alone (Jin *et al*., 2023). Likewise, mixtures of *Pseudomonas fluorescens* strains were more effective than individual strains in controlling late blight (Slininger *et al*., 2007).

Despite their considerable potential, most biological control agents provide lower and more variable disease control than synthetic fungicides when used alone (Daaboub *et al*., 2022; Põldmets *et al*., 2025). However, integrating biological control agents with fungicides or other sustainable management practices can substantially improve disease suppression. For instance, the combined use of *Glomus* spp. and *Pythium oligandrum* with fungicides significantly reduced late blight severity, while a *Chaetomium*-based mycofungicide integrated with biological fertilizers achieved disease control comparable to that of chemical fungicides (Cwalina-Ambroziak *et al*., 2015; Soytong & Ratanacherdchai, 2023).

Botanical extracts

The widespread and repeated use of synthetic fungicides has accelerated the development of fungicide resistance in *Phytophthora infestans*, increasing interest in botanical extracts as environmentally friendly alternatives for late blight management (Mehmood *et al*., 2022; Hari *et al*., 2025). Plant extracts and essential oils possess strong antifungal activity due to their high concentrations of bioactive compounds, including polyphenols, flavonoids, terpenoids, alkaloids, and other secondary metabolites that inhibit pathogen growth and development (Hari *et al*., 2025).

Numerous plant-derived products have demonstrated significant efficacy against potato late blight. Garlic and neem extracts effectively suppressed disease development, with garlic reducing disease incidence to 5.81% compared with 61.18% in the untreated control (Mehmood *et al*., 2022). Ethanolic extracts of clove and black pepper completely inhibited *P. infestans* mycelial growth in vitro, while thyme also exhibited strong antifungal activity (Shebannavar *et al*., 2022). Similarly, extracts of *Aloe vera*, ginger (*Zingiber officinale*), African basil (*Ocimum gratissimum*), and *Frangula alnus* bark significantly reduced late blight severity and improved potato yield, highlighting their potential as eco-friendly components of integrated disease management programs (Manju *et al*., 2024; Musa *et al*., 2025; Saxena *et al*., 2025).

Chemical control

Chemical control remains the primary strategy for managing potato late blight because fungicides provide rapid and reliable disease suppression when applied preventively and integrated with other management practices (Babarinde *et al*., 2025; Dey *et al*., 2024). Preventive spray programs consisting of contact fungicides followed by systemic or translaminar fungicides effectively reduce disease incidence and severity while significantly increasing potato yield and profitability (Dey *et al*., 2024).

Several fungicides have demonstrated excellent efficacy against *Phytophthora infestans*. Recently approved products such as Ninja 56 SC, Zam Gold 50 WP, and Oracol 70 WP achieved more than 95% disease suppression under field conditions (Rahman *et al*., 2026). Similarly, cymoxanil + mancozeb provided nearly complete control of late blight and produced the highest tuber yields when used as a preventive fungicide, while its combination with hexaconazole also showed strong curative activity (Siddique & Aktar, 2016). Ridomil Gold and Ridomil MZ (metalaxyl + mancozeb) consistently outperformed mancozeb and chlorothalonil, significantly reducing disease severity

and increasing tuber yield (Inam-ul-Haq *et al*., 2008; Kefelegn *et al*., 2012). Field studies in Nepal further demonstrated that dimethomorph, fenamidone + mancozeb, and mancozeb effectively suppressed late blight, with dimethomorph providing the greatest disease control and economic return (Khadka *et al*., 2020). In addition, cyazofamid, mandipropamid, and oxathiapiprolin + benthiavalicarb have emerged as effective alternatives to mancozeb for late blight management (Naim & Cohen, 2023).

Despite their effectiveness, the extensive use of fungicides has increased the risk of fungicide resistance in *P. infestans*. Reversible resistance to mancozeb and shifts in fungicide sensitivity associated with the increasing genetic diversity of pathogen populations highlight the importance of fungicide rotation, resistance monitoring, and integration of chemical control with cultural, biological, and host resistance strategies to ensure sustainable disease management (Fan *et al*., 2025; Babarinde *et al*., 2025). Compared with alternative chemical treatments such as ozone (O_3) and hydrogen peroxide (H_2O_2), conventional fungicides remain the most effective option for suppressing late blight and maximizing potato yield (Skrobacz *et al*., 2026).

