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GAMMA IRRADIATION DOSES INFLUENCES ON INSTRUMENTAL COLOUR ANALYSIS AND SENSORY CHARACTERISTICS OF IRISH POTATOES IS VARIETAL DEPENDENT

Victor Musitia[1*], Heka Kamau[1], Miriam Kinyua[2] and Ayua Emmanuel[1]

ABSTRACT: Gamma irradiation has been used over time to alter tuber's colour, which affects the sensory properties of potato products, but few studies have focused on explaining these effects. This study therefore investigated the effects of gamma irradiation on colour and sensory characteristics of French fries made from improved tubers (IP1, IP2, and IP3) irradiated at 15, 30, and 20 Gy, respectively, at a dose rate of 2Gy/minute relative to their parent tubers. From the results, gamma irradiation had varied effects on the colour parameters of tubers, with a significant ($p<0.05$) reduction recorded for the skin and flesh lightness of IP1 relative to the parent tuber post-irradiation. Similarly, an increase in flesh yellowness of the tubers was noted for IP2 and IP3, after irradiation. A significant ($p<0.05$) increase in all sensory parameters of French fries made from IP1, IP2 and IP3 relative to their parents was also noted, indicating that irradiation had a net positive effect on the sensory characteristics. A strong positive correlation was also noted between the texture, flavour, oiliness, and taste of the French fries, which all contributed to their overall liking. Gamma irradiation can be adopted to produce tubers with better colour and sensory attributes.

KEYWORDS: Gamma irradiation, sensory characteristics, Irish potatoes, colour

INTRODUCTION

Majority of the populace in developing world especially in Sub-Saharan Africa and Asia live at an increased risk of food and nutrition insecurity. This has been a major concern, leading to the commitment by world leaders to end hunger and malnutrition as stipulated in the Sustainable Development Goals (SDGs) by 2030 (von Braun *et al*., 2021). To achieve this SDG goal of zero hunger, concerted efforts including policy actions (Development Research of the University of Bonn [ZEF], 2020), which can involve diversified production, food fortifications, novel crop breeding strategies, and a shift from the overdependence of common staples such as maize, rice and wheat have been recommended. The Food and Agriculture Organisation [FAO] (2022) records that Irish potato (*Solanum tuberosum L.*) is a potential food crop that can help address this challenge. Irish potato is ranked third in production and it is the fourth most consumed food crop in the world after maize, rice and wheat worldwide (Mlaviwa & Missanjo, 2019; Lal *et al*., 2021; FAO, 2022). It is considered an excellent source of carbohydrates (starch) compared to cereals and other tubers and also supplies other nutrients, including fibre and vitamins such as vitamin C, some B-complex vitamins, carotenoids and other phenolic compounds (Bonierbale *et al*., 2010; Ndungutse *et al*., 2019; Gikundi, 2021).

Globally, Irish potato utilization has been shifting from the conventional use of fresh potatoes to the contemporary value addition and industrial application. More than 50% of the total harvest is used by food processors,

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animal feed production, and industrial purposes (International Potato Centre [CIP], 2022). Despite the demonstrated importance of Irish potatoes, production and utilization is often hampered by numerous challenges including diseases such as bacterial wilt. Nevertheless, it has been proposed that novel breeding technology using gamma irradiation can help address some of these challenges through improvement of potato traits, thus improving yield, growth habits, plant stature, disease and pest resistance, physiological characteristics, and its nutritional value (Zia *et al*., 2018; Chepkoech *et al*., 2018).

Typically, gamma irradiation can influence potato attributes including colour and sugar content among others. Colour is an essential attribute of tubers since it influences consumers choice when purchasing. The flesh colour of tubers varies from white to purple depending on the varietal type, and it affects the end product of the tubers (Oliveira *et al*., 2020). For instance, yellow to cream white tubers have been reported to produce golden-coloured products desirable in French fries and crisps (Oliveira *et al*., 2020). Colour is also perceived to have a link to their nutritional and phytochemical content. Yellow, purple and red-fleshed tubers are an excellent source of anthocyanin and carotenoid pigments, which can be used as natural colourants and antioxidants that play a significant role in the human body, such as scavenging for free radicals (Subía, 2013). Besides the flesh colour, the skin colour is also vital for selection. The red and purple coloured (skin and flesh) tubers tend to have high levels of these antioxidants and vitamin C, making them highly preferred by most people for domestic use (Lindqvist-Kreuze *et al*., 2015). Various factors influence the tuber's colour chief of which are the genotypes and the prevailing climatic conditions in the region where they are cultivated (Kumari *et al*., 2018). The location where tubers are planted and maturity stage, also influences the lightness, redness, and yellowness of the tuber's flesh (Githieya *et al*., 2021). According to Bordoloi *et al*. (2012), tuber flesh colour after peeling among different cultivars is influenced by variations in polyphenol oxidase, antioxidants, phenolic compounds and pigments in the tubers.

Despite the positive contributions of gamma irradiation on improving shelf life and aiding in preventing tuber susceptibility to pests and diseases, applying the rays can also confer unfavourable characteristics to the tubers by interfering with some physical or sensory properties. A study by Sarkar & Mahato (2020) on *Kufri Jyoti* potato varieties grown in India which were exposed to irradiation doses of 100 and 200 Gy found that there were noticeable changes in colour and weight of those tubers irradiated with 200 Gy, unlike those with 100 Gy which displayed insignificant changes. A study by Rezaee *et al*. (2013) also documented that gamma radiation treatment of Irish potatoes with doses ranging between 50 to 100 Gy decreased the specific gravity of the tubers and vitamin C, which resulted in an impact on the texture, mouthfeel and nutritional quality of French fries.

Similarly, the International Atomic Energy Agency (IAEA) noted that gamma irradiation of Irish potatoes at higher doses results in a significant reduction of colour parameters and appearance of the tubers and their processed products (World Health Organization, [WHO], 1997). Effects of irradiation on other nutrients like sugars in Irish potatoes are more variable, with reducing sugars increasing and non-reducing sugars decreasing with irradiation depending on the dosage used (Rezaee *et al*., 2013), which can have an impact on the overall taste and appearance of products made out of the tubers. To qualify gamma-irradiated tubers for consideration as a food and nutrition security alternative, consumer acceptability has to be achieved for products made out of these tubers. However, most of the existing literature focuses on tubers irradiated as a post-harvest handling strategy, and limited studies have been done to establish the effects of irradiation breeding on physical and sensory characteristics. The current study, therefore, is set to investigate the effects of gamma irradiation on the physical and sensory characteristics of improved tuber varieties that were developed from two common tubers in Kenya.

MATERIALS AND METHODS

Materials

Asante and Sherekea parent tubers and three improved tuber varieties (IP1, IP2, and IP3) were used in the study. Asante was used to produce IP1, while Sherekea was used to produce IP2, and IP3 through exposure to gamma radiation at dosage rates of two grays per minute (Gy/min) from a Co^{60} source at 15, 30, and 20 Gy, respectively (Chepkoech *et al*., 2018). The three were selected for their better agronomic characteristics after comparison with several other tubers exposed to different irradiation levels (Chepkoech *et al*., 2022). The tubers were collected from the Mau-Narok Agriculture Development Corporation (ADC) farm and taken to the Kenya Agricultural and Livestock Research Organization (KALRO) horticulture centre in Njoro, Nakuru. The collection and handling of the tubers were guided by the regulations and guidelines of the Kenya Plant Health Inspectorate Service (KEPHIS, 2020). The tubers were sorted, cleaned, and dried under ambient conditions in a naturally ventilated area for one week before subsequent experiments.

Colour of skin and flesh of irish potatoes

The skin and flesh colour of the tubers was determined following methods described by Yang *et al*. (2016) using a hand-held colourimeter (PCE-TCR 200, China). Standard black (L^*: 55.49, a^*: 527.08, b^*: 54.66) and white (L^*: 593.41, a^*: 521.18, b^*: 50.75) tiles were used to calibrate the colourimeter before use. Five randomly selected tubers from each variety were assessed at six different points to obtain the values for lightness (L^*), redness (a^*) and yellowness (b^*). The hue angle (H^*) and chroma (C^*) were derived using the formulas below:

$$H^* = \tan^{-1}(b^*/a^*) \text{ and } C^* = (a^{*2} + b^{*2})^{1/2}$$

French fries preparation

Tuber samples (3 kgs of each variety) were selected, peeled and sliced into 11 ×11 mm strips using a manual hand-held chipper (Figure 1). The potato strips were rinsed in cold water to remove the surface starch. The strips were then deep fried in an institutional batch-type deep-fryer (model MC-DF 1031, Cool Touch deep fryer, China) using corn oil in a 1:10 (w/v) potato to oil ratio for approximately 6-8 minutes at 170°C following the process outlined by Nairfana et al. (2021) and Ngobese et al. (2017)the effect of low-temperature long-time (LTLT. The fried strips were placed on glass trays lined with paper towels to drain off excess oil, cooled to an ambient temperature and taken for sensory evaluation.

Consumer acceptability

French fries' sensory acceptability for the three improved tuber varieties and the parents was done by 52 randomly selected panellists using a 9-point hedonic rating scale to evaluate the consumer acceptance of the

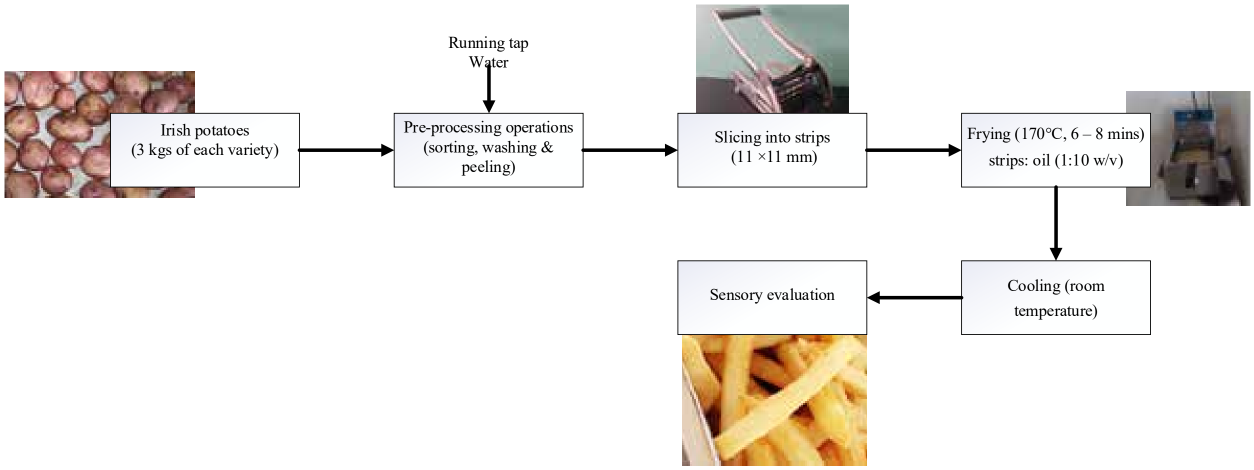

Fig. 1. French fries preparation process flow

products (1 = dislike extremely and 9 = like extremely). The participants were recruited from the University of Eldoret (UOE) through an advert that contained details of the tuber varieties to be evaluated to ensure those applying were consumers of Irish potatoes and were not allergic to the products from the tubers. The panellists consisted of students and staff members of age ranges between 18 to 55 years. Informed consent was sought from the members who signed and agreed to participate in the sensory evaluation exercise. The panellists were informed of the aspects of scoring for colour, flavour, taste, and overall acceptability of potato products. The samples were blinded using three-digit numbers generated from The Table of Random Numbers and served to each panellist following a random order fashion derived from the Table of Random Permutations of Nine. The panellists were provided with a glass of distilled water to cleanse the palate in between evaluation of the samples.

Data analysis

Data obtained from colour measurements and consumer acceptability tests were analysed using R software (Version 4.2.3). Considering tuber varieties as a source of variations, data was subjected to a one-way analysis of variance (ANOVA). The means were considered significantly different at $p<0.05$, and results were expressed as the mean ± standard deviation (SD). Tukey's HSD was used to separate the means for those that showed significant differences. A Principal Component Analysis (PCA) biplot was generated to illustrate the interrelationships between the sensory characteristics of the tubers, where eigenvalues were retained for varimax rotation to generate two dimensions.

RESULTS AND DISCUSSION

Irish potato skin colour

The results for skin colour are shown in Table 1. The skin colour measurements of the tubers showed significant differences in lightness, redness, yellowness, hue angles, and chroma values across the varieties. A significant decrease in L^* was recorded for IP1 (28.79 ± 0.57) relative to the parent Asante (49.91 ± 2.13); however, no significant differences were noted for values of a^*, b^*, H^* and C^* after irradiation. The decrease in lightness of IP1 relative to the parent Asante could have been due to the effects of gamma irradiation. Irradiation using gamma rays at lower doses (<20 Gy) has been noted to result in a reduction of carotenoid levels in

Table 1. Skin colour of tubers.

Variety	(L*) Lightness	(*a**) Redness	(*b**) Yellowness	(*H**) Hue angle	(C*) Chroma
Asante	49.91 ± 2.13^{c}	8.67 ± 2.01^{a}	21.34 ± 1.85^{b}	67.67 ± 6.03^{a}	23.15 ± 1.14^{a}
IP1	28.79 ± 0.57^{b}	8.14 ± 1.00^{a}	24.48 ± 1.04^{b}	71.58 ± 2.60^{a}	25.82 ± 0.87^{a}
Sherekea	25.16 ± 1.87^{a}	60.75 ± 4.18^{b}	-19.95 ± 4.09^{a}	341.97 ± 2.71^{b}	64.00 ± 5.06^{b}
IP2	26.35 ± 1.88^{ab}	65.59 ± 2.40^{b}	-24.06 ± 1.90^{a}	339.85 ± 1.47^{b}	69.88 ± 2.48^{b}
IP3	25.59 ± 2.34^{a}	60.02 ± 7.15^{b}	-22.60 ± 3.38^{a}	339.39 ± 1.73^{b}	64.16 ± 7.66^{b}

Values are means ± standard deviation. Means with different superscript letters along the same column are significantly different at *p<0.05*, as assessed by Tukey's HSD. Hue angle (*H**) and Chroma (*C**) were calculated from *a** and *b** values.

tubers and increases the amount of phenolic content, which affects the lighter appearance of the tuber (Maltsev *et al*., 2022; Mounir *et al*., 2022). The skin colour of IP1 and Asante was relatively yellow, as indicated by the positive *b** values. On the other hand, IP2, IP3, and Sherekea had no significant changes in the values for *L*, a*, b*, or H** and *C** post-irradiation. The high positive values of *a** indicate that the skin colour of Sherekea, IP2, and IP3 was relatively red. The distinct skin colours indicate that IP1 could easily be selected for preparation of brightly coloured potato products such as French fries or crisps.

Asante and IP1 were further classified with low hue angles (*h**) (67.67 ± 6.03 and 71.58 ± 2.60, respectively), which is found in the yellow region on the International Commission on Illumination (CIE) colour scale. On the contrary, Sherekea, IP2, and IP3 had very high hue angles in the fourth quadrant but leaned towards the first quadrant. The hue angles of the varieties indicated that the skin colour for Sherekea, IP1 and IP2 was darker than that of IP1 and Asante. Skin colour is an essential parameter for tuber selection since it is consumers' first impression of judgement (Spence, 2015). The colour of potatoes similarly affects the processing applications and directly influences the nutritional composition of the tubers (Zhu & He, 2020). Irish potato skin colour influences consumer preferences and selection, as noted by Zarzecka et al. (2023), since red and purple-fleshed tubers accumulate more vitamin C and tend to have distinct tastiness and cooking properties compared to the yellow-fleshed ones (Zarzecka *et al*., 2023). On the other hand, tubers with yellowish skin have high carotenoid levels, which are also essential antioxidants in the body; hence, visual selection of intense yellow-fleshed tubers can help consumers choose healthier options (Valcarcel et al., 2015).

Irish potato flesh colour

Results for the flesh colour measurements are presented in Table 2. Across the varieties, the flesh colour of most tubers did not differ significantly ($p<0.05$) in lightness except IP1. Relative to the parents, irradiation significantly reduced the lightness of 1P1 relative to the parent Asante, but no significant differences were noted between Sherekea and its daughters. Generally, the measures for redness, yellowness, hue angle, and chroma showed no significant differences between IP1 and Asante after irradiation. There was a significant increase in yellowness and chroma values for IP2 and IP3 relative to their parent Sherekea. However, a significant reduction in Hue angle was calculated between Sherekea and its daughters IP2 and IP3.

The tubers' *L** and *b** values indicated that most tubers had a light-yellow flesh

Table 2. Flesh colour of tubers.

Variety	(L*) Lightness	(a*) Redness	(b*) Yellowness	(H*) Hue angle	(C*) Chroma
Asante	62.99 ± 2.45^{b}	-4.14 ± 0.12^{b}	14.01 ± 0.66^{a}	106.48 ± 0.95^{a}	14.61 ± 0.63^{a}
IP1	47.15 ± 1.04^{a}	-4.46 ± 0.20^{b}	14.23 ± 0.70^{a}	107.44 ± 1.11^{ab}	14.91 ± 0.68^{a}
Sherekea	62.08 ± 4.09^{b}	-5.22 ± 0.39^{a}	13.45 ± 0.89^{a}	111.28 ± 1.95^{c}	14.43 ± 0.83^{a}
IP2	64.96 ± 2.76^{b}	-5.45 ± 0.30^{a}	18.91 ± 1.41^{c}	106.12 ± 0.96^{a}	19.68 ± 1.40^{c}
IP3	62.67 ± 4.56^{b}	-5.59 ± 0.24^{a}	15.81 ± 0.60^{b}	109.51 ± 1.38^{b}	16.77 ± 0.50^{b}

Values are means ± standard deviation. Means with different superscript letters along the same column are significantly different at *p<0.05*, as assessed by Tukey's HSD. Hue angle (*H**) and Chroma (*C**) were calculated from *a** and *b** values.

colour. However, there was a significant difference in the *b** values between IP2 and IP3, which had higher values for yellowness than the other three varieties. Furthermore, Asante, IP1, IP2, and IP3 had significantly lower value measures of hue angles relative to Sherekea, which are located in the second quadrant of the CIE *L*a*b** colour scale. This is indicative that they are in the yellow region (90°h) as the highest values are in the green region (180°h) (Cabezas-Serrano *et al.*, 2009). IP2 and IP3 also had relatively higher values for chroma (C*), signifying their yellow colour measure had higher intensity than other varieties. Tuber flesh colour is of significant importance since it directly impacts the selection criteria for food processing and indicates nutrient content. Potato varieties with yellow to cream-coloured flesh produce brightly golden colours for fried products and bright yellow for boiled potato products, which are desirable for consumers (Oliveira *et al.*, 2020; Kisakye S. *et al.*, 2020; Ooko, 2008). This implies that all the varieties in this study can be well suited for producing fried products and can also be boiled owing to the bright colours of the flesh.

From a nutrition standpoint, the high amount of yellowness in the tubers also indicates the presence of high amounts of carotenoids (Zhu & He, 2020), which are important antioxidants in the diet. Tubers with reddish or purple skin/ flesh colour contain high amounts of anthocyanin and phenolic compounds, in addition to essential antioxidants in the human diet (Subía, 2013; Yang *et al.*, 2016). The current findings agree with a study by Soares *et al*. (2016), who reported that gamma irradiation on tubers done to a rate of about 4 kGy results in a reduction in the values for lightness (*L**) of the potatoes. This is because induced mutation by gamma irradiation reduces the amounts of carotenoids in tubers and increases the amount of phenolic content (Blessington Tyann, 2005), reducing brightness in the tubers.

Consumer acceptability tests

The sensory attributes of French fries evaluated by the panel on a 9-point hedonic scale are shown in Figure 2. The sensory characteristics of French fries showed significant variations in colour, flavour, taste, texture, oiliness, and overall acceptability between the three tuber varieties relative to their parents. Asante and IP1 were generally rated as above fair (6.5) and good (7.0) for all attributes on a 9-point hedonic scale. French fries from Sherekea had the lowest scores (below fair 5.0) for all attributes, unlike its daughter tubers. Mostly, a significant difference was recorded between French fries made from the parent tubers and their corresponding daughters, with daughters scoring higher, thereby indicating that the developed tubers had better sensory characteristics than their parents. The sensory characteristics of Irish potato products depend partly on the tubers'

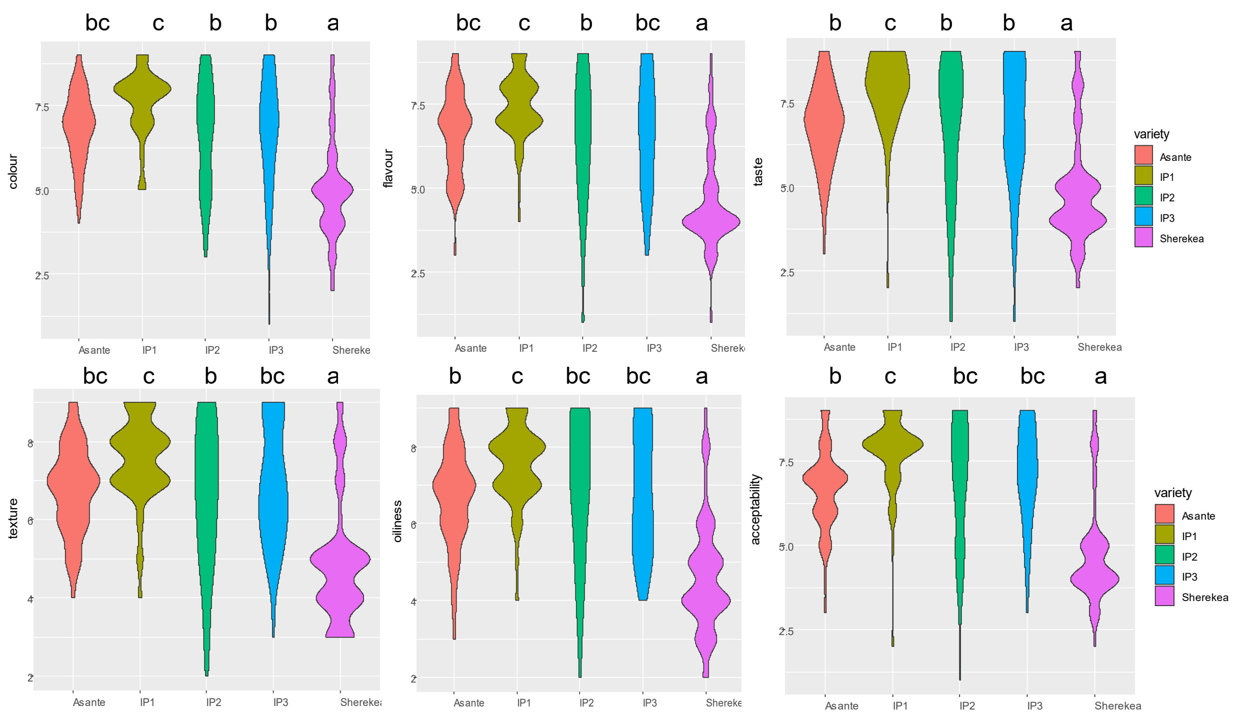

Fig. 2. Violin plots showing the sensory evaluation of products made from the tuber varieties
Plots with different superscript letters are significantly different at $p<0.05$, as assessed by Tukey's HSD.

physicochemical properties, such as colour, starch content, lipids, sugar contents, and amino acids (Ndungutse *et al*., 2019). High amounts of starch and lipids contribute to the French fries' flavour and result in products with a good texture. Higher scores recorded for the flavour of the daughter tubers could be due to the presence of a relatively higher concentration of amino acids, such as glutamate, which is known to contribute positively to desirable flavours in fried products (McKenzie & Corrigan, 2016).

However, high amounts of proteins and sugar content might produce darkened fried products when tubers are exposed to high temperatures, rendering them undesirable and unappealing to consumers (Ooko, 2008). Reducing sugars in Irish potatoes plays a vital role in determining the taste of fried tuber products, but low amounts of these sugars are preferred to increase consumer acceptability (Johnson *et al*., 2019). Based on the current findings, the French fries produced had both desirable taste and appealing colours to the panellists; hence, the tubers used had the right amounts of reducing sugars and protein composition suitable for the production of potato fried products. The study findings of superior sensory attributes for the daughter tubers could influence agricultural practices by shifting the focus towards cultivating these improved varieties for consumers' taste, appearance, and overall acceptability. Additionally, food processors and retailers might leverage these findings in tuber selection, potentially increasing and meeting the consumers' demands.

Correlation between sensory evaluation characteristics

A factor reduction method was used to determine the correlations between the sensory evaluation characteristics for the tuber varieties and their parents by reducing the variables into two components/dimensions, as shown in Figure 3. The first PCA dimension (taste, oiliness, texture and flavour) accounted for 81.3% of the total variations, while the second component (colour) accounted for 6.5%. The degree of representation for the attributes was high for the colour and taste of the French fries based on their square cosine values of above 0.90. Texture, flavour, and oiliness were strongly positively correlated, as represented by the angles between them on the biplot (less than 30°). All attributes (colour, texture, flavour, oiliness, and taste) strongly contributed to the liking of the French fries, as shown by the attribute values above 0.75 on the scale. Several studies have used PCA to explain the correlation between sensory evaluation attributes of food and to help determine the highly appreciated attributes of the sensory evaluation panellists. Principle component loading attributes close to each other are termed positively correlated; loadings separated by 180° are negatively correlated, whereas if separated by 90°, they are independent (Cañeque *et al*., 2004). From the current findings, all attribute loadings have angles less than 90°; hence, they are positively correlated.

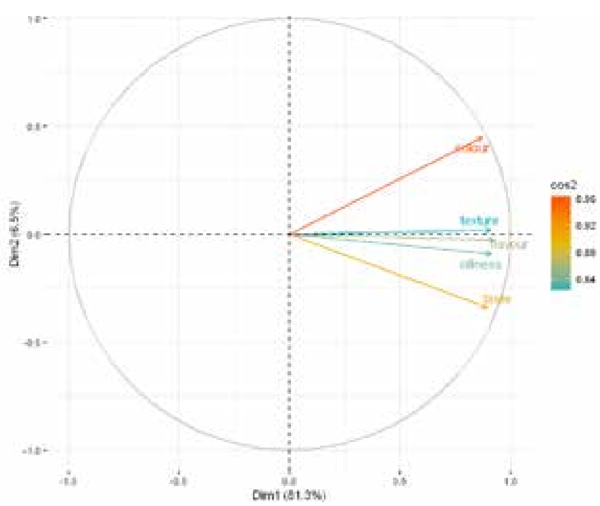

Fig. 3. Principal Component Analysis (PCA) biplot showing the correlation between sensory evaluation parameters.

A study by Ndungutse *et al*. (2019) reported two principle components that accounted for 80.3% of sensory attributes of French fries prepared from five Irish potato varieties. Concurrently, Mohapatra *et al*. (2007) noted 70% total variations in three principle components representing fermented sweet potatoes' sensory characteristics. According to Liu *et al*. (2003), principle component loadings are termed weak in representation when ranging between 0.3 and 0.5, moderate between 0.5 and 0.75, and strong when above 0.75. From the biplot generated, taste, oiliness, flavour, and texture loaded strongly (above 0.75) in the first PCA, as well as colour in the second PCA. Since the attributes (taste, oiliness, flavour, and texture) were loaded strongly in the same component, they are strongly correlated and directly contribute to the liking of the product; hence, priority should be given to these attributes during the processing of French fries to enhance acceptability by the consumers. The findings indicate that the tuber varieties used in the preparation of French fries had superior sensory characteristics (taste, oiliness, flavour, texture and colour) and could easily be adopted by potato processors for the production of fried products.

CONCLUSIONS

Gamma irradiation at a low dose of 15 Gy resulted in reduced values for lightness in skin and flesh colour of IP1 relative to its parent tuber, unlike the other tuber varieties that were done at a relatively high dose. However, the skin colour of IP2 and IP3 were darker than that of IP1; hence, consumers would easily select IP1 due to its bright colour. The flesh colour parameters (lightness and yellowness) of all tubers showed that they were relatively yellowish, making them easily applicable to processing fried potato products such as French fries and crisps.

Gamma irradiation was noted to significantly increase the flesh yellowness for IP2 and IP3 relative to the parent tuber, diversifying their applicability in preparing fried products and improving their selection criteria. The sensory characteristics of the French fries revealed that there was a significant increase in liking of colour, taste, texture, oiliness and overall acceptability of the products made from the daughter tubers relative to their parents, indicating that irradiation conferred better processing application to the daughter tubers. The PCA correlation also showed that the colour, texture, flavour, oiliness and taste of the prepared French fries were positively correlated, and all contributed positively to the overall liking of the French fries. Therefore, gamma irradiation might be proposed as a technique to generate Irish potato cultivars with improved processing characteristics for small-scale farmers, as most of them cannot afford to access the technology at the post-harvest stage.

DECLARATIONS

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DISCLOSURE STATEMENT

The authors declare no financial or non-financial interests directly or indirectly related to the article.

DATA AVAILABILITY

The data used to generate the findings in this study are available upon request from the corresponding author.

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IMPACT OF A LOCAL ORGANIC FERTILIZER ON POTATO GROWTH AND PRODUCTION AND SOIL PROPERTIES

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ABSTRACT: A local liquid organic fertilizer named SolOrga Ghbar containing beneficial microorganisms and essential elements for plant nutrition was used to evaluate its effect on potato growth and production in field conditions, as well as on soil properties. Different doses of organic fertilizer i.e 0, 50, 100, and 200 L/ ha were used at 100% plant emergence and tuber formation stages, along with a commercial imported organic fertilizer as a control. A statistically significant improvement in plant growth kinetics and yield was observed following application of SolOrga Ghbar organic fertilizer at all studied doses. By applying SolOrga Ghbar organic fertilizer, potato production was almost double when compared to non-biofertilized plants and 30 % increase in production when compared to commercial organic fertilizer. SolOrga Ghbar application resulted in a significant increase in potato tuber size, suggesting an enhanced efficiency of soil mineral utilization. In addition, the application of SolOrga Ghbar at all concentrations reduced the soil pH and increases the percentage of organic matter in the soil. Application of the local organic fertilizer resulted in increased potato yield and improved soil properties, potentially enhancing nutrient availability and soil structure for subsequent horticultural crops.

KEYWORDS: Organic fertilizers, Compost extract, Potato crop, Soil organic matter, Tuber size.

INTRODUCTION

Modern agriculture system is based on the use of chemical fertilizers to increase crop production. Although, these chemicals have significant positive impact on crop production but their excess of use leads to the accumulation of harmful residues in Agrofood products such as nitrate and heavy metals. Current agricultural trends demonstrate a shift towards the adoption of organic products as alternatives to chemical fertilizers, aiming to ensure consumer and environmental safety. Valorization of crop residues through a composting process for the production of organic fertilizers is of great importance for economic as well as environmental purposes.

The use of compost in agriculture is a well-known practice to enrich the soil with nutrients, organic matter and beneficial microorganisms, which contributes to increase agriculture production and resistance of plants to soil-borne pathogens (Ozores-Hampton *et al.*, 2022; Neher *et al.*, 2022). Thus, the use of compost reduces the application of chemical fertilizers and improves the resilience of the agrosystems. In the last decade, the use of compost products such as compost extracts are easier to use through drip irrigation system and showed rapid and positive effects on plant growth and production (Samuelson *et al.*, 2019). The compost extract is obtained by mixing mature compost with water, and stirring this mixture for a set period of time, which may or may not be aerated. This extract serves as a natural fertilizer, comprising organic matter, minerals, and a particularly high concentration of beneficial fungal and bacterial microorganisms. Compost extracts are proposed as biological inocula that

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promote plant growth, increase soil microbial abundance and diversity, suppress diseases, accelerate residue decomposition and nutrient cycling, and can suppress weeds (El-Masry *et al.,* 2002; Zinati, 2018).

In Africa, generally the organic fertilizers sector is underdeveloped, and the situation varies across the countries. The organic fertilizers market was estimated to 45.076 million US dollars in 2017 in Africa and is expected to grow by 5.9% annually during the forecast period 2020-2025 (Anonymous, 2022). In Tunisia, several organic fertilizers are marketed; however, the majority of them are imported mainly from European countries which are not particularly adapted to Tunisian pedoclimatic conditions. So, several Tunisian companies are moving toward the development of local organic fertilizers. A new local liquid organic fertilizer of plant origin named SolOrga Ghbar rich in beneficial microorganisms and macro- and micronutrients for plants was developed by Poulina Group Holding. In order to validate the benefits of this compost extract at a commercial scale, the objectives of this work were to evaluate its effect on the growth and production of a staple crop in Tunisia i.e. potato, as well as some soil properties through an on-farm research study.

MATERIAL AND METHODS

Plant material and culture conditions

The Spunta variety of potato was used in this study, which covers 80 % of cultivated potato areas in Tunisia. The potato seeds were acquired from the inter-professional group of vegetables in Tunisia and pre-germinated before planting. The planting was done on January 26th, 2022 in a clay-silt texture soil in the Takelsa region in Northeastern region of Tunisia (Fig. 1). The pre-germinated potato seed were planted with a spacing of 30 cm between the plants on the row and 85 cm between the rows. The test plot was about 0.5 ha divided into two blocks each containing all the treatments (Fig. 1). The fertilization of the plants was made by conventional chemical fertilizers based on NPK fertilization program with 313 units of nitrogen (N), 328 units of phosphorus (P_2O_5) and 262 units of potassium (K_2O) per hectare. The irrigation of the plants was done by the drip system according to the needs of the plants. The uniformity of the irrigation system coefficient was about 80 %.

SolOrga Ghbar properties, application and treatments

The organic fertilizer SolOrga Ghbar is an extract of plant debris compost rich in bacterial (10^5 CFU/mL of beneficial *Bacillus* spp.) and fungal microorganisms with a bio-stimulating effect on plant growth. SolOrga Ghbar, with an acidic pH of 5.5, provides essential plant nutrition through a composition of macronutrients (nitrogen 0.15% w/w, phosphorus 0.007% w/w, potassium 0.32% w/w, calcium 0.01% w/w, magnesium 0.0052% w/w) and micronutrients (iron, copper, manganese, zinc, molybdenum, boron), alongside 0.7% w/w humic acid. For plant fertilization, the SolOrga Ghbar product was applied through the drip system at two

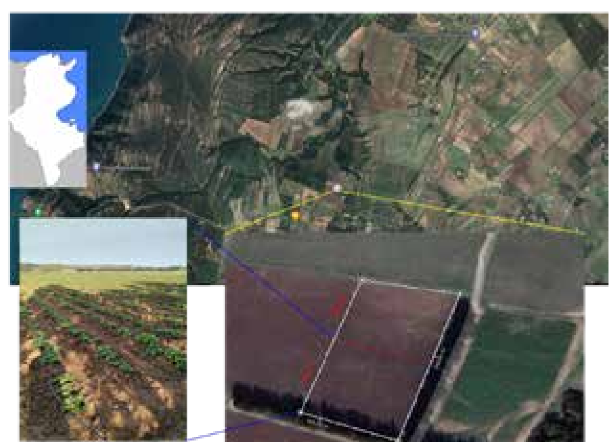

Fig. 1. Localization and experimental design of the essay of the organic fertilizer SolOrga Ghbar effect on potato crop in field conditions in the Takelsa region in Tunisia.

stages 100% emergence of potato plants and tuber formation. The SolOrga Ghbar product was applied at the doses of 50 L/ha (LDG50), 100 L/ha (LDG100) and 200 L/ha (LDG200). Plants receiving only the conventional chemical fertilization program without bio-fertilization were used as a control (LDG0). The imported liquid organic fertilizer of plant origin BioCAT15 containing 15 % w/w of humic-fulvic acids and 4.5 % w/w of potassium was used as a reference at 40 L/ha as recommended by the manufacturer.

Measured parameters on potato crop

Potato plant growth kinetics was monitored by measuring plant cover at three times corresponding to the initial state of potato culture (37 days after planting), 15 days after the first application (52 days after planting) and at tuber formation (67 days after planting) using the Canopeo application (Patrignani and Ochsner, 2015). The final production of the plants was estimated at 103 days after planting by uprooting the tubers from 4 rows of 48 m per treatment and per block. The total fresh weight, large size (Ø > 60mm), and small to medium size (35 mm > Ø >55 mm) tubers were measured at the final harvest using a commercial balance.

Soil parameters determination

The soil samples were taken from the upper 20 cm of the soil corresponding to the maximum root development area for potato plants. For the soil properties analyses of the pH, Electro-conductivity (µs/cm) and the percentage of organic matter were determined according to standard methods. For the determination of pH and electrical conductivity (EC), 200 g of dry and sifted soil were hydrated with distilled water gradually until a saturated paste was obtained. After 2 hours, the soil solution (extracted from the saturated paste) was recovered using a vacuum pump. The recovered solution was used to measure electrical conductivity using a conductivity meter and a pH meter. The determination of organic matter (OM) in agricultural soils was carried out by determining the organic carbon according to the Walkley-Black method which is based on the oxidation of organic carbon by potassium dichromate, $K_2Cr_2O_7$ (CAS: 7778-50-9) in a strongly acidic environment. 10 mL of the solution (1 N) of $K_2Cr_2O_7$ and 20 mL of concentrated sulfuric acid (96%) are added to 1 g of dry, sifted soil. Stir solution for 1 min and leave to rest for 30 min. Then add 200 mL of distilled water, 10 mL of orthophosphoric acid (85%), H_3PO_4 (CAS: 7664-38-2) and 1 mL of barium diphenylamine sulfonate indicator solution (0.10% W/V) (CAS: 6211-24-10). The titration is then carried out with the ferrous sulfate solution (0.5 N), $FeSO_4 \bullet 7H_2O$ (CAS: 7782-63-0) until the indicator turns green. The percentage of carbon is calculated by the following equation. Thus, the percentage of OM is given by the following equation.

Statistical analyses

All statistical analyses were performed using R x 64 3.5.1 software and Mixed Linear Models (MLM) was implemented for analyses of variance. All data were tested for normality using a Shapiro-Wilk's test to assess homogeneity of variance. Multiple mean comparisons were performed using Tukey HSD test at α = 0.05.

RESULTS

Effect of SolOrga Ghbar on potato growth kinetics

The analysis of variance showed a significant effect of the treatments with the organic fertilizers on the area under the curve of vegetative growth kinetics (AUDPC) (Table 1). The comparison of means by the Tukey test at α = 0.05 showed that the potato plants treated with SolOrga Ghbar at the different studied doses i.e. 50, 100 and 200 L/ha had significantly higher plant cover compared to plants without bio-fertilization and to those which received the organic fertilizer BioCAT15 (Fig. 2).

Effect of SolOrga Ghbar on potato production

Effect on total tuber production

The analysis of variance showed a significant effect of the treatments with the organic fertilizers on the total yield of the potato crop (Table 2). The comparison of the means showed that potato plants treated with SolOrga Ghbar using the three doses have significantly higher yields in comparison to non bio-fertilized plants and those which received the commercial product BioCAT15 (Fig. 3). Application of SolOrga Ghbar at 50 L/ha significantly increased potato tuber yield, achieving 43.28 t/ha, compared to 21.70 t/ha for the control. Yields of 42.81 t/ha and 46.41 t/ha were recorded for applications of 100 L/ha and 200 L/ha, respectively. BioCAT15 resulted in a

Table 1. Analysis of the variance of the area under the progression curve of potato plant cover. Potato plants were treated or not with different doses of a local (SolOrga Ghbar) and imported (BioCAT15) biofertilizers.

	Sum Sq	df	F value	Pr(>F)
Treatment	0.027352	4	2.5806	0.04213*

R significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 2. Analysis of variance of the total yield of potato crop. Potato plants were treated or not with different doses of a local (SolOrga Ghbar) and imported (BioCAT15) biofertilizers.

	Sum Sq	df	F value	Pr(>F)
treatment	1642.79	4	53.319	1.086e-08***

R significance codes 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

yield of 33.02 t/ha (Fig. 3). Notably, SolOrga Ghbar exhibited no adverse effects on potato development throughout the growth cycle, even at the highest application rate (200 L/ha).

Effect on the tuber size

The analysis of variance showed a significant effect of the treatments with

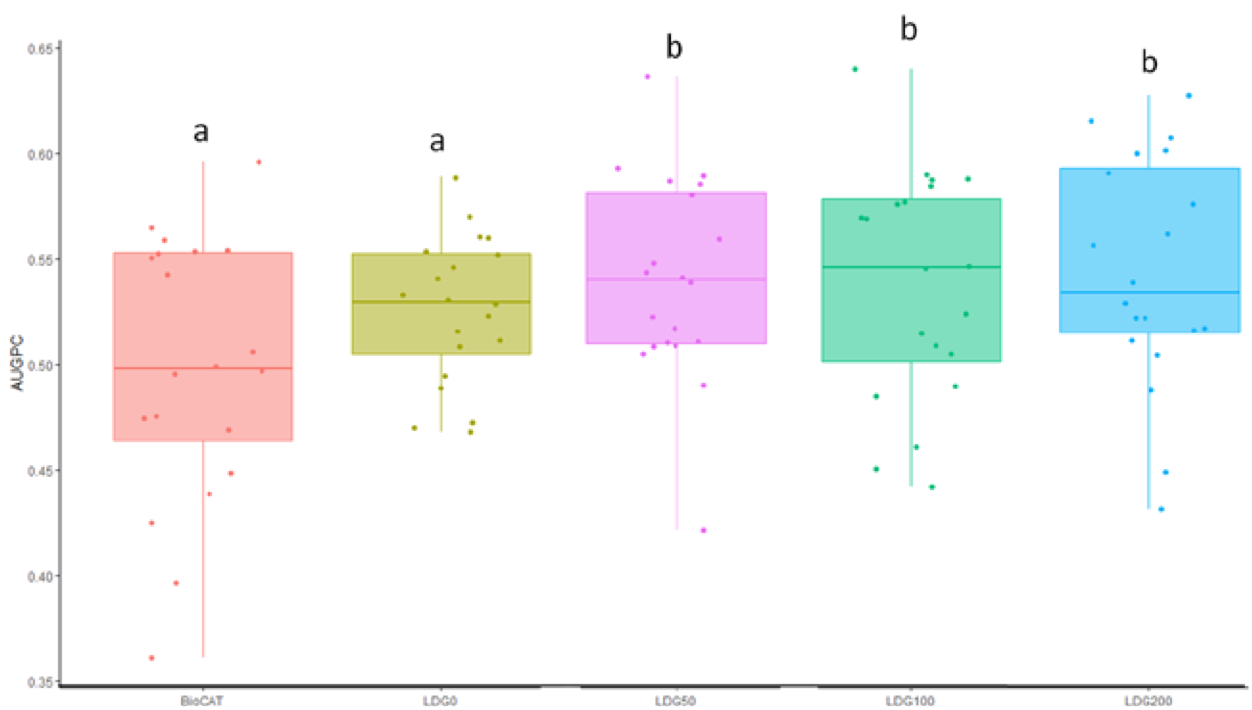

Fig. 2. Effect of the organic fertilizer SolOrga Ghbar on the area under the growth progression curve (AUGPC) of potato plants cv. Spunta.