Late blight and climate change

Climate change is reshaping plant–pathogen interactions by altering the survival, distribution, virulence, and epidemiology of plant pathogens, thereby increasing disease pressure and crop losses worldwide (Ali *et al*., 2024; Kumar & Mukhopadhyay, 2024). It is also projected to shift the geographical distribution of potato pests, creating new areas of infestation and emphasizing the need for early monitoring and adaptive pest management strategies (Xian *et al*., 2023).

Potato late blight is highly sensitive to changes in temperature, humidity, and rainfall. In Finland, warmer and wetter conditions resulted in late blight outbreaks occurring 2–4 weeks earlier during the late 1990s and increased the likelihood of epidemics by 17-fold, leading to greater fungicide use and illustrating the impact of climate change on disease management (Hannukkala *et al*., 2006). However, simulation studies suggest that the effects of climate change on late blight are region-specific. Although early disease onset causes the greatest yield losses, increasing temperatures may suppress *Phytophthora infestans* more than potato growth in some environments, resulting in variable disease responses under future climates (González-Jiménez *et al*., 2023).

Projected climate scenarios (RCP 4.5 and RCP 8.5) indicate temperature increases of up to 3.8°C and highly variable rainfall (–721 to +448 mm), with potato yields expected to decline by 37–59%, highlighting the crop's vulnerability to climate change (Pushpalatha *et al*., 2021). Strengthening adaptation capacity through farmer education, participation in farmer groups, improved agricultural infrastructure, and supportive institutional and economic policies will be essential for enhancing the resilience of potato production under changing climatic conditions (Purwanti *et al*., 2022).

CONCLUSION

Potato late blight, caused by *Phytophthora infestans*, remains one of the most destructive diseases affecting potato production worldwide, resulting in substantial yield losses and economic damage. The pathogen's rapid evolution, genetic diversity, and ability to develop fungicide resistance, together with the increasing influence of climate change, continue to challenge

effective disease management. Advances in understanding the biology, epidemiology, host–pathogen interactions, and disease cycle of *P. infestans* have significantly improved the development of integrated management strategies. Sustainable control of late blight cannot rely on a single approach but instead requires the integration of host plant resistance, cultural practices, biological control agents, botanical products, disease forecasting systems, and judicious fungicide application. The adoption of integrated disease management (IDM) strategies offers the most effective and environmentally sustainable approach to minimizing disease losses while reducing dependence on synthetic fungicides and improving potato productivity.

FUTURE PROSPECTS

Future research should prioritize the development of durable late blight-resistant cultivars through conventional breeding, gene pyramiding, marker-assisted selection, and genomic selection, utilizing the diverse resistance available within the cultivated potato gene pool. Where existing resistance sources are insufficient, novel resistance genes from wild *Solanum* species should be introgressed into cultivated germplasm through hybridization and modern breeding approaches. CRISPR-based genome editing can subsequently be explored to complement conventional breeding and accelerate the development of improved resistance. Greater attention should also be given to biological control agents, botanical fungicides, RNA interference technologies, and nano-based formulations as sustainable alternatives to conventional fungicides. The integration of artificial intelligence, remote sensing, unmanned aerial vehicles, precision agriculture, and weather-based disease forecasting models will enhance early disease detection and optimize management decisions. Continuous monitoring of *P. infestans* population dynamics, virulence, and fungicide sensitivity is essential for detecting emerging pathogen genotypes and fungicide resistance. Climate change adaptation should also be incorporated through climate-resilient cultivars, location-specific integrated disease management programs, and strengthened farmer education and extension services. Collaborative efforts among researchers, breeders, policymakers, and farmers will be critical for translating scientific advances into practical and sustainable solutions for the long-term management of potato late blight and global food security.

ETHICAL STANDARDS

This review article does not involve experiments on humans, animals, or living subjects. The authors declare that the work complies with the current laws and regulations of the country in which it was performed.

LEGAL REQUIREMENTS

The author declares that this manuscript is original, has not been published previously, and is not under consideration for publication elsewhere. The author has read and approved the manuscript and agrees to its submission.

PERMISSIONS

The author confirms that all figures and tables included in this manuscript are original and that all sources of information have been appropriately cited. No copyrighted material requiring permission has been reproduced in this manuscript.