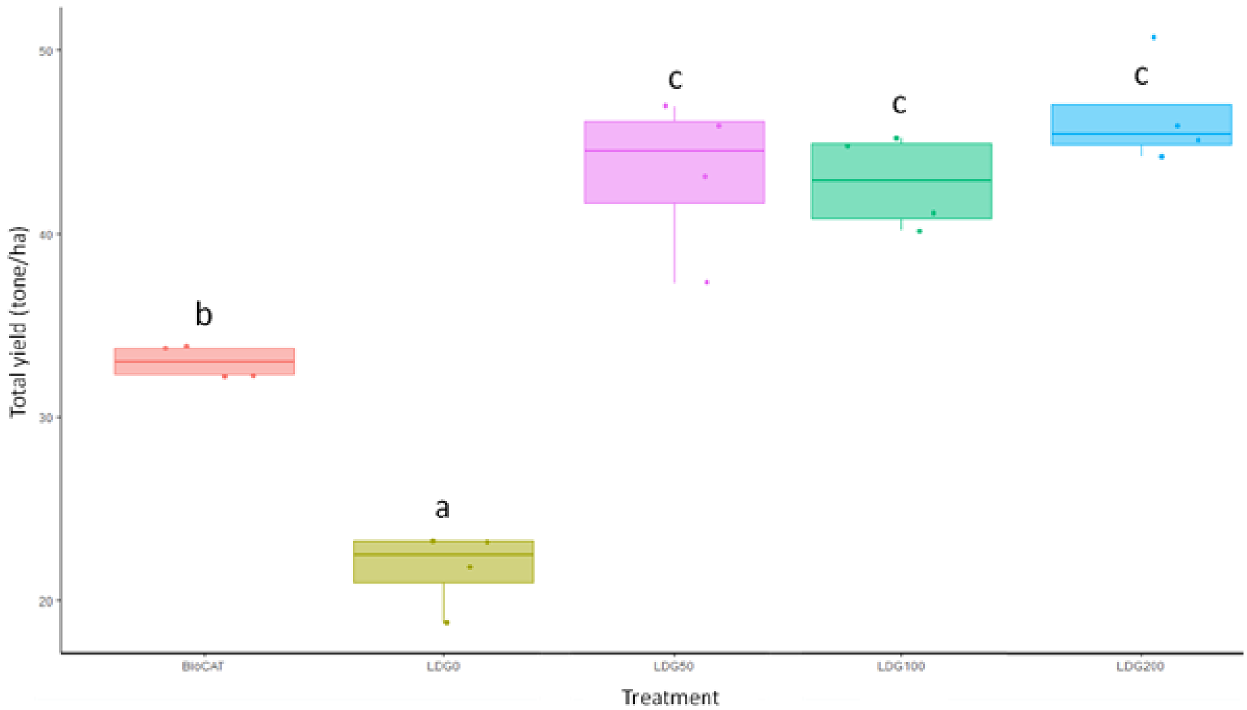

Fig. 3. Effect of the organic fertilizer SolOrga Ghbar on the total yield of potato plants cv. Spunta.

the organic fertilizers on the percentage of small-medium and large size tubers of potato crop (Table 3). The comparison of means showed that control potato plants produced significantly more small-medium size tubers in comparison to plants treated either by the local SolOrga Ghbar and the imported BioCAT15 organic fertilizers (Fig. 4). In general, the fertilization with SolOrga Ghbar and BioCAT15 organic fertilizers improved the percentage of large size tubers compared to the control plants (Fig. 5). Potato plants treated with SolOrga Ghbar at 100 L/ha and 200 L/ha exhibited the highest percentage of large-sized tubers compared to all other treatments (Fig. 5).

Effect of SolOrga Ghbar on soil properties

The results of the soil analysis after potato harvest showed that the two organic fertilizers used SolOrga Ghbar and BioCAT15 reduced the pH of the soil with the lowest values obtained for the treatments 100 L/ha and 200 L/ha of SolOrga Ghbar (Table 4). SolOrga Ghbar product at given doses also reduces EC of Soil when compared to control (Table 4). The analysis of the percentage of organic matter in the soils showed that the two organic fertilizers increased this parameter compared to the control with superiority for BioCAT15 which is a product

Table 3. Analysis of the variance of the percentage of small-medium and large size tubers in the potato crop. Potato plants were treated or not with different doses of a local (SolOrga Ghbar) and imported (BioCAT15) biofertilizers.

	Sum Sq	df	F value	Pr(>F)
Effect of treatment on the percentage of tubers of small to medium size	724.32	4	12.726	0.0001026***
Effect of treatment on the percentage of large size tubers	329.82	4	5.8016	0.005005**

R significance codes 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

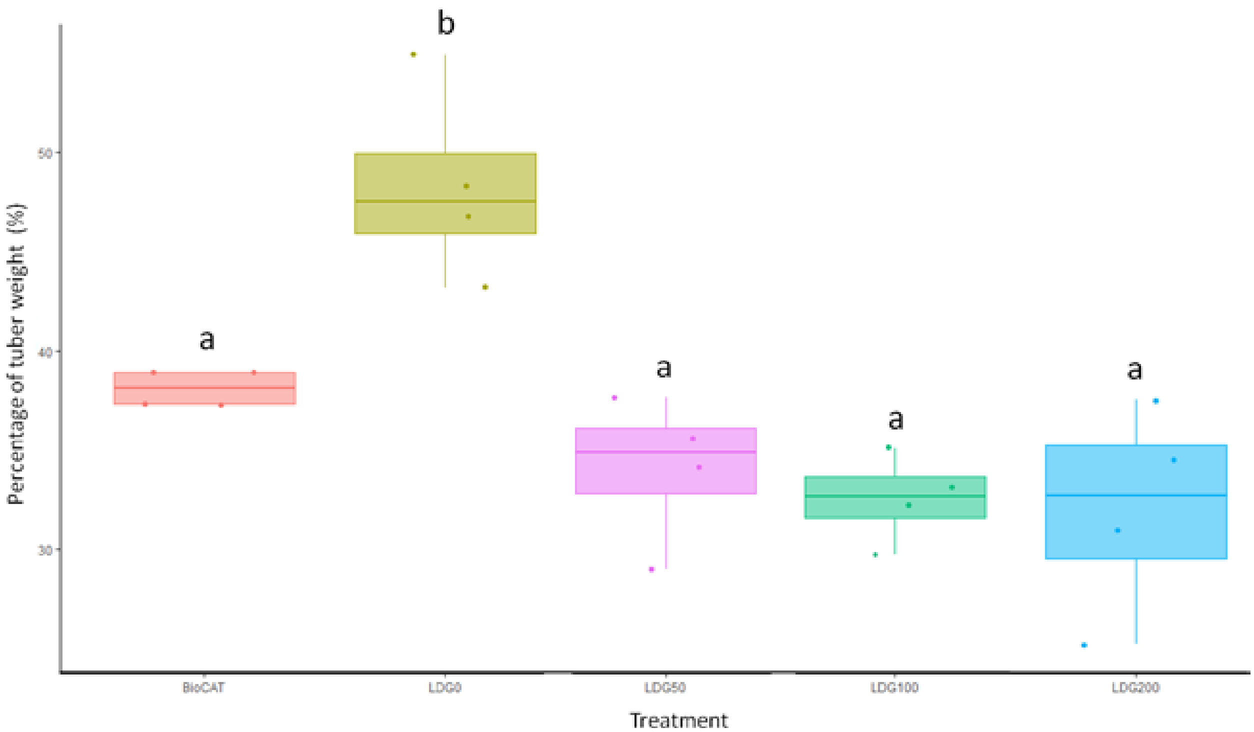

Figure 4. Effect of the organic fertilizer SolOrga Ghbar on the percentage of small-medium size tubers produced by potato plants cv. Spunta.

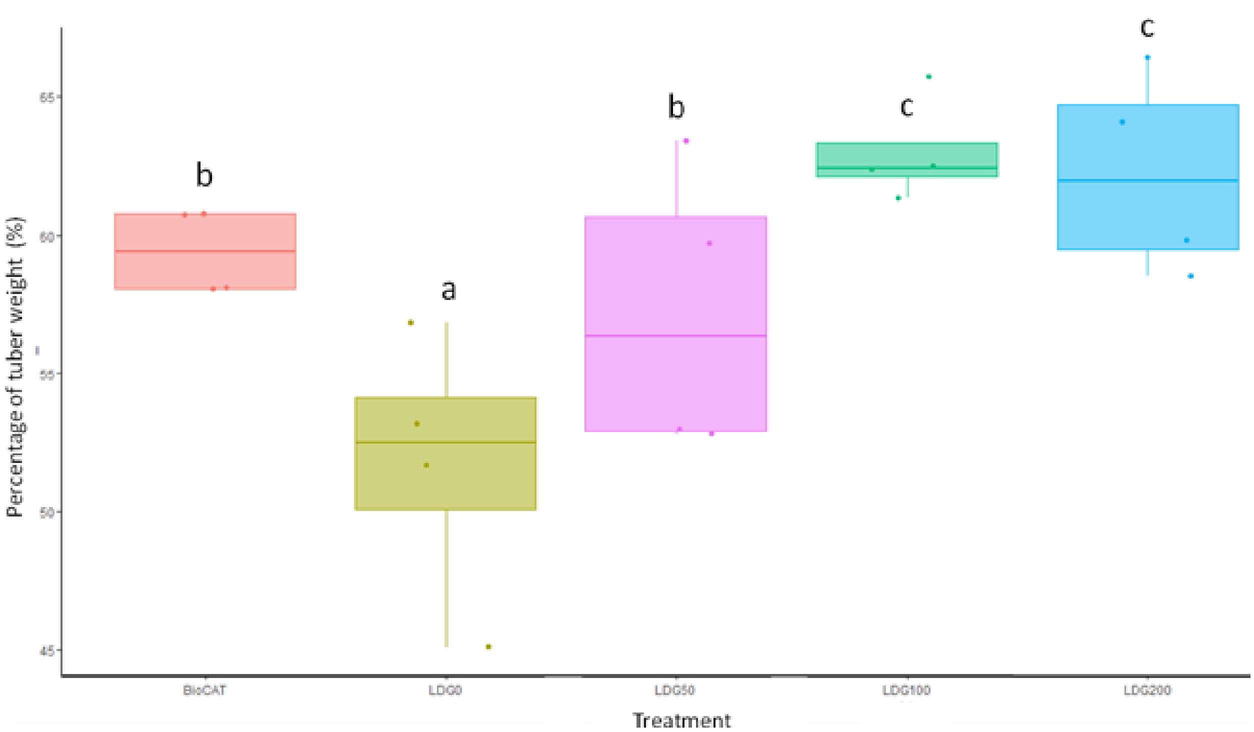

Figure 5. Effect of the organic fertilizer SolOrga Ghbar on the percentage of large size tubers produced by potato plants cv. Spunta.

Table 4. Effect of the SolOrga Ghbar biofertilizer on soil properties.

Treatment	Soil properties		
	pH	Electroconductivity (μs/cm)	Organic matter (%)
LDG0	8.26	79.2	3.80
LDG50	7.90	67.5*	5.20*
LDG100	7.60	59.7*	5.30*
LDG200	7.26	66.4*	7.80*
BioCAT15	7.99	78.7	8.70*

R significance codes 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

with high content (15%) in humic-fulvic acids (Table 4).

DISCUSSION

The intensive agricultural production system based on the exclusive use of chemical fertilizers is more than ever questioned because of its negative repercussions on human health, the environment, and the accentuation of climate change. For this reason most countries in the world claim to include agriculture in their potential climate change mitigation options. Thus, to adapt and improve its resilience, while reducing its impact on the climate, agriculture can rely on the principles of agro-ecology. The concept of agro-ecology is based on the optimization of biological regulation processes, the economical management of natural resources and the recycling of nutrients aimed at ensuring sustainable agricultural production, healthy and diversified nutrition. The agro-ecological transition of agriculture can be based on solutions of a technical nature which consist in mobilizing functional biodiversity to improve the performance of cropping systems. The use of organic fertilizers from which composts and their extracts fit within this scope, which make possible to reduce the use of chemical fertilizers and even naturally regulate the attacks of bio-aggressors reducing also the use of pesticides and thus reduces the risk of environmental pollution.

Fortunately, developed countries are moving toward the regulation of the use of chemical agro-products and encourage the production and use of biopesticides and organic fertilizers through the revision of their national policy. Generally, the organic fertilizer production sector is underdeveloped in Africa, and the situation varies across countries and regions, depending on the status of ecological organic agriculture policy, and government support (Willer *et al.*, 2022). In Tunisia the organic fertilizers are increasingly available in the market due to the development of the organic agriculture sector, but they are mainly imported from European countries. However, many research studies showed that indigenous microorganisms based organic fertilizers were more adapted to local pedoclimatic conditions in comparison to foreign products made from allochthonous microbial strains (Mhadhbi *et al.*, 2009; Ferchichi *et al.*, 2019; Ben Romdhane *et al.*, 2022). Thus, several research laboratories and private companies are moving toward the development of local organic fertilizers to ensure efficiency in the field to meet farmer's expectations. So, the objective of this study was to evaluate the performance of a novel liquid local organic fertilizer named SolOrga Ghbar developed by Poulina Company on the growth and production of potato, as well as on some soil properties.

This study showed that SolOrga Ghbar increased the growth of potato plants following its application at two stages of 100 % plant emergence and at tuber formation at the doses of 50, 100 and 200 L/ha. By applying this local organic fertilizer, the potato yield increased by 2-folds in comparison to the control and by 30 % in comparison to the imported organic fertilizers BioCAT15 used as a reference. This yield improvement was in part due to the increase of the percentage of large tubers produced by potato plants treated with

SolOrga Ghbar. This result shows that SolOrga Ghbar treated plants produced appropriate commercial tuber size when compared to non-biofertilized plants which indicate an increase in precocity of production when using this local organic fertilizer. This observed beneficial effect may be attributed to the product's high content of plant growth-promoting and biocontrol microorganisms, including bacteria (Bacillus spp.) and fungi (Ben Slimene *et al.*, 2012; Metoui-Ben Mahmoud *et al.,* 2020; Ayed *et al.,* 2021; Sharma *et al.,* 2022).

Soil pH, electroconductivity and organic matter contents influence crop growth and yield, because they determine nutrients availability for plants. The local organic fertilizer SolOrga Ghbar improves the quality of the soil by lowering the pH of the soil, reducing its conductivity and increasing its organic matter content. Indeed, soil pH affects nutrient solubility of nutrients and microbial activity in particular the activity of nitrogen fixing microbes, as well as a direct effect on root cells multiplication which determine plant growth and development (Marschner, 1986; Neina, 2019). The soil electroconductivity is correlated to its salinity level which directly influences crop growth and development. The soil organic matter consists of organism's debris at various stages of decomposition, as well as their synthesized substances which provide numerous benefits to soil physical and chemical properties determining soil functions and quality (Beare *et al.,* 1994).

CONCLUSION

In conclusion, this study demonstrated that SolOrga Ghbar, a local organic fertilizer, outperformed the imported BioCAT15 (at its recommended dose) in enhancing potato growth and yield when applied at 50 L/ha during 100% plant emergence and tuber formation stages. By applying SolOrga Ghbar the average yield registered was about 44 tones/ha, showing an increase by 2-folds and 30 % in comparison to the control and BioCAT15, respectively. The significant effect of SolOrga Ghbar on increasing tuber size supports the hypothesis of its beneficial effect on the precocity of production. In addition, soil analyses showed that SolOrga Ghbar decreases the pH, and electroconductivity and increased organic matter content which improves soil properties.

AUTHOR CONTRIBUTIONS:

BK and AS: conducted the experiments. ND analyzed the data. ND and BK: interpreted the results. ND: wrote and corrected the paper. ND, SRJ and RZ: supervised the work. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

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

ETHICAL STATEMENT

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

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EFFECT OF DIFFERENT IRRIGATION FREQUENCIES AND METHODS ON PERFORMANCE OF POTATO IN NORTH-EASTERN GHATS OF ODISHA

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ABSTRACT: An experiment was conducted at CUTM, Odisha to evaluate the influence of different irrigation frequencies and methods on performance of potato. The experiment was designed in strip plot design with 4 irrigation frequencies and 3 irrigation methods together, replicated thrice. The significantly higher LAI at 60 DAP, haulm dry weight at 60 and 86 DAP, chlorophyll total at 60 and 75 DAP were recorded with 20 mm ET_c than all other irrigation frequencies. In case of irrigation methods, every furrow irrigation (EFI) showed significantly higher LAI at 60 DAP, dry weight of tubers at 86 DAP, arithmetic and geometric mean diameter of grade A tubers, chlorophyll total content at 60 and 75 DAP than all others. The maximum tuber yield was recorded with 20 mm ET_c which was statistically *at par* with 30 mm ET_c. But highest starch content was recorded under 30 mm ET_c and it was significantly decreased at 20 mm ET_c due to plenty of soil moisture under this treatment. Starch content was also decreased significantly under EFI than AFI due to the same fact. The tuber yield obtained under EFI was statistically *at par* with alternate furrow irrigation (AFI). According to the linear regression, proportionate tuber yield increase will be higher with decrease in the irrigation water use efficiency. The treatment combination, 20 mm ET_c-EFI showed highest gross return, net return and B:C which could be recommended for the potato growers in north-eastern ghats of Odisha. This was closely followed by the treatment combination, 30 mm ET_c-EFI or 20 mm ET_c-AFI and could also be adopted as a remunerative technique in the areas having water crisis.

KEYWORDS: Irrigation frequency; irrigation method; potato; water use efficiency; yield

INTRODUCTION

Potato (*Solanum tuberosum* L.) is the fourth largest food crop in the world followed by rice, wheat, and maize. This crop is acting as high-quality food with rich, comprehensive and balanced nutrition (FAO, 2022). In India, the area under cultivation of potato was 2.20 million hectares, production is 56.17 million tonnes along with an average yield of 25.50 t ha^{-1} during the year, 2022 (Govt. of India, 2022). Odisha contributed around 0.50% of national potato area and 0.21% of national potato production along with the potato productivity of 10.62 t ha^{-1} (APC, 2021-22). The world's largest consumption of water sources is mainly interlinked with food crop production by utilizing irrigation water (Wahyuningsih *et al.*, 2021). One of the major technological constraints in potato cultivation is lack of assured source of irrigation (Nand and Kokate, 1990) and an economic constraint in adoption of potato cultivation technology is high irrigation cost (Lal *et al.*, 2011), which can be curtail by reducing the no. of irrigations. In this regard, (Shekhawat, 2001) has opined that potato cultivation would be a possible alternative to enhance the farm income, if efficient and reliable irrigation management strategies are adopted. Partial

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root zone drying (PRD) irrigation technique is an imperative strategy of conserving water and from the last 10 years, is highly adopted for agricultural crops to increase water productivity in crops in water scarce areas. PRD is a more efficient technique than deficit irrigation (DI) and can save agricultural water about 50% without showing decrement in production and enhance the quality of the produce as compared to conventional and deficit irrigation (Iqbal *et al.*, 2020). PRD induce new roots as a consequence of alternate drying and rewetting cycle, these newer roots increase hydraulic conductance (Kang *et al.*, 2000; Kang *et al.*, 2003). Alternate furrow irrigation (AFI) is a PRD technique (Sepaskhah and Kheradnam, 1977). Generally, irrigated furrows are alternated at every irrigation operation under AFI. If irrigated furrows are fixed by following permanent skip furrow irrigation (PSFI), more water may be saved by minimizing the wetting area and salts may accumulate on the dry side of the ridge (Onishi *et al.*, 2021).

Duration of alternating wet and dry sides has its own impact on the absorption of water. More than three days alternation drying of the soil can increase water absorption (Dodd *et al.*, 2006). Potato is a short-duration crop and sensitive to water stress because of its shallow root depth and distribution of around 85% of potato roots in the upper 30 cm of top soil (Dalla Costa *et al.*, 1997; Onder *et al.*, 2005; Ahmadi *et al.*, 2011; Gitari *et al.*, 2018a, b). Potato responds well to favorable amounts of soil moisture in excess or in case of deficit conditions decreasing crop productivity. Hence, by adopting the irrigation scheduling strategies, we can enhance the production of potatoes throughout the growing period (Kashyap and Panda, 2003), understanding its pattern of root uptake, water movement in the soil and evapotranspiration of crop (ET_c) which is essential to design the scheduling of irrigation for the crop (Shankar *et al.*, 2009; Kumar *et al.*, 2013; Satchithanantham *et al.*, 2014; Paredes *et al.*, 2018). To enhance crop productivity while conserving resources at the same time, it has to support the need for more crops per drop of water (Mukherjee *et al.*, 2010). By combining the irrigation frequencies with methods, the number of irrigations to the crop can be minimized and the water use efficiency can be increased with the achievement of satisfactory tuber yield.

MATERIALS AND METHODS

Experimental site and design

The field experiment was performed at Post Graduate Research Farm of M. S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha during *Rabi*, 2023-24. The field was situated at 18°48' N latitude, 84°10' E longitude and altitude of 90 m above mean sea level. The crop received rainfall of 35.35 mm during the growing period, 90% of that was considered as effective rainfall (31.8 mm) as per U.S. Bureau of Reclamation method (Ali and Mubarak, 2017). The experimental soil was sandy loam in texture having pH 6.1, organic carbon 0.41% and initial soil status of available nitrogen, phosphorus, and potassium values were 240.4, 14, and 141 kg ha^{-1}, respectively. The experiment was designed in strip plot design with the treatments consisted of four irrigation frequencies at 20 mm ET_C, 30 mm ET_C, 40 mm ET_C and 50 mm ET_C as 1st factor and three different irrigation methods *i.e.*, every furrow irrigation (EFI) where all the furrows kept wetted, alternate furrow irrigation (AFI) where alternate furrows being wetted every time and permanent skip furrow irrigation (PSFI) by fixing the wetting furrows permanently, were taken as 2nd factor. In each occasion, 30 mm irrigation water was applied. The crop was planted on 4th November, 2023.

The crop was planted at row to row spacing of 60 cm and plant to plant spacing of 20 cm and net plot size was 6.6 × 3.0 m^2.

Potato variety and fertilizer rate

The potato variety was used in this experiment was "Kufri Jyoti" which was of 90-110 days duration. Recommended dose of fertilizer was 120:60:120 kg ha^{-1} N: P_2O_5: K_2O which was given through urea, single super phosphate (SSP) and muriate of potash (MOP), respectively.

Chlorophyll and SPAD meter reading

Chlorophyll total was determined at 60 and 75 DAP by the formula (Pérez-Patricio *et al.,* 2018):

Chlorophyll total (mg g^{-1}) = (8.2 × A663) + (20.2 × A645)

Where, A663 and A645 were the absorbance value measured from 663 nm and 645 nm wavelength, respectively. The Spectrophotometer was adjusted to zero using the acetone mixture.

For measurement of relative chlorophyll content from leaf handheld Chlorophyll Meter SPAD 502 was used to obtain readings estimating chlorophyll concentration on the fourth or fifth leaf down from the top of the plant at 60 and 75 DAP. The SPAD reading of potato leaf was recorded at three locations: (a) about one-third of the leaf length from the petiole, (b) at the midpoint of leaf, and (c) about one-third of the leaf length from the apex (Lin *et al.*, 2010). Ten readings from each plot, were taken and averaged.

Tuber diameters

To find the mean size of potato tubers, three linear dimensions *i.e.*, length (L, mm), width (W, mm) and thickness (T, mm) were measured. The geometric mean diameter (mm) and the arithmetic mean diameter were calculated as follows (Arfa, 2007; Elbatawi *et al.*, 2008; Abd Elhay, 2017):

Geometric mean diameter (mm) = $\sqrt[3]{L \times W \times T}$

Arithmetic mean diameter (mm) = $\frac{L+W+T}{3}$

All these dimensions were measured in a medium at room temperature (25°C).

Starch content

To measure the starch content, a fresh potato sample of 0.5 g was taken and the method mentioned by Mondal *et al.* (2021) was followed.

Soil moisture study

Soil samples were taken just before irrigation and 48 hours after irrigation from 0-20 and 20-40 cm depth with the help of the screw soil auger. Soil moisture from two different soil layers was calculated on oven dry weight basis as per the method mentioned by Singha *et al.* (2018).

The profile contribution of soil moisture was determined with the help of change of moisture status between sowing and harvesting of the crop (Qiu *et al.*, 2001). Bulk density of soil was 1.43 g cm^{-3} at 0-20 cm soil layer and 1.48 g cm^{-3} at 20-40 cm soil layer.

Total water use or actual evapotranspiration (AET or ET_c) was calculated as per soil water balance equation (Yang *et al.*, 2023):

AET (mm) = Total applied irrigation water (mm) + Effective rainfall (mm) + Soil profile contribution (mm)

Here, total impact of contribution of capillary rise and drainage was considered negligible.

Water use efficiency (WUE) = Y/AET; Irrigation use efficiency (IUE) = Y/Total amt. of irrigation

In both the cases, Y was calculated by considering the average of tuber yield and irrigation water yield. Finally, Y was converted in kg ha^{-1}. WUE and IUE were expressed in kg m^{-3}.

$WUE_{ET} = Y_i - Y_{I12}/I_i\text{-}I_{I12}$; $WUE_I = Y_i - Y_{I12}/$ Total irrigation amount

Where, Y_i was the yield (kg ha^{-1}) of ith treatment combination, Ii was the amount of irrigation (mm) applied under ith treatment combination, Y_{I12} was the yield (kg ha^{-1}) of 12th treatment combination; I_{I12} was the irrigation amount (mm) of 12th treatment combination.

The irrigation dates and ET_c values at each irrigation was calculated (Gonzalez *et al.*, 2023) in Table 1:

Statistical analyses

All the data on growth parameters were taken periodically, yield attributing parameters and yield were taken at harvest and analyzed statistically at 5 per cent level of significance.

RESULTS AND DISCUSSION

Growth parameters of potato plants

The plant height, no. of shoots plant^{-1} and no. of leaves plant^{-1} at 86 DAP, leaf area index (LAI) at 60 DAP, dry weight of haulm at 60 and 86 DAP were significantly influenced by irrigation frequencies and methods (Table 1). At 86 DAP, highest plant height (71.2 cm), no. of shoots plant^{-1} (15.19) and no. of leaves plant^{-1} (47.70) were recorded 20 mm ET_c. Similarly, this treatment attained maximum LAI (3.50) at 60 DAP and haulm dry weight at 60 (236.09 g m^{-2}) and 86 DAP (515.88 g m^{-2}). There was no significant variation in no. of shoots plant^{-1} obtained under 20 and 30 mm ET_c. Previous report of Kumar *et al.* (2007) was in line with the results obtained for the no. of shoots plant^{-1}. Haulm dry weights were significantly increased under higher soil moisture regimes (Irfan *et al.*, 2015). This might be due to production of a greater no. of haulms, leaves and taller plants which ultimately increased plant weight (Yadav *et al.*, 2003). The higher soil moisture regime has encouraged stolonization during the entire growing period. These stolons being unable to go deep in the soil in order to develop a tuber and have become the haulms (Irfan *et al.*, 2015). But the height of plants (70.2 cm) and no. of shoots plant^{-1} (14.76) at 86 DAP obtained under 30 mm ET_c were statistically *at par* with 20 mm ET_c. That was might be due to the availability

Table 1. Details of crop evapotranspiration (AET or ET_c) based on irrigation frequencies.

Irrigation was given when ET_c value reached to							
20 mm (F_1)		30 mm (F_2)		40 mm (F_3)		50 mm (F_4)	
Date	ET_c (mm)	Date	ET_c (mm)	Date	ET_c (mm)	Date	ET_c (mm)
30/11/2023	18.52	03/12/2023	30.59	08/12/2023	39.79	11/12/2023	50.03
08/12/2023	21.28	14/12/2023	30.71	19/12/2023	39.33	28/12/2023	49.50
13/12/2023	21.51	24/12/2023	29.45	06/01/2024	39.68	23/01/2024	50.22
19/12/2023	21.51	07/01/2024	30.60	29/01/2024	39.83		
28/12/2023	20.40	24/01/2024	29.48				
06/01/2024	19.28						
16/01/2024	20.09						
29/01/2024	19.74						
Total irrigation	240 mm		150 mm		120 mm		90 mm

*Crop coefficients (k_c) were taken from FAO K_c values of potato (Chapter 6 - ET_c - Single crop coefficient); Satisfactory plant emergence was noted down on 24th November, 2023 *i.e.*, 20 DAP.

of optimum soil moisture under 20 and 30 mm ET_c treatments during the crop growing period. Patel and Patel (2001); Kumar *et al.* (2007); Dash *et al.* (2018) also observed similar decreasing trend of plant height with lowering irrigation frequencies. At 30 DAP, LAI was non-significantly varied among irrigation frequencies and methods because ET_c based irrigation was not started at 30 DAP. The lowest values were obtained for plant height (65.3 cm), no. of shoots plant^{-1} (13.21) and no. of leaves plant^{-1} (42.74) at 86 DAP, LAI (3.00) at 60, haulm dry weight at 60 and 86 DAP (187.27 and 412.94 g m^{-2}, respectively) with irrigation at 50 mm ET_c. But all these data were statistically *at par* with 40 mm ET_c. Significant decrease in LAI at 80 DAP with decreasing irrigation frequency had been reported by Tyagi *et al.* (2012). Significant increase in dry weight of haulm with higher irrigation frequencies was also reported previously by Panigrahi *et al.* (2001). These were mainly due to amplifying effect of irrigation frequency on irrigation depth (Demelash, 2013). The no. of plants m^{-2} at 86 DAP was not varied significantly due to various irrigation frequencies.

In case of irrigation methods, the tallest plants (71.4 cm) with higher no. of shoots plant^{-1} (14.86) and no. of leaves plant^{-1} (46.80) at 86 DAP, LAI (3.41) at 60, haulm dry weight at 60 (221.67 g m^{-2}) and 86 DAP (472.58 g m^{-2}) were recorded with EFI method. But the plant height (69.3 cm), no. of shoots plant^{-1} (14.33) and no. of leaves plant^{-1} (45.05) at 86 DAP, dry weight of haulm at 60 (203.78 g m^{-2}) and 86 DAP (460.82 g m^{-2}) recorded under AFI were statistically *at par* with EFI. This finding strengthened the fact that crop growth of potato is not significantly hampered with shifting of irrigation method from EFI to AFI. LAI at 60 DAP obtained under EFI (3.41) was significantly higher than AFI (3.09). LAI of potato obtained under traditional furrow irrigation varied significantly with other methods in the earlier report of Amer *et al.* (2016). Similarly, no. of shoots plant^{-1} (13.73) at 86 DAP, no. of leaves plant^{-1} (42.68) at 86 DAP, LAI (3.08) at 60 DAP, dry weight

Table 1. Growth parameters of potato plants as influenced by irrigation frequencies combined with irrigation methods.

Treatments	Plant height at 86 DAP (cm)	No. of shoots plant^{-1} at 86 DAP	No. of leaves plant^{-1} at 86 DAP	LAI		Dry weight of haulm (g m^{-2})		No. of plants m^{-2} at 86 DAP
				30 DAP	60 DAP	60 DAP	86 DAP	
Irrigation frequencies								
20 mm ET_c (F_1)	71.2	15.19	47.70	0.53	3.50	236.09	515.88	10.9
30 mm ET_c (F_2)	70.2	14.76	45.33	0.46	3.22	210.48	478.47	11.2
40 mm ET_c (F_3)	67.7	14.07	43.39	0.39	3.06	194.69	430.52	11.2
50 mm ET_c (F_4)	65.3	13.21	42.74	0.36	3.00	187.27	412.94	10.7
S.Em. (±)	0.83	0.15	0.63	0.05	0.06	2.30	5.96	0.58
C.D. (P=0.05)	3.3	0.51	2.19	NS	0.22	7.95	20.61	NS
Methods of Irrigation								
EFI (M_1)	71.4	14.86	46.80	0.46	3.41	221.67	472.58	11.3
AFI (M_2)	69.3	14.33	45.05	0.43	3.09	203.78	460.82	10.8
PSFI (M_3)	65.1	13.73	42.68	0.42	3.08	195.95	444.97	10.8
S.Em. (±)	1.04	0.28	0.93	0.03	0.05	5.25	5.79	0.53
C.D. (P=0.05)	3.6	1.11	3.24	NS	0.18	18.56	20.34	NS

*Dehaulming was done at 86 DAP

of haulm at 60 DAP (195.95 g m^{-2}) and 86 DAP (444.97 g m^{-2}) recorded with PFSI were significantly lower than EFI. The no. of plants m^{-2} at 86 DAP was not varied significantly due to various irrigation methods.

Growth parameters of potato tubers

The fresh weight of tubers at 45, 60 and 75 DAP, dry weight of tubers at 60 and 86 DAP were varied significantly under different irrigation frequencies and methods (Table 2). Maximum tuber fresh weight at 45 (540.93 g m^{-2}), 60 (1090.71 g m^{-2}) and 75 DAP (1770.50 g m^{-2}) and tuber dry weight at 60 (221.44 g m^{-2}) and 86 DAP (550.83 g m^{-2}) were recorded under 20 mm ET_c. But the fresh weight of tubers at 45 (515.65 g m^{-2}), 60 (1029.23 g m^{-2}) and 75 DAP (1669.35 g m^{-2}) and dry weight of tubers at 60 (217.10 g m^{-2}) and 86 DAP (540.05 g m^{-2}) obtained under 30 mm ET_c were statistically *at par* with 20 mm ET_c. This was might be due to the availability of optimum soil moisture under 20 and 30 mm ET_c during the period of tuber bulking and growth. The lowest tuber fresh weights were obtained with the irrigation frequency of 50 mm ET_c at all the dates of observation (398.25, 860.95, 1476.85 g m^{-2} at 45, 60 and 75 DAP, respectively). But the results achieved at 60 (946.92 g m^{-2}) and 75 DAP (1577.69 g m^{-2}) under 40 mm ET_c were statistically *at par* with 50 mm ET_c. This result explored the chances of achieving statistically similar tuber yield under 40 and 50 mm ET_c.

In case of irrigation methods, the maximum tuber fresh weight at 45 (516.04 g m^{-2}), 60 (1006.10 g m^{-2}) and 75 DAP (1753.12 g m^{-2}), tuber dry weight at 60 (217.39 g m^{-2}) and 86 DAP (559.72 g m^{-2}) were recorded with EFI which were significantly higher than PSFI (445.42. 949.29, 1511.38 g m^{-2} of tuber fresh weight at 45, 60 and 75 DAP; 188.76 and 514.22 g m^{-2} of tuber dry weight at 60 and 86 DAP). These results corroborated the fact that the tuber yield of potato significantly reduces when PSFI method is followed instead of EFI.

Chlorophyll total and SPAD reading

The chlorophyll total and SPAD values at 60 and 75 DAP were significantly influenced by irrigation frequencies and methods

Table 2. Growth parameters of potato tubers as influenced by irrigation frequencies combined with irrigation methods.

Treatments	Fresh weight of tubers (g m^{-2})			Dry weight of tubers (g m^{-2})	
	45 DAP	60 DAP	75 DAP	60 DAP	86 DAP
Irrigation frequencies					
20 mm ET_c (F_1)	540.93	1090.71	1770.50	221.44	550.83
30 mm ET_c (F_2)	515.65	1029.23	1669.35	217.10	540.05
40 mm ET_c (F_3)	464.63	946.92	1577.69	206.67	536.66
50 mm ET_c (F_4)	398.25	860.95	1476.85	177.43	507.93
S.Em. (±)	9.86	29.36	33.35	2.53	5.90
C.D. (P=0.05)	34.13	101.58	115.41	8.75	20.42
Methods of Irrigation					
EFI (M_1)	516.04	1006.10	1753.12	217.39	559.72
AFI (M_2)	478.13	990.46	1606.30	210.83	527.66
PSFI (M_3)	445.42	949.29	1511.38	188.76	514.22
S.Em. (±)	12.71	15.80	52.91	3.65	8.14
C.D. (P=0.05)	42.91	55.55	187.75	12.78	28.49

*Dehaulming was done at 86 DAP

(Table 3). At 60 and 75 DAP, the significantly higher content of chlorophyll total (0.18 and 0.10 mg g^{-1} at 60 and 75 DAP, respectively) were recorded by 20 mm ET_c than all other irrigation frequencies. SPAD (39.49 and 37.97 at 60 and 75 DAP, respectively) on both dates were measured highest under 20 mm ET_c which was statistically *at par* with 30 mm ET_c (38.53 and 35.92 at 60 and 75 DAP, respectively).

Similarly, at 60 and 75 DAP, the significantly higher results of chlorophyll total (0.16 and 0.09 mg g^{-1} at 60 and 75 DAP, respectively) than all others were recorded under EFI. But in case of SPAD, the values obtained under EFI (39.17 and 36.99 at 60 and 75 DAP, respectively) were statistically *at par* with the SPAD values obtained under AFI (38.68 and 36.01 at 60 and 75 DAP, respectively) on both dates.

Table 3. Chlorophyll total and SPAD value of potato plants as influenced by irrigation frequencies combined with irrigation methods.

Treatments	Chlorophyll total ($mg\ g^{-1}$)		SPAD value	
	60 DAP	75 DAP	60 DAP	75 DAP
Irrigation frequencies				
20 mm ET_c (F_1)	0.18	0.10	39.49	37.97
30 mm ET_c (F_2)	0.16	0.07	38.53	35.92
40 mm ET_c (F_3)	0.14	0.05	38.03	36.33
50 mm ET_c (F_4)	0.12	0.04	37.30	33.35
S.Em. (±)	0.002	0.004	0.45	0.72
C.D. (p = 0.05)	0.007	0.013	1.44	2.48
Methods of irrigation				
EFI (M_1)	0.16	0.09	39.17	36.99
AFI (M_2)	0.15	0.06	38.68	36.01
PSFI (M_3)	0.14	0.05	37.16	34.67
S.Em. (±)	0.002	0.004	0.36	0.55
C.D. (p = 0.05)	0.007	0.013	1.28	1.83

Table 3A. Interaction effect of irrigation frequencies × irrigation methods on total chlorophyll content at 75 DAP.

Treatments	20 mm ET_c (F_1)	30 mm ET_c (F_2)	40 mm ET_c (F_3)	50 mm ET_c (F_4)	Mean
EFI (M_1)	0.14	0.10	0.05	0.05	0.09
AFI (M_2)	0.10	0.05	0.05	0.04	0.06
PSFI (M_3)	0.07	0.05	0.04	0.03	0.05
Mean	0.10	0.07	0.05	0.04	
S.Em. (±)			0.006		
C.D. (p = 0.05)			0.019		

From the interaction table (Table 3A), it was found that the combination of irrigation frequency, 20 mm ET_c with EFI method had significantly higher total chlorophyll content (0.14 mg g^{-1}) than all other treatment combinations at 75 DAP.

Yield attributes, arithmetic and geometric mean diameter of tubers

Most of the yield attributes were influenced significantly by the irrigation frequencies and methods (Table 4). The highest no. of tubers $plant^{-1}$ (4.9) at harvest was observed with the irrigation frequency of 20 mm ET_c which was statistically *at par* with 30 mm ET_c treatment (4.6). Similarly, the highest arithmetic (6.9 and 5.3 cm under grade A and B, respectively) and geometric mean diameters (6.5 and 5.0 cm under grade A and B, respectively) of grade A and B tubers were observed with 20 mm ET_c which were statistically *at par* with the arithmetic (6.7 and 5.0 cm under grade A and B, respectively) and geometric mean diameters (6.3 and 4.8 cm under grade A and B, respectively) of tubers obtained under 30 mm ET_c. Arithmetic and geometric mean diameter of C grade tubers were not varied significantly due to following the various irrigation frequencies and methods.

The no. of tubers $plant^{-1}$ at harvest was not varied significantly due to various irrigation methods. Earlier report of Onder *et al.* (2005) and Akram *et al.* (2020) supported this result. The maximum arithmetic mean tuber diameters were obtained under EFI method (6.9 and 5.2 cm under grade A and B, respectively) which were statistically *at par*

Table 4. Yield attributes of potato, arithmetic and geometric mean diameter of tubers as influenced by irrigation frequencies combined with irrigation methods.

Treatments	No. of tubers plant^{-1} at harvest	Arithmetic mean diameter of tubers (cm)			Geometric mean diameter of tubers (cm)		
		Grade A (≥75 g sized)	Grade B (50≤75 g sized)	Grade C (25≤50 g sized)	Grade A (≥75 g sized)	Grade B (50≤75 g sized)	Grade C (25≤50 g sized)
Irrigation frequencies							
20mm ET_c (F_1)	4.9	6.9	5.3	3.7	6.5	5.0	3.6
30mm ET_c (F_2)	4.6	6.7	5.0	3.7	6.3	4.8	3.5
40mm ET_c (F_3)	4.1	6.5	4.8	3.6	6.1	4.5	3.4
50mm ET_c (F_4)	4.1	6.2	4.5	3.5	5.8	4.3	3.4
S.Em. (±)	0.10	0.09	0.12	0.13	0.12	0.12	0.11
C.D. (P=0.05)	0.36	0.31	0.40	NS	0.40	0.42	NS
Methods of Irrigation							
EFI (M_1)	4.6	6.9	5.2	3.7	6.6	4.9	3.6
AFI (M_2)	4.4	6.5	5.0	3.6	6.1	4.7	3.5
PSFI (M_3)	4.3	6.3	4.5	3.5	5.9	4.3	3.4
S.Em. (±)	0.12	0.11	0.12	0.05	0.10	0.12	0.06
C.D. (P=0.05)	NS	0.44	0.47	NS	0.41	0.47	NS

*Dehaulming was done at 86 DAP

with AFI method (6.5 and 5.0 cm under grade A and B, respectively). In case of geometric mean diameter of tubers, highest result under grade A (6.6 cm) and B (4.9 cm) were recorded with the EFI method. Geometric mean diameter of grade B tubers obtained with the AFI method (4.7 cm) was statistically *at par* with EFI.