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MANUSCRIPT PREPARATION GUIDELINES FOR AUTHORS

1. The Potato Journal publishes reviews (by invitation), full length papers, short notes and book reviews (by invitation) on basic and applied research on potato. Manuscripts type-written in English, double spaced with at least 4 cm margin on all sides should be submitted online after getting registered on : http://epubs.icar.org.in/ejournal/index.php/PotatoJ/user. All the authors should be members of the association (foreign authors are exempted).

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3. Title of the paper, name(s) and address(es) of authors, a short running title of the paper (<50 characters conveying main theme of the article), acknowledgements (if any), and name of the corresponding author (with **E-mail address)** should be submitted in seprate file (**supplementary file**). **Identity of authors** should not be disclosed/ indicated in any form in the text of the paper. **Footnotes** should be numbered in plain Arabic superscripts (Use MS word→insert footnote facility in default form).

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The last name(s) of the author(s) and the year of publication should be cited in the text as per style given below.

- .....the late blight of potato (**Singh, 2011**); or .....the late blight of potato (**Singh and Kumar, 2011**); or .....the late blight of potato (**Singh *et al*., 2011**).
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Anonymous (2010) Agribusiness in India: green shoots. *Economist* **394**(13-19 March): 65-66

Chakravarty C and Pandey B (2005) Growing roots in farmlands: an interview with Ms Indra Nooyi, worldwide president and CFO, PepsiCo. *Econ Times* 29 August 2005

Online sources

FAO (2008) Potato world: Africa-international year of the potato 2008. Food and Agriculture Organisation, Rome. http://www.potato2008.org/en/world/africa.html, 31 December 2008

Hirtle PB (2008) Copyright renewal, copyright restoration, and the difficulty of determining copyright status. *D-Lib Magazine* **14**(7-8), DOI:10.1045/july2008-hirtle

Anonymous (2008) *Encyclopaedia Britannica*. http://search.eb.com, 6 May 2008

E-Views (2006) E-Views quantitative software. http://www.eviews.com, 28 September 2006

Book and book chapter

Guenthner J (2001) The International Potato Industry. Woodhead Publishing Limited, Cambridge: 312p, ISBN-13: 978 1 85573 465 4

Adiyoga W and Norton GW (2009) Costs and benefits of Bt potato with resistance to potato tuber moth in Indonesia. In, Projected Impacts of Agricultural Biotechnologies for Fruits and Vegetables in the Philippines and Indonesia. Norton GWH (ed), Los Banos, Philippines: 105-40

Annual report, bulletin or working paper

CPRI (2010) Annual report 2009-10. Central Potato Research Institute, Shimla, India: 203p

Chand R (2003) Government intervention in food grain markets in the new context. National Centre for Agricultural Economics and Policy Research, New Delhi. Policy paper-19: 118p

CPRI (1999) Package of practices of ware and seed potato production in central Indo-Gangetic plains. Central Potato Research Institute, Shimla, India. Extension bulletin-16: 9p

Theisen K and Thiele G (2008) Implementing CIP's vision: impact targeting. International Potato Center (CIP), Lima, Perú. Working paper 2008-4: 24p

Conference presentation

Haq I, Farooq K and Mahmood MM (2008) Screening of potato genotypes for late blight resistance/ tolerance in Pakistan. Poster presented in Global Potato Conference-2008, New Delhi, 9-12 December 2008

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Thesis

Kaur RJ (2004) Effect of nitrogen management through organic and inorganic sources in potato. Department of Agronomy, Punjab Agricultural University, Ludhiana, India, Ph.D. thesis: 99p

Encyclopaedia or dictionary

Kinni TB (2004) Walt Disney (1901-1966): founder of the Walt Disney company. Encyclopaedia of Leadership. Sage Publications, Thousand Oaks, CA: **1**: 345-49

Cowie AP (1989) Oxford Advanced Learner's Dictionary, 2nd ed. Oxford University Press, Oxford

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Unit	Abbreviation	Unit	Abbreviation
Centimetre	cm	Milligram	mg
Cubic centimetre	cm^3	Millilitre	ml
Gram	g	Minute	min
Hectare	ha	Nanometre	nm
Kilogram	kg	Second	s
Litre	l	Square cm	cm^2
Metre	m	Square km	km^2
Mega gram	Mg	Tonne	t

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