Yield

The haulm yield, tuber yield and total marketable tuber yield were differed significantly by applying different irrigation frequencies and methods (Table 5). The maximum haulm (15.56 t ha^{-1}) and tuber yield (21.25 t ha^{-1}) were noted down with treatment 20 mm ET_c which was statistically *at par* with 30 mm ET_c (14.97 and 20.25 t ha^{-1} were the haulm and tuber yield, respectively) and significantly least tuber yield was noted down with 50 mm ET_c (18.06 t ha^{-1}) which was in agreement with the earlier report of Demelash (2013). The highest total marketable yield (18.75 t ha^{-1}) was recorded from 20 mm ET_c which was statistically *at par* with 30 mm ET_c (17.75 t ha^{-1}).

In case of irrigation methods, the maximum tuber yield (21.01 t ha^{-1}) was obtained with EFI but this result was statistically *at par* with AFI (19.57 t ha^{-1}). Similar results were reported earlier by Sarker *et al.* (2019). Similarly, the tuber yield (18.50 t ha^{-1}) recorded with PSFI method was statistically *at par* with AFI but significantly lesser than EFI. Previous report of Onishi *et al.* (2021) supported this result. The significantly higher result of haulm yield (15.09 t ha^{-1}) was obtained with EFI method than all other irrigation methods. This was probably because of the adequate availability of soil moisture for prolonged period (Verma *et al.*, 2013) under EFI treatment.

Starch content

The starch content in tuber was influenced significantly due to different irrigation frequencies and methods. The highest starch content (18.50 mg g^{-1}) was recorded under 30 mm ET_c which was significantly higher than all others (Table 5). Starch content of tuber was significantly decreased at 20 mm ET_c (17.26 mg g^{-1}) than 30 mm ET_c. Pahuja and Sharma (1982) reported likewise. This decrement in starch content was due to hydrolysis of starch into sugar at higher water supply (Irfan *et al.*, 2017).

But the starch content was recorded significantly higher in AFI method of irrigation (18.05 mg g^{-1}) than all other irrigation methods. Water deficit induced changes in the activities of major carbohydrate metabolizing enzymes shifting the tuber from a starch synthesizing to a starch mobilization function (Shock *et al.*, 1992).

Table 5. Yield and starch content of potato as influenced by irrigation frequencies combined with irrigation methods

Treatments	Haulm yield (t ha^{-1})	Tuber yield (t ha^{-1})	Total marketable tuber yield (t ha^{-1})	Starch content (mg g^{-1})
Irrigation frequencies				
20 mm ET_c (F_1)	15.56	21.25	18.75	17.26
30 mm ET_c (F_2)	14.97	20.25	17.75	18.50
40 mm ET_c (F_3)	14.18	19.20	14.74	17.87
50 mm ET_c (F_4)	13.84	18.06	13.41	16.53
S.Em. (±)	0.19	0.32	0.36	0.10
C.D. (P=0.05)	0.66	1.10	1.25	0.35
Methods of Irrigation				
EFI (M_1)	15.09	21.01	17.98	17.46
AFI (M_2)	14.64	19.57	15.85	18.05
PSFI (M_3)	14.19	18.50	14.66	17.11
S.Em. (±)	0.05	0.48	0.42	0.16
C.D. (P=0.05)	0.17	1.68	1.60	0.57

Table 5A. Interaction effect of irrigation frequencies irrigation methods on non-marketable tuber yield of potato (t ha^{-1})

Treatments	20 mm ET_c (F_1)	30 mm ET_c (F_2)	40 mm ET_c (F_3)	50 mm ET_c (F_4)	Mean
EFI (M_1)	1.62	1.89	3.72	5.27	3.12
AFI (M_2)	2.93	2.60	4.97	4.38	3.72
PSFI (M_3)	2.86	3.40	4.70	4.32	3.82
Mean	2.47	2.63	4.46	4.66	
S.Em. (±)			0.31		
C.D. (P=0.05)			0.96		

Graded tuber yield

The non-marketable tuber yield and yield of grade A and B tubers were varied significantly by various irrigation frequencies and methods (Table 5). Significant variation in non-marketable tuber yield and tuber yield of grade A and B due to different irrigation frequencies were also reported earlier by Irfan *et al.* (2015). The non-marketable (<25 g sized) tuber yield was found maximum with 50 mm ET_c (4.66) which was statistically *at par* with 40 mm ET_c treatment (4.46 t ha^{-1}). The maximum marketable yield of grade B (50≤75 g sized) tubers and grade A (≥75 g sized) tubers (6.45 and 7.07 t ha^{-1}, respectively) were recorded with 20 mm ET_c (Table 6). This treatment showed significantly higher marketable yield of grade A tubers than other treatments. But the yield of grade B tubers obtained under 30 mm ET_c (6.27 t ha^{-1}) were statistically *at par*

Table 6. Non-marketable and marketable tuber yield of potato as influenced by irrigation frequencies combined with irrigation methods.

Treatments	Non-marketable tuber yield (t ha^{-1}) (<25 g)	Marketable tuber yield (t ha^{-1})		
		Grade A (≥75 g)	Grade B (50≤75 g)	Grade C (25≤50 g)
Irrigation frequencies				
20 mm ET_c (F_1)	2.47	7.07	6.45	5.23
30 mm ET_c (F_2)	2.63	6.37	6.27	5.11
40 mm ET_c (F_3)	4.46	5.29	4.45	5.00
50 mm ET_c (F_4)	4.66	4.54	3.90	4.97
S.Em. (±)	0.31	0.17	0.15	0.26
C.D. (P=0.05)	1.06	0.60	0.54	NS
Methods of Irrigation				
EFI (M_1)	3.12	6.46	6.32	5.19
AFI (M_2)	3.72	5.66	5.12	5.06
PSFI (M_3)	3.82	5.33	4.36	4.98
S.Em. (±)	0.22	0.11	0.27	0.09
C.D. (P=0.05)	NS	0.39	0.96	NS

with 20 mm ET_c. Similar results were reported earlier by; Kashyap and Panda (2003); Irfan *et al.* (2015). Much more production of large sized tubers under 20 and 30 mm ET_c might be due to continuous and adequate supply of soil moisture throughout the crop growing season (Irfan *et al.*, 2015).

Maximum marketable yield of grade B and grade A tubers as well as total marketable tuber yield (6.32, 6.46 and 17.98 t ha^{-1}, respectively) were recorded when EFI method was followed. These results were significantly higher than all others. This was probably because of the adequate availability of soil moisture for prolonged period (Verma *et al.*, 2013) under this treatment.

The interaction effects of irrigation frequencies combined with irrigation methods for all the yields remained non-significant except for non-marketable tuber yield (Table 5A). The lowest non-marketable tuber yield (1.62 t ha^{-1}) was recorded with the combination of 20 mm ET_c and EFI method which was statistically *at par* with the non-marketable tuber yield (1.89 t ha^{-1}) recorded with the combination of 30 mm ET_c and EFI method (Table 5A). These findings supported the fact that potato plants need irrigation for development of high-quality tubers (Gültekin and Ertek, 2018).

Crop evapotranspiration and water use efficiency of potato

The maximum AET (299.93 mm) were recorded with treatment 20 mm ET_c due to the application of maximum amount of irrigation water (Table 7). Similarly, the highest water use efficiency (WUE) (43.6 kg m^{-3}) was obtained with the irrigation at 20 mm ET_c. This was because of maximum tuber yield recorded under this irrigation frequency option. Highest field capacity (Fc) in the rootzone depth (33.3%), soil profile contribution (47.43 mm) and IUE (60.0 kg m^{-3}) were recorded under the irrigation frequency of 50 mm ET_c. Crosby and Wang (2021) reported similar result related to highest IUE. This might be due to increase in irrigation interval resulted in more soil water storage in the root zone depth and more contribution of that stored water during the entire crop growing period. The variation in IUE between 30 and 40 mm ET_c was 1.2 kg m^{-3}. The earlier report of Crosby and Wang (2021) corroborated this result.

In case of irrigation methods, EFI recorded highest results in all the WUEs (*i.e.*, WUE, WUE_I, IUE and WUE_{ET} were 38.9, 17.5, 57.8 and 40.7 kg m^{-3}, respectively) whereas, Fc in the rootzone depth was recorded maximum (32.7%) under AFI method of irrigation. AFI could be an alternative to EFI or PSFI in South Asian countries with limited irrigation water availability due to this fact (Sarker *et al.*, 2019). AET and soil profile contribution were found maximum (224.67 and 42.87 mm, respectively) under PSFI method of irrigation.

The interaction effect between irrigation frequencies and methods showed that highest amount of irrigation under I_1 and lowest amount of irrigation under I_{12} treatment combination were responsible for these results. The opposite results were obtained for soil profile contribution where highest contribution had come from I_{12} (52.28 mm) and lowest contribution had come from I_1 (23.28 mm) treatment combination. Again, WUE and WUE_I were recorded highest under I_1 treatment combination (44.4 and 32.4 kg m^{-3}, respectively). But Fc in rootzone depth and WUE_{ET} were highest (34.2% and 56.9 kg m^{-3}, respectively) under I_7 (F_3-M_1) treatment combination. IUE was recorded maximum (61.0 kg m^{-3}) under the treatment combination I_{10} (F_4-M_1) due to maximum proportionate yield increase with minimum irrigation water. Maximum AET (303.82 mm) was recorded under I_3 (F_1-M_3) treatment combination because of highest amount of irrigation water applied.

Table 7. Fc of soil moisture, AET, soil profile contribution, WUE, WUE_I, IUE and WUE_{ET} as influenced by irrigation frequencies combined with irrigation methods.

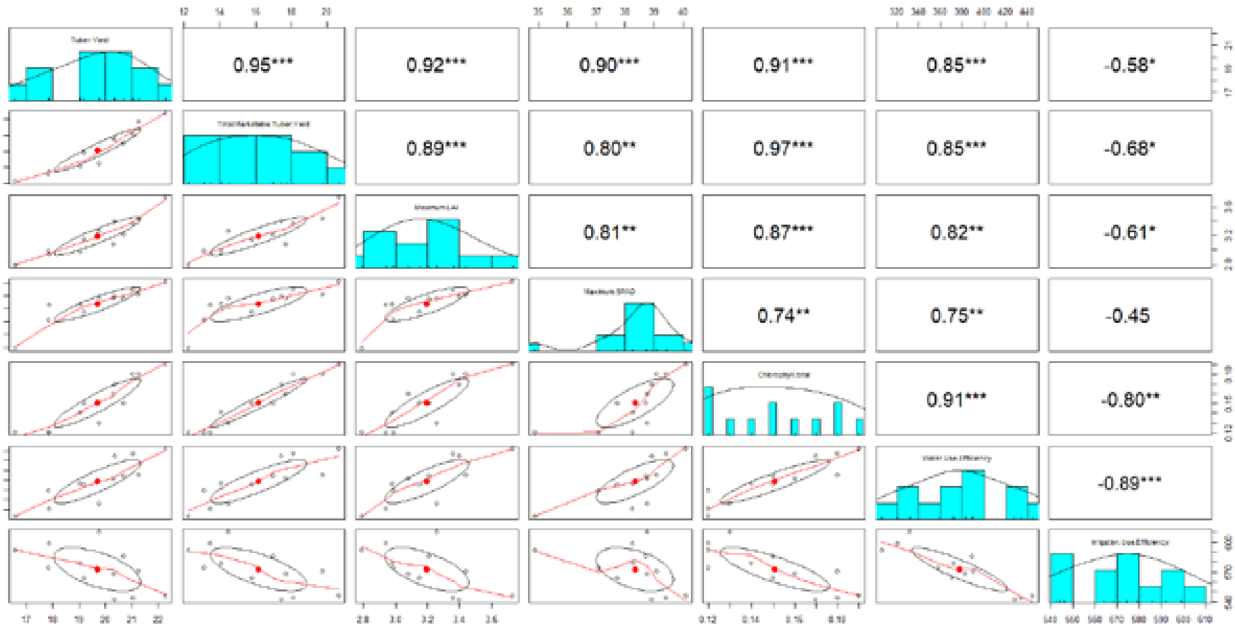
Treatments	Fc of soil moisture (%)	AET (mm)	Soil profile contribution (mm)	WUE (kg m^{-3})	WUE_I (kg m^{-3})	IUE (kg m^{-3})	WUE_{ET} (kg m^{-3})
Irrigation frequencies							
20 mm ET_c (F_1)	31.2	299.93	28.13	43.6	32.2	54.4	51.6
30 mm ET_c (F_2)	32.2	223.43	41.63	38.1	21.2	56.8	53.1
40 mm ET_c (F_3)	32.0	186.68	34.88	37.3	13.6	58.0	54.4
50 mm ET_c (F_4)	33.3	169.23	47.43	31.9	0.8	60.0	
Methods of Irrigation							
EFI (M_1)	32.3	215.21	33.41	38.9	17.5	57.8	40.7
AFI (M_2)	32.7	219.58	37.78	37.7	16.9	57.3	39.7
PSFI (M_3)	31.6	224.67	42.87	36.6	16.5	56.8	38.9
Irrigation frequencies × Methods of irrigation							
I_1 (F_1-M_1)	30.7	295.08	23.28	44.4	32.4	54.6	51.9
I_2 (F_1-M_2)	32.6	300.88	29.08	43.4	32.2	54.4	51.5
I_3(F_1-M_3)	30.5	303.82	32.02	42.8	32.0	54.2	51.3
I_4 (F_2-M_1)	31.4	219.54	37.74	39.0	21.6	57.1	53.9
I_5 (F_2-M_2)	33.8	222.48	40.68	38.3	21.2	56.8	53.1
I_6(F_2-M_3)	31.4	228.28	46.48	37.1	20.9	56.4	52.2
I_7 (F_3-M_1)	34.2	180.88	29.08	38.9	14.2	58.6	56.9
I_8 (F_3-M_2)	30.8	186.68	34.88	37.2	13.5	57.9	54.1
I_9 (F_3-M_3)	31.1	192.48	40.68	35.8	13.0	57.4	52.1
I_{10}(F_4-M_1)	32.8	165.34	43.54	33.2	1.8	61.0	
I_{11} (F_4-M_2)	33.9	168.28	46.48	32.0	0.7	59.9	
I_{12} (F_4-M_3)	33.2	174.08	52.28	30.6		59.2	

*Here, Fc: field capacity in rootzone depth during the entire crop growing period
**Soil moisture just before planting of potato was 34.6%; One irrigation of 30 mm was given just after planting to all the plots for satisfactory germination

Correlation matrix

Tuber yield of potato showed very highly significant positive correlation with total marketable tuber yield (correlation coefficient, r = 0.95***), maximum LAI (correlation coefficient, r = 0.92***), maximum SPAD value (correlation coefficient, r = 0.90***), highest chlorophyll total content (correlation coefficient, r = 0.91***) and WUE (correlation coefficient, r = 0.85***). But the IUE showed significant negative correlation (correlation coefficient, r = - 0.58*) with the tuber yield of potato (Table 8). This result indicated that the IUE was increased significantly with the reduction of tuber yield. But tuber yield was enhanced when the results of other parameters were improved. The other parameters also showed very highly significant positive correlation with each other except IUE. The maximum SPAD value showed only strong significant positive correlation with maximum chlorophyll total content (correlation coefficient, r = 0.74**) and WUE (correlation coefficient, r = 0.75**) but no significant correlation with IUE (correlation coefficient, r = - 0.45). The IUE also showed significant negative

Table 8. Correlation matrix among tuber yield (t ha^{-1}), total marketable tuber yield (t ha^{-1}), maximum LAI, maximum SPAD value, highest chlorophyll total content (mg g^{-1}), WUE (kg m^{-3}) and IUE (kg m^{-3}) of potato.



#Maximum LAI, SPAD value and chlorophyll total content (mg g^{-1}) was recorded at 60 DAP in this experiment.
*Correlation is significant at the 0.10 level
**Correlation is significant at the 0.05 level
***Correlation is significant at the 0.01 level

correlation with the total marketable tuber yield (correlation coefficient, r = - 0.68*) and maximum LAI (correlation coefficient, r = - 0.61*) whereas, a strong significant negative correlation was noted down between IUE and maximum chlorophyll total content (correlation coefficient, r = - 0.80**). These results indicated that the IUE was increased with the significant reduction of total marketable tuber yield and maximum LAI. But there was a highly significant decrease in chlorophyll total content occurred with the enhancement of IUE. Very strongly significant negative correlation (r = - 0.89***) was recorded in case of WUE versus IUE. This was due to the fact that profile contribution soil moisture fulfilled the water requirement of potato crop when irrigation interval was increased along with different methods of irrigation were followed.

Regression analysis of the tuber yield versus IUE

The functional relation between the IUE and tuber yield was expressed in the equation, y = m.x (Fig. 1). The value of regression coefficient (R^2) was 0.9889 which implied that around 99% of the tuber yield was contributed by the single factor, irrigation water management. Fabeiro *et al.* (2001) reported likewise. This strong regression was suggestive of the influence of IUE on the

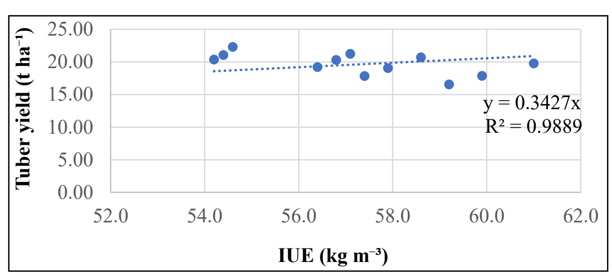


Fig. 1. Relationship between IUE (kg m^{-3}) and tuber yield (t ha^{-1})

tuber yield of potato. According to the linear regression, proportionate yield increase will be higher with decrease in the IUE which indicates that the higher amount of irrigation water is required than earlier for further enhancement of one unit in tuber yield.

Economics

Among the different irrigation frequencies, maximum cost of cultivation (₹ 78349 ha^{-1}) was obtained under irrigation at 20 mm ET_c and the cost of cultivation was obtained minimum under 50 mm ET_c treatment (₹ 76609 ha^{-1}). Similarly, maximum gross return (₹ 276186 ha^{-1}), net return (₹ 197838 ha^{-1}) and benefit-cost ratio (2.52) was obtained under irrigation at 20 mm ET_c treatment.

In case of irrigation methods, cost of cultivation (₹ 77986 ha^{-1}) was obtained maximum under EFI and the minimum (₹ 77007 ha^{-1}) under AFI and PSFI, both. The highest gross return (₹ 273071 ha^{-1}), net return (₹ 195085 ha^{-1}) and benefit-cost ratio (2.50) was obtained under EFI treatment.

The treatment combination, I_1 (F_1-M_1) showed highest cost of cultivation (₹ 79509 ha^{-1}), gross return (₹ 289907 ha^{-1}), net return (₹ 210398 ha^{-1}) and B:C ratio (2.65) (Table 9). Highest cost of cultivation was recorded under I_1 treatment combination due to highest amount of irrigation water application under this combination and achievement of highest tuber yield was responsible behind the highest gross and net return as well as B:C ratio under this treatment combination.

Table 9. Economics of potato as influenced by irrigation frequencies combined with irrigation methods.

Treatments	*Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	B:C ratio
Irrigation frequencies				
20 mm ET_c (F_1)	78349	276186	197838	2.52
30 mm ET_c (F_2)	77479	263314	185835	2.40
40 mm ET_c (F_3)	76899	249626	172728	2.25
50 mm ET_c (F_4)	76609	234791	158182	2.06
Methods of irrigation				
EFI (M_1)	77986	273071	195085	2.50
AFI (M_2)	77007	254370	177362	2.30
PSFI (M_3)	77007	240497	163490	2.12
Irrigation frequencies × Methods of irrigation				
I_1 (F_1-M_1)	79509	289907	210398	2.65
I_2 (F_1-M_2)	77769	273793	196025	2.52
I_3(F_1-M_3)	77769	264859	187090	2.41
I_4 (F_2-M_1)	78204	276342	198138	2.53
I_5 (F_2-M_2)	77116	263867	186751	2.42
I_6(F_2-M_3)	77116	249731	172615	2.24
I_7 (F_3-M_1)	77334	269159	191826	2.48
I_8 (F_3-M_2)	76681	247689	171008	2.23
I_9 (F_3-M_3)	76681	232030	155349	2.03
I_{10}(F_4-M_1)	76899	256877	179979	2.34
I_{11} (F_4-M_2)	76464	232129	155665	2.04
I_{12} (F_4-M_3)	76464	215367	138903	1.82

*The water application cost was taken @₹ 1.45 m^{-3} of water as reported earlier by Singha *et al*. (2018).

CONCLUSION

From this investigation, it can be concluded that the irrigation at 20 mm ET_c performed best in terms of growth and yield of potato. Similarly, the growth and yield of potato was better under every furrow method of irrigation than others. The treatment combination of 20 mm ET_c-EFI showed highest water use efficiency, gross return, net return and B:C ratio. Therefore, this treatment combination could be recommended for adoption by the potato farmers in north-eastern ghats of Odisha as a viable strategy to curtail the excess irrigation. This was closely followed by the treatment combination, 30 mm ET_c-EFI (2.53) or 20 mm ET_c-AFI (2.52) with respect to B:C ratio which can also be adopted as a remunerative technique in the areas having water crisis.

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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EFFECT OF INTEGRATED NUTRIENT MANAGEMENT ON GROWTH, YIELD AND QUALITY OF POTATO (*SOLANUM TUBEROSUM* L.) IN SOUTHERN ODISHA

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ABSTRACT: Objective of this study was to investigate the effect of the integrated nutrient management on growth, yield and quality of Potato (*Solanum tuberosum* L.). Continuous application of chemical fertilizers causes nutritional imbalance and adverse effects on the physico-chemical and biological characters of soil. Thus, an integrated nutrient supply by chemical fertilizer along with organic manures is given importance, especially in heavy feeder crops like potato. The experiment was conducted at PG Research Farm of M.S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Odisha during *rabi* season of 2023-24 under the sandy clay loam soil with an altitude of 90 m above the mean sea level. The experiment was laid out in randomized complete block design (RCBD) with three replications and eight treatments: 100% recommended dose of nitrogen (RDN) (T_1), 90% RDN + 10% N through farm yard manure (FYM) (T_2), 90% RDN + 10% N through vermicompost (T_3), 80% RDN + 20% N through FYM (T_4), 80% RDN + 20% through vermicompost (T_5), 70% RDN + 30% through FYM (T_6), 70% RDN + 30% through vermicompost (T_7) and control (without any chemical fertilizer or organics) (T_8). The application of 100% RDN resulted in a significant increment till harvest in terms of growth parameters over the control. A significant increase in total tuber yield (239.1%), starch content (8.7%), carbohydrate content (15.8%), net return (17.26 times) was also observed under 100% RDN when compared to no chemical or organics application. Treatments integrating 90% RDN with organic amendments such as farm yard manure (FYM) and vermicompost closely matched the performance of 100% RDN. The study advocates for a balanced use of chemical and organic fertilizers, emphasizing the importance of optimizing nutrient management to achieve sustainable agricultural practices that ensure high productivity, quality and economic profitability.

KEYWORDS: Farmyard manure, nitrogen, tuber, vermicompost

INTRODUCTION

The potato (*Solanum tuberosum* L.) has a rich history, originating in the Peru-Bolivian region of the Andes in South America, and was introduced to India from Europe by the Portuguese during the seventeenth century. This crop has become integral to Indian agriculture, particularly in regions where cool season temperatures remain below 18°C, allowing it to flourish in various latitudes and altitudes within India's tropics and subtropics. Globally, the potato ranks fourth among food crops, following rice, wheat, and maize. Between 1991 and 2007, potato production increased by 21%, underscoring its rising importance as a staple food (Jimwan *et al*. 2022). Currently, about 19 million hectares are dedicated to potato cultivation worldwide, with an average yield of around 17 tonnes per hectare (FAO, 2012).

Potatoes are nutritionally significant, consisting of approximately 80% water and 20% dry matter. Their carbohydrate content, mainly in the form of starch and sugar, constitutes about 16% of their fresh weight. They also contain about 2% crude protein and

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minimal fat at 0.1%. Additionally, potatoes are rich in fiber, vitamins, and glycoalkaloids. When boiled, they provide an estimated 69 Kcal per 100 grams, offering high-quality protein with a well-balanced amino acid profile. Potatoes are known for their efficiency in yielding the highest consumable product per unit area in the shortest time, supplying 2.5 times more calories than wheat and rice (Singh *et al.* 2022).

India is the second-largest potato producer globally after China, with the crop occupying approximately 2.22 million hectares and yielding 53.6 million metric tonnes (MT) in 2020-21 (NHB Database, 2021). In Odisha, potatoes are becoming a major crop, especially during the dry season, with cultivation spanning about 15,000 hectares and yielding approximately 2.5 lakh MTs annually. However, potato productivity in Odisha is 16.48 MT/ha, below the national average of 22.76 MT/ha (GoO, 2019). Farmers in Odisha primarily grow potatoes during the *rabi* season and as a monsoon crop during kharif, particularly in the hilly regions of Koraput and Kandhamal. The main potato-growing districts in Odisha include Puri, Cuttack, Kandhamal, Mayurbhanj, Balasore, Sambalpur, and Koraput, with planting seasons extending from July to November and November to March (GoO, 2019).

Potatoes are one of the most efficient food crops, yielding significant dry matter and serving as a rich source of vitamins, minerals, dietary fiber, and quality proteins, thus constituting a substantial energy source (Zaheer and Akhtar, 2016). However, intensive potato cultivation can deplete soil nutrients, making it necessary to add organic matter to restore soil health. Integrated Nutrient Management (INM) presents a viable approach to sustainably maintain soil quality while enhancing potato productivity (Shubha *et al.* 2018). Recent studies have underscored the importance of nutrient management in optimizing potato growth. Yadav *et al.* (2017) conducted a field experiment at the ICAR- Central Research Station, Shillong, Meghalaya, and noticed that the highest tuber yield (18.8 t ha^{-1}) was recorded with the application of 75% RDN + 25% FYM when compared to the 100% RDN application (17.1 t ha^{-1}).

Given the importance of maintaining soil health and enhancing crop productivity, this study aims to investigate the effectiveness of integrated nutrient management strategies in improving potato productivity and soil health in Odisha, with a focus on optimizing fertilizer application to achieve higher yields while ensuring sustainable agricultural practices. Specifically, the objectives of this study are to study the effect of integrated nutrient management on the growth and yield of potatoes and to find out the effect of integrated nutrient management on the economics of potato cultivation. By examining these aspects, the study seeks to provide valuable insights for farmers and policymakers to improve potato cultivation in Odisha.

MATERIALS AND METHODS

The field experiment was carried out at the post Graduate research farm (23˚39' N latitude, 87˚42' E longitude) of M.S. Swaminathan School of Agriculture, Centurion University of Technology and Management, Paralakhemundi, Gajapati district, Odisha under the sandy clay loam soil with an altitude of 90 m above the mean sea level during the *rabi* season of 2023. During the crop growing season, which lasted from 4th November, 2023 to 4th February, 2024. The crop received a total rainfall of 35.35 mm. The experiment was laid out in a randomized complete block design (RCBD) with eight treatments. The treatment details are T_1:

100% recommended dose of nitrogen (RDN), T_2: 90% RDN + 10% N through FYM (*i.e.*, 2.4 t ha^{-1}), T_3: 90% RDN + 10% N through vermicompost (*i.e.*, 1.0 t ha^{-1}), T_4: 80% RDN + 20% N through FYM (*i.e.*, 4.8 t ha^{-1}), T_5: 80% RDN + 20% through vermicompost (*i.e.*, 2.0 t ha^{-1}), T_6: 70% RDN + 30% through FYM (*i.e.*, 7.2 t ha^{-1}), T_7: 70% RDN + 30% through vermicompost (*i.e.*, 3.0 t ha^{-1}) and T_8: Control (Without any chemical fertilizer or organics). The variety, Kurfi Jyoti was sown with a spacing of 50 cm x 20 cm, and all the required agronomic practices were followed to raise the crops successfully. For treatments involving the 100% recommended dose of fertilizer, the following amounts were used: 120 kg ha^{-1} of N, 60 kg ha^{-1} of P_2O_5 and 120 kg ha^{-1} of K_2O. Inorganic fertiliser sources included urea, single super phosphate (SSP), muriate of potash (MOP) and organic fertilisers like farm yard manure and vermicompost. The farm yard manure and vermicompost were applied to the soil before ten days of sowing, mixing it with soil properly. Half nitrogen and a full dose of phosphate and potash were incorporated into the soil before planting. The other half dose of nitrogen was side dressed in two equal splits at 30 and 45 DAP during earthing up. For nitrogen estimation, potassium permanganate method out lined by Subbaiah and Asija (1965) was followed. The methodology for analyzing starch involved treating the sample with 80% alcohol to remove sugars, followed by starch extraction using perchloric acid. In a hot, acidic medium, starch undergoes hydrolysis to glucose and subsequent dehydration to hydroxymethyl furfural. This compound forms a green-colored product with anthrone, as described by Hodge and Hofreiter (1962). The glucose content of the sample was determined using a standard graph, and the value was multiplied by a factor of 0.9 to obtain the starch content. For carbohydrate analysis, concentrated sulfuric acid was used to convert the carbohydrate into furfural or its derivatives, which then reacted with β-naphthol to produce a purple-colored product, also described by Hodge and Hofreiter (1962). The data were analyzed statistically by following the standard ANOVA technique, and the difference between the treatment means was tested for their statistical significance with appropriate critical difference (CD) values at a 5% level of significance (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Influence of integrated nutrient management on plant height of potato

The findings revealed that the treatments significantly impacted potato growth parameters (Table 1). In the context of the influence of integrated nutrient management on the growth and productivity of potato, the plant height served as a valuable parameter to assess the response of the crop to various nutrient management practices. The maximum plant height (64.7 cm) at harvest was recorded with the application of 100% recommended dose of nitrogen (RDN), which remained statistically at par with the application of 90% RDN + 10% N through vermicompost and 90% RDN + 10% N through farm yard manure (FYM). The lowest plant height (50.5) was noted with the control treatment, where no chemical fertilisers and organics were applied. Applying 100% RDN likely provided the plants with optimal nitrogen levels for growth, leading to the maximum plant height observed. The similar performance of the 90% RDN combined with organic sources suggests that these treatments could supply the necessary nitrogen effectively as well (Koch *et al*. 2020). Earlier, Choudhary *et al*. (2022) and Tirkey *et al*. (2023) reported similar results.

Influence of integrated nutrient management on dry matter accumulation of potato

The data on dry matter accumulation of haulm at harvest was statistically analyzed and presented in Table 1. Integrated nutrient management practices significantly influenced the accumulation of dry matter in haulm. The highest dry matter accumulation of haulm occurred where 100% RDN was applied followed by 90% RDN + 10% N through Vermicompost which was also on par with the highest recorded treatment. As anticipated, the control treatment resulted in the lowest dry matter accumulation in haulm. The data on dry matter accumulation in the tuber exhibited similar results to those of the haulm. The highest results were achieved with application of 100% RDN as nitrogen is a critical component of chlorophyll, amino acids and protein and its adequate supply influenced the vegetative growth and haulm dry matter accumulation (Congera *et al*. 2013). The close performance of 90% RDN + 10% N through vermicompost indicates that organic amendments can effectively complement chemical fertiliser to provide a balanced nutrient supply and enhance soil organic matter and structure (Sahoo *et al*. 2021). The results are in conformity with the findings of Kumar *et al*. (2020) and Narayan *et al*. (2013).

Influence of integrated nutrient management on leaf area index of potato

Observation on leaf area index recorded at 30 DAP, 60 DAP and harvest have been statistically analysed and presented in Table 2. The leaf area index of potato increased steadily up to 60 DAP and then decreased due to the rapid senescence of the older leaves as the crop progressed towards maturity. Applying 100% RDN through chemical fertiliser resulted in the maximum leaf area index in all three stages of plant growth. Among all the crop growth stages, the highest leaf area index was observed at 60 DAP. The leaf area index of potato obtained the maximum value with the application of 100% RDN at all three stages of plant growth, and it was statistically at par with the application of 90% RDN + 10% N through Vermicompost during 30 DAP and at harvest. However, during 60 DAP and at harvest, the treatment which received 90% RDN + 10% N through Vermicompost and 90% RDN + 10% N through FYM were also statistically

Table 1. Influence of integrated nutrient management on plant height, dry matter accumulation of haulm and dry matter accumulation of tuber of potato.

Treatments	Plant height (cm) at harvest	Dry matter accumulation (g m^{-2}) of haulm	Dry matter accumulation (g m^{-2}) of tuber
T_1 : 100% Recommended Dose of Nitrogen (RDN)	64.7	441.0	542.6
T_2 : 90% RDN + 10% N through Farm Yard Manure (FYM)	62.3	401.7	446.4
T_3 : 90% RDN + 10% N through Vermicompost	62.8	429.0	525.9
T_4 : 80% RDN + 20% N through FYM	61.7	344.0	436.4
T_5 : 80% RDN + 20% N through Vermicompost	61.9	361.0	444.6
T_6 : 70% RDN + 30% N through FYM	61.1	280.7	390.6
T_7 : 70% RDN + 30% N through Vermicompost	61.7	299.0	415.2
T_8 : Control (Without any chemical fertilisers or organics)	50.5	259.7	341.6
S. Em. ±	0.8	9.3	15.5
C.D. (0.05)	2.4	27.8	46.0

Table 2. Influence of integrated nutrient management on Leaf Area Index (LAI) of potato at different growth stages.

Treatments	Leaf Area Index (LAI)		
	30 DAP	60 DAP	HARVEST
T_1 : 100% Recommended Dose of Nitrogen (RDN)	0.98	3.74	2.68
T_2 : 90% RDN + 10% N through Farm Yard Manure (FYM)	0.85	3.41	2.55
T_3 : 90% RDN + 10% N through Vermicompost	0.90	3.44	2.66
T_4 : 80% RDN + 20% N through FYM	0.72	3.31	2.44
T_5 : 80% RDN + 20% N through Vermicompost	0.84	3.34	2.46
T_6 : 70% RDN + 30% N through FYM	0.60	3.19	2.26
T_7 : 70% RDN + 30% N through Vermicompost	0.74	3.21	2.32
T_8 : Control (Without any chemical fertilisers or organics)	0.26	1.54	0.89
S. Em. ±	0.03	0.13	0.89
C.D. (0.05)	0.09	0.38	0.06

at par with the highest recorded treatment. This indicates that adequate nitrogen is critical for maximising leaf expansion and canopy development. It also indicates that organic amendments can be nearly as effective as chemical fertilisers in supporting leaf growth, especially during the mid to late stages of the crop cycle (Sudhakar *et al*. 2018; Diacono and Montemurro, 2011). The results confirm the findings of Kazamba *et al.* (2019) and Mohammed *et al.* (2018).

Influence of integrated nutrient management on SPAD meter reading of potato

The data pertaining to SPAD meter reading as influenced by integrated nutrient management indicated non-significant results during 30 DAP. At 60 DAP, the 100% RDN application resulted in a significantly higher SPAD value (1.68), which was superior to all other treatments. The treatment which received 90% RDN + 10% N through vermicompost and 90% RDN + 10% N through FYM were statistically at par with the highest recorded treatment. The significant increase in SPAD value at 60 DAP with 100% RDN application suggests that nitrogen availability is closely linked to chlorophyll synthesis and leaf accumulation, which is crucial for photosynthesis and plant growth (Ghosh *et al*. 2020). It also shows that a reduced amount of chemical fertiliser, when supplemented with organic sources like FYM and vermicompost, can still support optimal chlorophyll content and plant health (Xiong *et al*. 2015). The results corroborate the findings of Kafle *et al*. (2019) (Table 3).

Influence of integrated nutrient management on growth rate (g m^{-2} day^{-1}) of potato

Crop Growth Rate (CGR) of Potato as estimated during 30-60 DAP have been presented in Table 4. It was observed that in all the stages of nutrient management the CGR significantly increased with the application of 100% RDN, followed by the treatment which received 90% RDN + 10% N through vermicompost. The lowest value was obtained with the control treatment. The higher CGR with 100% RDN suggest that the plants had an optimal nitrogen supply for vigorous growth during the critical growth period (Aytenew and Bore, 2020). Additionally, it indicates that applying organic amendments such as FYM and vermicompost with reduced doses of

Table 3. Influence of integrated nutrient management on SPAD reading of potato at different growth stages.

Treatments	SPAD reading	
	30 DAP	60 DAP
T_1 : 100% Recommended Dose of Nitrogen (RDN)	45.2	41.5
T_2 : 90% RDN + 10% N through Farm Yard Manure (FYM)	41.9	38.7
T_3 : 90% RDN + 10% N through Vermicompost	42.3	40.8
T_4 : 80% RDN + 20% N through FYM	41.1	35.3
T_5 : 80% RDN + 20% N through Vermicompost	41.2	36.3
T_6 : 70% RDN + 30% N through FYM	40.7	34.1
T_7 : 70% RDN + 30% N through Vermicompost	40.8	37.0
T_8 : Control (Without any chemical fertilisers or organics)	30.5	27.9
S. Em. ±	1.5	1.2
C.D. (0.05)	4.5	3.5

Table 4. Influence of integrated nutrient management on growth rate (g m^{-2} day^{-1}) of potato at different growth stages.

Treatments	Crop Growth Rate (g m^{-2} day^{-1}) (30 – 60 DAP)	Tuber growth Rate (g m^{-2} day^{-1}) (60 – 90 DAP)	Tuber Bulking Rate (g m^{-2} day^{-1}) (30 – 60 DAP)
T_1 : 100% Recommended Dose of Nitrogen (RDN)	9.1	15.7	0.49
T_2 : 90% RDN + 10% N through Farm Yard Manure (FYM)	8.0	11.7	0.47
T_3 : 90% RDN + 10% N through Vermicompost	8.8	15.0	0.48
T_4 : 80% RDN + 20% N through FYM	7.1	12.6	0.46
T_5 : 80% RDN + 20% N through Vermicompost	7.3	12.7	0.47
T_6 : 70% RDN + 30% N through FYM	6.0	10.0	0.44
T_7 : 70% RDN + 30% N through Vermicompost	6.1	11.3	0.44
T_8 : Control (Without any chemical fertilisers or organics)	5.6	9.3	0.28

synthetic fertiliser can be nearly as effective as sole synthetic fertiliser application (Ranjan *et al.*, 2023). Similar results were reported by Hensh *et al.* (2020) and Koireng *et al.* (2018).

The tuber growth rate (TGR) estimated from tuber dry weight during 60-90 DAP has been presented in Table 4. The data on the TGR showed similar results among all the treatments except the control treatment, which obtained the lowest value (13.6 g m^{-2} day^{-1}) where no nutrient was applied. This suggests that nitrogen is a vital component for plant growth, and its adequate supply during the tuber bulking stage is crucial for optimal tuber development and the markedly lower TGR in the control treatment, where no nutrients were applied, underscores the importance of nutrient management in potato cultivation (Akkamis and Caliskan, 2023). The results are in agreement with the previous findings of Rahman *et al.* (2020) and Mondal *et al.* (2016).

The tuber bulking rate (TBR) estimated from fresh tuber weight during 30-60 DAP is presented in Table 4. The maximum TBR was obtained with the treatment that received 100% RDN (15.7 g m^{-2} day^{-1}) followed by the treatment that received 90% RDN + 10% N through Vermicompost The lowest value was obtained with the control treatment regarding TBR where no nutrients were applied. The above result signifies the importance of nitrogen for maximising the tuber bulking process and also indicates that organic amendments can play a significant role in providing nitrogen and other nutrients, thereby supporting robust tuber growth (Akkamis and Caliskan, 2023; Meena *et al*. 2016). Earlier, Koireng *et al*. (2018) reported similar results in their study.

Influence of integrated nutrient management on Grade tuber yield, marketable yield and non-marketable yield of potato

The data on the tuber yield of potato comprising all graded at maturity has been statistically analysed and presented in Table 5. The result showed that the highest total tuber yield (23.37 t ha^{-1}) was obtained from the treatment receiving 100% RDN. Thereafter there was a decrease in the yield by 7.7%, 12.41%, 49.71%, 56.74%, 50.80%, 108.29% and 240.67% with the application of 90% RDN + 10% N through FYM, 90% RDN + 10% N through vermicompost, 80% RDN + 20% N through FYM, 80% RDN + 20% N through vermicompost, 70% RDN + 30% N through FYM, 70% RDN + 30% N through vermicompost and control treatment, respectively. The total tuber yield and the non-marketable yield showed a similar trend. The highest yield obtained with 100% RDN suggests that this nitrogen application level may be optimal for maximising potato tuber yield under the conditions tested. Nitrogen is a critical nutrient for plant growth, particularly for tuber formation and development (Rittl *et al*. 2023). The decrease in yield with reduced RDN levels and increased organic amendments indicates that while organic amendments can provide essential nutrients, they may not be as immediately available or as efficiently utilised by the plants as synthetic fertilisers (Lynch *et al*. 2008). Similar findings were reported by Chaurasiya *et al.* (2020), Kumar *et al*. (2023) and Tiwari *et al*. (2022).

Influence of integrated nutrient management on starch and carbohydrate content (%) of potato

The data on the starch and carbohydrate content was statistically analysed and presented in Table 6. The administration of 100% RDN produced the maximum starch content, and this result was statistically

Table 5. Influence of integrated nutrient management on Grade wise tuber yield, marketable yield and non-marketable yield of potato (t ha^{-1}).

Treatments	Grade wise tuber yield of potato (t ha^{-1})					Total tuber yield (t ha^{-1})
	A >75g	B >50g – 75g	C >25g – 50g	Marketable yield (t ha^{-1})	Non-Marketable yield ≤ 25g	
T_1 : 100% Recommended Dose of Nitrogen (RDN)	7.6	7.2	6.9	21.7	1.7	23.4
T_2 : 90% RDN + 10% N through Farm Yard Manure (FYM)	6.6	6.4	6.3	19.3	1.5	21.8
T_3 : 90% RDN + 10% N through Vermicompost	6.9	6.4	6.6	20.1	1.6	22.7
T_4 : 80% RDN + 20% N through FYM	4.8	5.1	3.8	13.6	1.3	14.9
T_5 : 80% RDN + 20% N through Vermicompost	5.0	5.3	3.9	14.2	1.4	15.6
T_6 : 70% RDN + 30% N through FYM	3.4	3.6	3.1	10.1	1.1	11.2
T_7 : 70% RDN + 30% N through Vermicompost	4.6	5.0	3.6	13.3	1.1	14.4
T_8 : Control (Without any chemical fertilisers or organics)	2.2	1.8	1.7	5.8	1.1	6.9
S. Em. ±	0.8	0.6	0.4	1.4	0.1	1.4
C.D. (0.05)	2.4	1.9	1.2	4.2	0.3	4.2

Table 6. Influence of integrated nutrient management on Starch and carbohydrate content (%) of potato.

Treatments	Quality parameter	
	Starch Content (%)	Carbohydrate content (%)
T_1 : 100% Recommended Dose of Nitrogen (RDN)	18.6	60.6
T_2 : 90% RDN + 10% N through Farm Yard Manure (FYM)	17.1	57.6
T_3 : 90% RDN + 10% N through Vermicompost	18.1	59.5
T_4 : 80% RDN + 20% N through FYM	15.9	57.4
T_5 : 80% RDN + 20% N through Vermicompost	17.9	57.6
T_6 : 70% RDN + 30% N through FYM	16.5	57.2
T_7 : 70% RDN + 30% N through Vermicompost	17.6	57.3
T_8 : Control (Without any chemical fertilisers or organics)	14.1	52.3
S. Em. ±	0.7	0.8
C.D. (0.05)	2.2	2.3

comparable to treatments that received 90% RDN + 10% N through vermicompost and 90% RDN + 10% N through FYM. The treatment with the lowest starch level was the control treatment, which did not receive any organic or chemical fertiliser. Similar trends were seen in the data on the amount of carbohydrates, except the treatment that received 90% RDN + 10% N through vermicompost, which stayed on par with the 100% RDN application. This can be attributed to nitrogen, which plays a crucial role in the synthesis of starch, a primary storage carbohydrate in potato. The high starch content with 100% RDN suggests the plants had an optimal nitrogen supply for starch synthesis during the tuber development stage (Goss *et al*. 2013). The comparable starch content in treatments with 90% RDN + 10% N through FYM and vermicompost indicates that organic amendments can effectively supplement chemical fertilisers to provide the necessary nitrogen for starch production (Iqbal *et al*. 2022). Similar results were observed by Walia *et al.* (2023), Srija *et al*. (2022), Biswas and Dutta (2020) and Mohamed *et al*. (2016).

Influence of integrated nutrient management on the economics of potato

The data presented in Table 7 demonstrates the economics of potato cultivation as

Table 7. Influence of integrated nutrient management on the economics of Potato.

Treatments	Economics			
	Cost of cultivation (Rs. ha^{-1})	Gross return (Rs. ha^{-1})	Net return (Rs. ha^{-1})	B:C
T_1 : 100% Recommended Dose of Nitrogen (RDN)	90236	350600	260364	2.89
T_2 : 90% RDN + 10% N through Farm Yard Manure (FYM)	111938	311900	199962	1.79
T_3 : 90% RDN + 10% N through Vermicompost	111538	325550	214012	1.92
T_4 : 80% RDN + 20% N through FYM	132872	223675	90003	0.67
T_5 : 80% RDN + 20% N through Vermicompost	133672	234200	101328	0.76
T_6 : 70% RDN + 30% N through FYM	155437	168275	12838	0.08
T_7 : 70% RDN + 30% N through Vermicompost	154237	215850	61613	0.40
T_8 : Control (Without any chemical fertilisers or organics)	88671	102925	14255	0.16

affected by integrated nutrient management practices. Applying 100% RDN resulted in the highest gross return (350600 Rs. /ha) and net return (260364 Rs. /ha) followed by the treatment that received 90% RDN + 10% N through vermicompost. The highest benefit cost ratio was obtained with 100% RDN application which is likely due to lower cost of cultivation and it was followed by the treatment which received 90% RDN + 10% N through vermicompost. This indicates that the investment in nitrogen fertilization paid off significantly, resulting in increased yield and profitability. Interestingly, the treatment that received 90% RDN + 10% N through vermicompost closely followed the returns of the 100% RDN treatment. This suggest that integrating organic amendments like vermicompost can be a effective strategy compared to FYM. The results are in conformity with the findings of Chaudhary *et al.* (2022), Pandit *et al.* (2021) and Patel *et al.* (2022).

CONCLUSION

This study has demonstrated the significant impact of integrated nutrient management (INM) practices on the growth, yield, and quality of potato. The application of a 100% recommended dose of nitrogen (RDN) resulted in the highest growth, yield and quality performance, underscoring the critical role of nitrogen in potato cultivation. Notably, treatments integrating 90% RDN with organic amendments such as vermicompost closely matched the performance of 100% RDN in several parameters, highlighting the effectiveness of INM practices.

The findings emphasize the potential of INM to optimize crop productivity while enhancing soil health and sustainability. The economic analysis revealed that the highest gross and net returns were achieved with 100% RDN, with the benefit-cost ratio affirming its financial viability. However, the near-equivalent performance of specific treatments with organic amendments suggests that by fine-tuning nutrient levels and integrating organic sources, potato growers can achieve a balance between yield optimization and long-term profitability.

In response to the scientific hypotheses and objectives raised, the study confirms that INM can significantly enhance potato growth and yield, as well as improve the economics of potato cultivation. Future research should focus on refining nutrient management strategies and exploring additional organic amendments to further enhance sustainable potato production.

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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EVALUATION OF SOME NANO-FERTILIZERS, BIOFERTILIZERS AND CHEMICAL FERTILIZERS ON POTATO VARIETY SPRIT

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ABSTRACT: Potato is one of the most important crops grown worldwide. Current research was performed to identify the influences of various types of nano-fertilizers, biofertilizer and bulk fertilizers on tuber yield and some other traits of the Sprit potato variety. The trial was arranged in a randomized complete block design with three replicates with six nutritional treating; control, NPK in bulk form, MOG biofertilizer, nano-calcium, nano-zinc plus nano boron and complete nano-fertilizer and various twelve traits of potato were measured. They were number of leaves (NL), number day to initiation of tuberization (DIT), days to row closure (DRC), days to flowering (DF), number of tubers per plant (NTP), number of stems (NS), tuber yield (TY), mean tuber diameter (MTD), mean tuber weight (MTW), tuber weight per plant (TWP), dry matter content (DM) and starch total (ST). The factor analysis indicated that the first two factors, accounted 92% of variability and revealed that MOG biofertilizer was related to days to row closure and mean tuber diameter, while NPK produced the high numbers of stems. Also, no fertilizer usage (control) caused delay to initiation of tuberization, while complete nano-fertilizer had the higher amounts of the other traits like tuber yield. For obtaining the more number of leaves per plant, using complete nano-fertilizer following to nano-zinc plus nano boron is advise while for more numbers of tubers per plant, application of all tested nano-fertilizers is useful. The nano-fertilizers have beneficial ability in comparison to bulk-form and biologic fertilizers, thus nano-fertilizers especially the complete nano-fertilizer should be used to minimize the harmful influences of nutrient shortage and reaching targets of sustainable and low-input agricultural systems in production of potato under semi-arid environments.

KEYWORDS: Factor analysis, Cluster analysis, Sustainable agriculture, Nanoparticles

INTRODUCTION

The potato holds a significant position as a crucial food source for humanity. Its global production stands as the fourth highest, following cereals, amounting to 370 million tons whereas Iran, ranking twelfth globally and third in Asia (after China and India) (FAOSTAT, 2022). Despite Iran's notable standing as a major potato producer, managing the nutritional needs of this crop has proven to be a considerable challenge. A portion of nutrients accumulates in the topsoil and is subsequently extracted from the field during tuber harvesting (Job *et al.*, 2019). Several factors contribute to the low yields experienced in cold semiarid areas, including: the soil-plant system experiences high nutrient turnover, shortage of nutrients, a substantial nutrient shortage, and inefficiency in nutrients utilization further compounds the challenges (Mukhopadhyay *et al.*, 2021). The fields of cold semiarid areas exhibit low levels of potassium, phosphorus, iron, manganese, and zinc, so effective nutrient management emerges as a crucial strategy to enhance potato productivity in this region (Janmohammadi *et al.*, 2016).

The limited availability of local nutrient sources such as farmyard manure, compost, and biologically nitrogen fixation emphasizes the urgent requirement for the using fertilizers in a more efficiently system. Nanotechnology has emerged the development of a new fertilizers that boast enhanced nutrient utilization efficiency (Janmohammadi & Sabaghnia, 2023). Distinguished by unique

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physico-chemical properties, nano-structured fertilizers efficiently meet plant root demands in comparison to routine fertilizers in salt form. The gradual release of nutrients occurs through processes like ion exchange activities (Vejan *et al.,* 2021). Nano-fertilizers exhibit controlled release properties, ensuring a gradual supply of nutrients over time, which is achieved through processes like dissolution and ion exchange reactions. These fertilizers are formulated at the nanoscale, imparting unique physico-chemical properties which allow for efficient nutrient delivery to plant roots (Das *et al.,* 2021). Nano-fertilizers possess novel physico-chemical properties that set them apart from conventional fertilizers, which contribute to their ability to satisfy plant root demands more efficiently. The advent of nanotechnology in agriculture, particularly in the form of nano-fertilizers, has the potential to revolutionize traditional agricultural practices (Sabaghnia & Janmohammadi, 2023). Given the increased demand for nutrients in intensive cropping systems, nano-fertilizers offer a promising solution to meet these demands more effectively.

There is a growing focus on biological fertilizers like biofertilizer of MOG via various plants residues by enriching of different enzymes, nutrients and vitamins. This organic fertilizer offers significant advantages in generating fertile field and nutrients needs through the supply of natural elements (Shokouh *et al.,* 2018). However, there is limited information available regarding the impact of enzymatic fertilizers on potato production systems. In the context of potato production, there has been a positive response to conventional NPK fertilizer, especially in soils with poor texture. There are some nutrient deficiencies in potato production systems of Iran and in spite of some research on nutrient management in potato, there is limited information about the effects of biologic and nanoform fertilizers on potato tuber yield. Therefore, the target of the investigation is to explore the effect of biofertilizer, nano-fertilizers, and bulk fertilizers, in improving potato production.

MATERIAL AND METHODS

Materials

The research took place at the experiment farm in Sarab, Iran (37°56′N 47°32′E), with climate as cold semi-arid (BSk), indicative of semiarid conditions characterized by cold winters. Meteorological data spanning last decade for the region revealed min 2°C and max 17°C, with mean temperature 9/26°C day/night during growing season. The farm is identified as sandy loam, composed of 56% sand, 31% silt, and 13% clay. The soil analysis indicated a low organic matter (0.7%), N (0.07%), K (324 mg kg^{-1}), and P (11.3 mg kg^{-1}). For this study, the potato variety Spirit fall into the category of late-medium maturity. The field preparation was performed in November, followed by two disking sessions before seed planting. The seeds were sown at a depth of approximately 20 cm on May 10, 2014. Each plot covered an area of 36 m^2, comprising eight 6-meters rows, with of 75 cm between rows space and 25 cm within rows space. A surface irrigation is applied and plants received furrow irrigation. The employed design was a randomized complete block design with three replicates.

Treatments

The six nutritional treating, each representing a specific fertilizer treatment: Control (no fertilizer application), NPK (chemical nitrogen, potassium and phosphorus fertilizers in 20:10:5 rate), MOG (2 L ha^{-1} biofertilizer), Nano-Ca (2 kg ha^{-1} nano-calcium), Nano-Zn+B (2 kg ha^{-1} nano-zinc plus nano-boron), and Nano-C (1 kg ha^{-1} nano-complete fertilizer). The NPK was used at a rate of kg ha^{-1}; 100 kg ha^{-1} served as a pre-sowing and the remained amount was applied on the tuber initiation. The remined treatments were administered through fertigation, a method where nutrients are applied directly via irrigation on sowing and tuber initiation. Fertigation allows for the targeted application of nutrients directly to areas of root zone, meeting the crop's needs. The nano-nutritional treating sources were received from the SepehrParmis Co., Iran, which contain nanoparticles of CaO, ZnO and B_2O_3. Morphological characterization of the synthesized nanoparticles was conducted using a SEM (**Fig. 1**). The MOG enzymatic biofertilizer utilized in the study was provided from the Azarabadegan Co., Iran. Irrigation was administered on a weekly and to manage weeds, disease, and pests, cultivation practices and recommended amounts of agrochemicals commonly used in the Sarab region were applied.

Traits Measurement

The number of leaves (NL) was recorded in the tuber bulking. Some phenological traits like DIT, number day to initiation of tuberization (No.); DRC, days to row closure (No.) and DF, days to flowering (No.) were recoded. At the harvesting stage; NTP, number of tubers per plant (No.); NS, number of stems and TY, tuber yield (t ha^{-1}) were measured. Also, some yield components like MTD, mean tuber diameter (cm); MTW, mean tuber weight (g); TWP, tuber weight per plant (g) were registered. The dry matter content (DM, %) and the starch total (ST, %) from newly cut tubers was evaluated based on Noda *et al.* (2004).

Data analysis

The normal distribution of data was evaluated by the Ryan-Joiner goodness of fit test. The factor analysis was used for the decrease of associated traits to a small number of factors and the extracted factor loadings were rotated via varimax orthogonal method. For graphic presentation of traits' associations, the scores of first two factors were plotted each other. Also, for simultaneous presentation of treatments and traits in a single graph, a scatter plot that benefits both signs of treatments and traits which is known as biplot was generated to show data pattern. Finally, treatments and traits were clustered by their distance from each other using Squared Euclidean Distance and clustered by Ward's minimum variance procedure. The cutoff point for determine the number of final clusters was verified using λ statistic of MANOVA. The data analysis was performed via STATISTICA version 10.0 application.

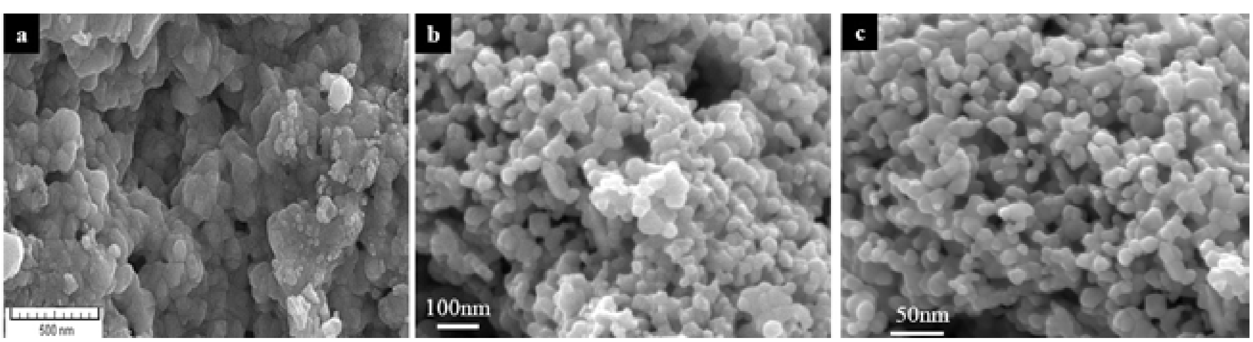

Fig. 1. SEM of nanoparticles which are used in nano-fertilizer treatments (a) CaO, (b) B_2O_3, and (c) ZnO.

RESULTS AND DISCUSSION

Phenotypic Traits

The first two factors explained 92% of the variability for the potato characteristics under various treating (**Fig. 2**), and the associations among them can be understand via the vectors of each characteristic to the center of the plot. The longitude of each line indicates the bias of association and the cosine of the lines' angle indicates the magnitude of association between the traits. The right lines' angle representative of no association (cos 90°=0), the opposite lines' angle representative of negative association (cos 180°= -1), and closed lines' angle representative of positive association (cos 0°= +1). From **Fig. 2**, DM, NTP, DF, NL, TWP, ST, TY and MTW were positively associated and showed relatively the same information about response of potato to the fertilizers. Most of the above traits were related to tuber properties like NTP, TWP, TY and ST, so improving one of them can increase the other related traits results in higher yield performance. Our findings were in good compromise with those mentioned by Zelalem *et al.* (2009), who reported tuber yield had positive association with tuber number and tuber weight and increasing of number and weight of tubers by appreciate fertilizer application cause to increase in tuber yield. Also, DRC and MTD were positively correlated and gave the similar information about the fertilizers impacts on potato (**Fig. 2**). Similarly, Blauer *et al.* (2013) reported that number of the days to row closure had positive association to mean tuber diameter. Regarding the right lines' angle of DIT and NS, there is not any significant association between these traits (**Fig. 2**). Also, NS did not show any significant association with DM, NTP, DF, NL, TWP, ST, TY and MTW due to relatively right angles (**Fig. 2**). Although, according to Knowles & Knowles (2006), number of stems has positive association with number of tubers and positive association with tuber size, but we could not identify such association. The DIT showed significant negative association with DM, NTP, DF, NL, TWP, ST, TY and MTW (**Fig. 2**), so early tuberization can be regarded for obtaining the high magnitudes of above traits specially yield and its components.

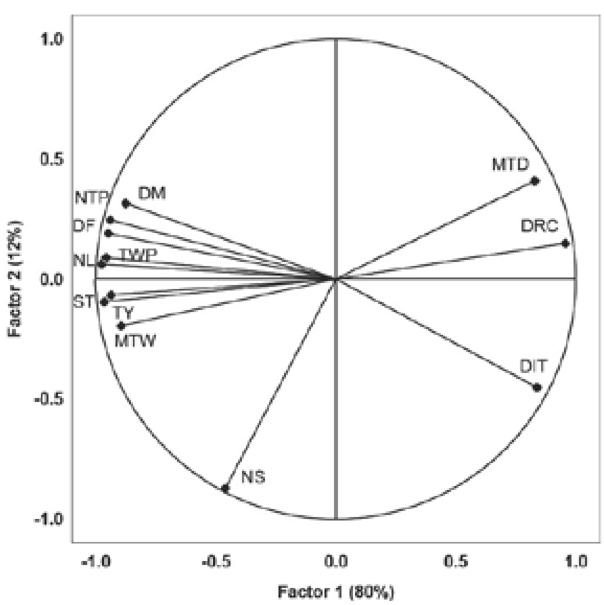

Fig. 2. Plot of first two factors showing the interrelationships among traits of potato.

Factorial Analysis

For simultaneous evaluation of treatments and traits, biplot, a scatter plot that benefits both signs of treatments and traits to show data pattern, was generated (**Fig. 3**). It indicates the scores of the individuals and variables of the principal components analysis in a single plot, so using this plot, fertilizers can be studied for their influence in measured traits. **Fig. 3** shows Nano-C treatment produced high amounts of DM, NTP, DF, NL, TWP, ST, TY and MTW traits in potato while MOG treatment caused high magnitudes of DRC and MTD traits (**Fig. 3**). So, it seems using complete nano-fertilizer can help potato grow better and produce more tuber yield. It has 11 important nutrients in it, consist on

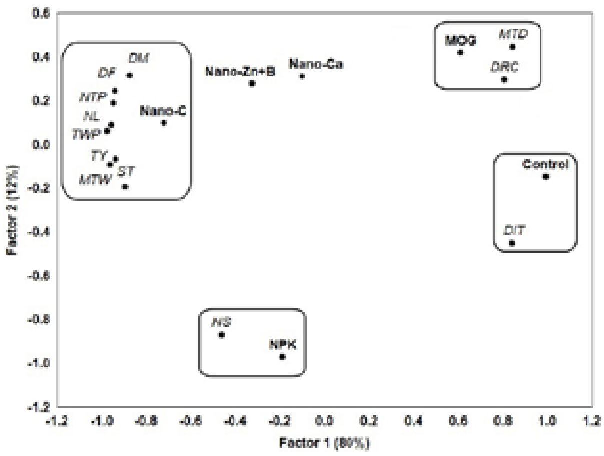

Fig. 3. Biplot of first two factors showing the interrelationships among fertilizer treatments and traits in potato.

nitrogen, phosphorus, potassium, iron, zinc, calcium, manganese, magnesium, copper, boron and molybdenum, that are all needed for potato growth and production. There is a lot of documented information about how potato responds to various nutrients especially about nitrogen, phosphorus and potassium, as well as some information about magnesium, zinc, and manganese (Zarzecka *et al.,* 2016; Baranowska *et al.,* 2017). But there is less information about how potato's response to iron and molybdenum as well as limited information reaction of potato to calcium, boron, and copper (Singh & Maiti, 2022). The reaction of potato to macronutrient fertilizers application changes with micronutrient fertilizer regarding to the field circumstances, variety type whereas most micronutrients like iron, zinc, manganese, copper and molybdenum influence potato yield performance (Lal *et al.,* 2020). Also, high DIT (day to initiation of tuberization) is seen in no-fertilizer treatment which emphasize the role of fertilization in early tuberization. The NPK treatment generated a greater number of stems (NS) while both other nano-fertilizers (zinc plus boron and calcium) were not the best treatment for any of characteristics in potato. It was shown that using fertilizers in nanoform enhanced chickpea to grow better and faster with aiding chickpea grow better and survive in the stress of climate change problem (Bala *et al.,* 2014).

Cluster Analysis

For verification discussed results of factor analysis, the cluster analysis as an agglomerative hierarchical tool was used to grouping traits (**Fig. 4**) as well as treatments (**Fig. 5**). The measured twelve traits of potato could be agglomerated into four clusters and this number of clusters was confirmed by λ statistic of Wilks which is obtained from MANOVA (λ=0.0051, p<0.01). In dendrogram of **Fig. 4**, Cluster-I consist on DM, NTP, DF, NL, TWP, ST, TY and MTW traits which is verified the obtained results of **Fig. 3**. Also, Cluster-II contains NS; Cluster-III consist on DIT and Cluster-IV contains DRC and MTD traits (**Fig. 4**). While it is expected that most results of factor analysis and clustering can be verified from each other, but some results were not consistent because the factor analysis usually describes less than 100% of the total variability. In this research, two first factors explained 92% of total variance and only 8% was remined for the other factors, but the overall results were in good agreement with

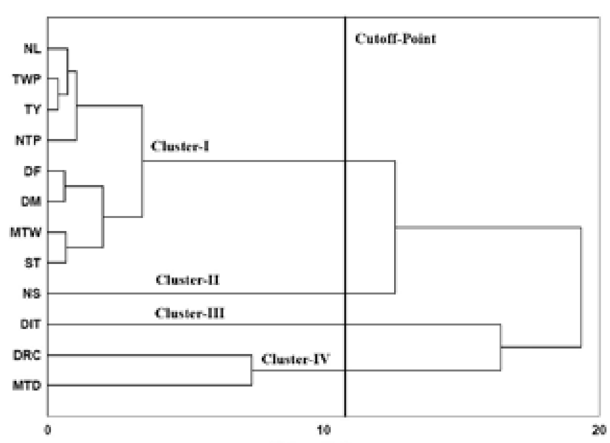

Fig. 4. Dendrogram of cluster analysis showing the grouping of measured traits of potato.

the clustering method which used 100% of observed variance. Finally, both methods give visual understanding on the data pattern, which is more practical and reliable than the univariate statistics. The six fertilizer treatments could be categorized into five clusters via confirmation of λ statistic of Wilks in MANOVA (λ=0.0064, p<0.01). In dendrogram of **Fig. 5**, Group-I was Control, Group-II was MOG, Group-III was NPK, Group-IV was two nano-fertilizers (Nano-Zn+B and Nano-Ca) and Group-V was Nano-C. Similar to traits, clustering of fertilizer treatments verified the results of factor analysis in **Fig. 3**.

Means of Clusters

The mean values of traits for fertilizer treatments were compared, and it can be indicated that Nano-C treatment was the best for DM, NTP, DF, NL, TWP, ST, TY and MTW traits while for NTP and NL traits, the other treatments can be regarded as the same with Nano-C. In other word, for obtaining the grater NL, we can use both Nano-C and Nano-Zn+B while for reach to the higher NTP, we can use Nano-C, Nano-Zn+B and Nano-Ca (Results are not shown). Such details are missed in multivariate analysis and they gave general grasp from data pattern. However, for obtaining the grater NS, using NPK is suitable while for reach to the higher DIT, DRC and MTD, no using any fertilizer is advised. However, using MOG treatment result is same results of Control treatment in MTD trait.

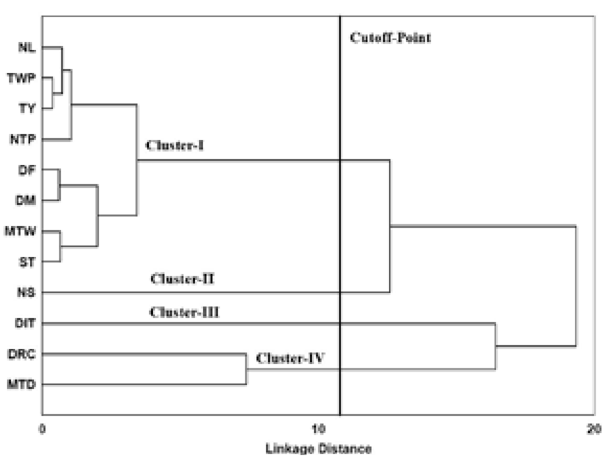

Fig. 5. Dendrogram of cluster analysis showing the grouping of fertilizer treatments.

Importance of Nano-fertilizers

The current investigation indicated that application of complete nano-fertilizer positively induced the potato growth in comparison to the other fertilizer, so the field soil has some nutritional deficiencies. The need of calcium is essential in saline fields of semiarid conditions for control the balance of potassium and sodium ions while using only calcium is less useful and the applying of Nano-C had the best impact on potato in comparison to Nano-Zn+B. This may be the result of synergy phenomena between the calcium and other macro and micro nutrients, like the positive effect of zinc on calcium for next uptake of P and K from the soil (Lambers *et al.,* 2019). Thus, calcium fertilizer is important in the potato and it has been shown that even if calcium application is sufficient, its deficiency can be compensated and calcium is allocated in tubers allocation of calcium within the plant (Naumann *et al.,* 2020).

Our results showed that Nano-C followed by NPK increased the tuber yield while application of chemical fertilizers like nitrogen is related with nitrate accumulation in potato tubers, so nitrogen management is one of the important issues needed to achieve good yield performance. Bulk N is very mobile element and can move the root area, so preparing the N as nano-form can eliminate the problem of bulk form. The nutrients use efficiency can be ameliorated by application of nano-fertilizers because they can deliver in exact targets in a slowly release mood. Also, nano-fertilizers can release in dynamic reaction to biologic and non-biologic factors. Using bulk form of macronutrients can decrease the uptake of micronutrients Fe, Ca, Mg, Mn, Zn and Cu.

Importance of Bio-fertilizers

Nowadays, healthier food market is increasing and governmental policy in many countries emphasized on sustainable agriculture, so organic food production is advised in many regions. Although the positive effects of most biofertilizers like MOG has been mentioned in literature (Janmohammadi *et al.,* 2014), but its application in this study could improve only DRC and MTD traits. However, it can be concluded that in cold semiarid areas using biofertilizers will not be adequate for crop growth, so using complementary sources of nutrients is essential. This result is in good agreement with the report of Helmy (2019), who have found the nonefficiency of biofertilizers in semiarid areas due to due to soil properties and humidity. In present investigation, the highest mean values were seen under complete nano-fertilizer which has balance adequate magnitudes of all required elements. Production of high yielding health potato needs all required elements in essential amount, and either deficiency or overdose can decrease tubes. There are several investigations for verification of nutrients' shortage as critical phenomena in the semiarid areas of the Mediterranean regions (Bastida *et al.,* 2019; Brahimi *et al.,* 2022), so nano-fertilizers by slowly release of nutrients can remove this problem. Rate of using for nano-fertilizers can be lower than bulk form because the chelated form is more efficient and available for more time, so their benefits are increase. Our findings indicated that Spirit variety reacted to the fertilizer treatments in compression to Control similar to Jafari-Jood *et al.* (2013), who indicated that this variety has the best performance with application of nitrogen, boron and manganese.

CONCLUSION

We found the best efficient fertilizer application to ameliorate yield performance and yield components of potato is using Nnao-C (complete nano-fertilizer) while the other nano-fertilizers (Nano-Zn+B; nano zinc plus nano boron and Nano-Ca; nano calcium) did not have any considerable impact on potato. Similarly, using chemical NPK fertilizer and MOG biofertilizer did not indicate any considerable effect on potato's traits. We found the useful influence of nano fertilizer compared to bulk and biologic fertilizers, but more investigations are required to evaluate the other aspects of nano-fertilizers, and determining their interactions with soil and other environmental factors.

CONFLICT OF INTEREST

The authors confirm that this manuscript has 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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AN EFFICIENT *AGROBACTERIUM*-MEDIATED TRANSFORMATION METHOD FOR POTATO C.V. KUFRI CHANDRAMUKHI

Anupama Singh[1,2]*, Ankita Sharma[1], Hemant B. Kardille[2], Vinay Bhardwaj[2], Som Dutt[2] and Brajesh Singh[2]

ABSTRACT: An optimized regeneration and *Agrobacterium*-mediated transformation protocol based on internode explants was developed in potato cultivar 'Kufri Chandramukhi'. Potato internodes were transformed by cocultivation with *A. tumefaciens* strain EHA 105 harboring vector pRI101. MS medium with IAA 0.042mg L^{-1} + GA_3 3.0 mg L^{-1} + Zeatin 3.0 mg L^{-1} showed the maximum percentage of callus formation i.e. 76% with average number of shoots per explants was 7.00. This medium showed mimimal number of days for callus initiation as compared to other medium compositions The best combination for shoot regeneration was a medium of Murashige & Skoog salts with 0.042 mg L^{-1} IAA, 3.0 mg L^{-1} GA_3, 3.0 mg L^{-1} Zeatin and 0.008 mg L^{-1} NAA. Use of 50 mg L^{-1} Kanamycin, 250 mg L^{-1} Carbenicillin and 100 mg L^{-1} Cefotaxime in the callus induction medium minimized contamination. This method is useful for genetic transformation studies in KCM.

KEYWORDS: Potato, *Agrobacterium tumefaciens*, Transformation, Regeneration

INTRODUCTION

Globally potato is the third most important crop after rice and wheat It produces more food per unit area and time than any other crop, in the form of tuber with high dry matter, carbohydrates, proteins and vitamins. Potato is viewed to have potential to alleviate hunger and malnutrition in the developing world. Being autotetraploid and highly heterozygous, its improvement via conventional breeding has been slow. Therefore, various biotechnological tools like somatic hybridization, *in vitro* mutagenesis and genetic transformation can be exploited for potato improvement (Beaujean *et al.*, 1998]. Two methods of genetic transformation in potato have been used; direct gene transfer, using particle gun bombardment, and, indirectly through *Agrobacterium*-mediated transformation. However, the cost of gene transfer using particle bombardment is high, and low regeneration is often observed. Apart from this, direct gene transfer methods lead to integration of high copy number of genes resulting in gene suppression and silencing. On the contrary, *Agrobacterium*-mediated transformation is an efficient protocol for single gene transfer. Single gene expression is often stable to subsequent generations (Chakravarty *et al.*, 2007).

An efficient plant regeneration system is a prerequisite for developing an *Agrobacterium* mediated genetic transformation protocol. Successful genetic transformation and regeneration in potato is highly genotype specific. Both gene transfer and subsequent regeneration of plants is affected by several factors. These include the genotype of the plant, type of explant used, preculture time, co-cultivation time, antibiotics used for suppression of *Agrobacterium* overgrowth and the composition of the callus induction and

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regeneration medium. In potato regeneration has been reported to be strictly influenced by genotype. Significant differences in shoot formation efficiency in commercial cultivars have been observed (Martel *et al*., 1992 Kumlay and Ercisli; 2015). The choice of antibiotics and their concentration also influences potato regeneration. The phytotoxicity of the antibiotic varies with the genotype, its interaction with the medium components, explant type and age. Several investigations highlight the different effects of phytohormones on the regeneration ability in potato (Rawat *et al*., 2017, Dhaka *et al*., 2015).

Kufri Chandramukhi (KCM) is one of the earliest developed and a popular variety in India producing optimal yield, attractive tubers with good processing attributes. However, it is also highly susceptible to various diseases and many abiotic stresses. Genes conferring tolerance to these stresses can be introgressed in KCM to get transgenic potato with desirable characteristics (Singh *et al*., 2015) Thus, medium composition was optimized for transformation in KCM, using binary vector PRI10, harboring a potato annexin gene. Comparison of different phytohormones on callus induction, shoot and root initiation was done to establish an efficient regeneration protocol for *Agrobacterium*-mediated gene transfer in KCM. This protocol would be helpful to further study gene functions and transgenic development in potato.

MATERIAL AND METHODS

Plant material

Mother plant was obtained from germplasm lab of division of crop improvement, ICAR-CPRI Shimla. The tissue culture plant was sub-cultured routinely (Singh *et al*., 2016) and maintained in MS medium (Murashige and Skoog, 1962). Four-week-old plantlets were selected for the experiment

Agrobacterium Strain and Plasmid

The construct was generated by introducing the full-length cDNA of potato annexin p34 gene (GenBank Accession no:**CAB92956)** into the binary vector pRI101 and driven by the cauliflower mosaic virus 35S promoter. The vector was transformed into the *Agrobacterium tumefaciens* strain EHA105. Cells were grown overnight in LB medium containing 50 mg L^{-1} kanamycin. About 20% of primary culture was inoculated into a flask containing 100 ml LB with 50 mg L^{-1} kanamycin and was allowed to grow overnight till OD_{600}- reading of the culture reached 0.8–1. *Agrobacterium* cells were harvested by centrifugation at 5000 rpm, 4°C and the pellets were resuspended in MS liquid media (MS salts +10 g glucose +20 g L^{-1} sucrose and pH5.8) so that OD600 of the culture was 0.6–0.8. *Agrobacterium* cells were activated by the addition of 100 mM acetosyringone in dark before cocultivation.

Pre treatment

Four-week-old tissue cultured potato plants was selected, internodes were excised (4-6 mm) and placed on plates containing preculture medium (Table 1). Plates were then incubated in tissue culture room for two days at 24±2°C with photoperiod of 16 h.

Co-cultivation and shoot induction

The internodes after two days of pretreatment were incubated in the *Agrobacterium* suspension in the petri plate for 15-20 minutes covered in foil paper. Gentle shaking was done 4-5 times. The explants were then blotted on autoclaved and sterilized tissue paper gently until they were dried completely. Internodes were then placed on Petri plate with preculture medium having

Table 1. Composition of media used in the present study.

S.No	Medium	Composition
1	Preculture medium	MS+20g L^{-1} sucrose+2g L^{-1}gelrite
2	**Selective medium**	
2a	Selective medium M1	MS + IAA 0.042mg L^{-1} + GA_3 3.0 mg L^{-1} + Zeatin 3.0 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefotaxime 100 mg L^{-1} + NAA 0.008 mg L^{-1}
2 b	Selective medium M2	MS + NAA 0.4mg L^{-1} + BAP 1.2 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefotaxime 100 mg L^{-1}
2c	Selective medium M3	MS + IAA 0.05mg L^{-1} + GA_3 2.5 mg L^{-1} + Zeatin 2.5 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefotaxime 100 mg L^{-1}
3	**Rooting medium**	
3 a	Rooting medium R1	MS+ 50mg L^{-1} Kanamycin+ 0 IAA
3 b	Rooting medium R2	MS+ 50mg L^{-1} Kanamycin+ 0.2mg L^{-1} IAA
3 c	Rooting medium R3	MS+ 50mg L^{-1} Kanamycin+ 0.3mg L^{-1} IAA
3 d	Rooting medium R4	MS+ 50mg L^{-1} Kanamycin+ 0.4mg L^{-1} IAA

Whatman filter paper (grade 1; 110 mm) on it. Plates were then kept in tissue culture room for two days at 22°C with photoperiod of 16 h. After 2-3 days after incubation, co-cultivated explants were transferred to different selective media (Table 1).

Shoot induction

The explants were placed carefully on the plates with different compositions of phytohormones for selective medium. (Table 1) Internode explants were placed directly without any filter paper on the medium. Plates were watched regularly and growth was observed. Plates were discarded if any contamination occurred. After 20-30 days, explants were shifted to new plate. Shoots emerged on the calli developed which were then excised and transferred to tubes containing same medium composition for proliferation.

Root induction

After the emergence of putative transgenic shoots, (2.5-3.0cm height) obtained on the best suitable selective shoot medium, these were excised and transferred to the four selective root regeneration media to select the best possible medium (Table 1). The whole plantlet was then sub-cultured on basal medium for further analysis

Analysis of potato transgenics

Genomic DNA was isolated from the transformed plants using DNeasy® Plant mini kit (Qiagen) PCR amplification was done using primers specific for nptII gene. The sequence of the forward and reverse primers was 5´GAGGCTATTCGGCTATGAGTG 3´ and 5´GCGATACCGTAAAGCACGAGG.3´ respectively. The PCR was carried out at the following conditions: 94 °C for 3 min, 94 °C for 30 s, 54 °C for 30 s, 72 °C for 1 min, 35 cycles and followed by 1 cycle at 72 °C for 7 min. PCR products were visualized after electrophoresis in 1.2 % agarose gel photographed on gel documentation system (Bio Rad)

RESULTS AND DISCUSSION

Transformation and callus induction

In present study we optimized the *Agrobacterium* mediated transformation of potato cultivar Kufri Chandramukhi. using *Agrobacterium tumefaciens* strain EHA105, containing binary vector PRI101 with a potato annexin gene (GenBank Accession no: **CAB92956)** and *npt-II* (neomycin phosphotransferase-II) genes as a selectable marker. The gene construct was developed as a part of our ongoing studies in potato thermotolerance.

Three media for shoot regeneration were selected using prior studies to find the best one for KCM transformation (**Table 2**). M1 medium showed the maximum percentage of callus formation i.e. 76% with average number of shoots per explants was 7.00. This medium showed mimimal number of days for callus initiation as compared to other medium compositions (~ 53 and ~38 days respectively). The cells or tissues that were not transformed gradually turned brown after 45-50 days. Plates were monitored regularly for contamination. Approximately after three months, the emergence of putative transgenic shoots from callus was observed (**Fig. 1**). The best combination of growth regulators for shoot initiation in KCM was that of GA_3, zeatin and IAA. Using these growth regulators, a transformation rate of 28.97% and 24.37% has been reported in potato varieties "Asterix" and "Diamante" respectively (Molla *et al*., 2011). In potato a combination of BAP, GA_3 and NAA have also been used for successful shoot initiation

Fig. 1. Standardisation of callus and shoot regeneration medium for KCM transgenicsA; medium with composition MS + NAA 0.4mg L^{-1} + BAP 1.2 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin20 mg L^{-1} + Cefotaxime 40 mg L^{-1}; B: medium with composition MS + IAA 0.05mg L^{-1} + GA_3 2.5 mg L^{-1} + Zeatin 2.5 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefo 100 mg L^{-1}; C: Best medium with composition MS + IAA 0.042mg L^{-1} + GA_3 3.0 mg L^{-1} + Zeatin 3.0 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefotaxime 100 mg L^{-1} + NAA 0.008 mg L^{-1}

Table 2. Effect of medium composition on the callus and shoot initiation in potato cultivar Kufri Chandramukhi.

S.No.	Treatment	Medium Composition	Percent Callus Formation	Average number of shoots per explants	Average number of days for callus initiation
1	M1	MS + IAA 0.042mg L^{-1} + GA_3 3.0 mg L^{-1} + Zeatin 3.0 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefotaxime 100 mg L^{-1} + NAA 0.008 mg L^{-1}	76%	7.00 ± 1.15	22.33± 1.45
2	M2	MS + NAA 0.4mg L^{-1} + BAP 1.2 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefotaxime 100 mg L^{-1}	20%	2.33 ± 0.33	53.66 ± 2.18
3	M3	MS + IAA 0.05mg L^{-1} + GA_3 2.5 mg L^{-1} + Zeatin 2.5 mg L^{-1} + Kanamycin 50 mg L^{-1} + Carbenicillin 250 mg L^{-1} + Cefotaxime 100 mg L^{-1}	45%	3.66 ± 0.33	38.66 ± 2.33
	CD ±SE(m)			0.48 ± 0.14	0.56 ± 0.16

(Rawat *et al*., 2017, Khatun *et al*., 2012 and Beaujean *et al*., 1998 Farhatullah and Abbas; 2007). Optimum Kanamycin concentration is crucial for the selection of transformants. Previous studies have reported use of kanamycin concentration of 20 mgL^{-1}, 25 mgL^{-1}, 50 mgL^{-1} and 80 mgL^{-1}. (Onamu *et al*., 2012 and Saker *et al*., 2012) We used 50 mgL^{-1} kanamycin to select the growth of transformed shoots in all the selective media. The use of higher concentration of the antibiotics allows less escapes but lowers the regeneration potential o (Wenzler *et al*., 1989).

Root induction

The *in vitro* developed putative transgenic shoots were then transferred on the tubes containing same selective shoot regeneration medium having kanamycin 50 mg/Cefotaxime 100 mg L^{-1} and carbenicillin 250 mg L^{-1} for multiplication. After obtaining 2-3 cm height, the shoots were transferred to the selective root regeneration medium. The putative transgenic shoots (2.5-3.0 cm height) obtained on the selective shoot multiplication medium were excised and transferred to the selective root regeneration medium. All four different rooting media were significantly different from each other in terms of number of roots and root length (Table 3). The roots initiated after 12-15 days of inoculation on the selective medium and within 25-28 days well developed roots were observed (**Fig. 2**). However, in medium, with no hormone i.e. R1, no rooting was observed till 3 months. Medium R3 with MS+ 50 mg L^{-1} Kanamycin+ 0.3mg L^{-1} IAA showed maximum rooting within minimal number of days as compared to other medium. Average number of roots were also observed maximum in same rooting medium. (**Fig. 3**) The best rooting was observed in medium composition with MS+ 50mg L^{-1} Kanamycin+ 0.3mg L^{-1} IAA. Alternative to IAA many researchers have used IBA for the rooting of potato plants with concentration varying from 0.5mg L^{-1} 1.0mg L^{-1} IBA *In vitro* root induction of callus-regenerated shoots was studied in potato cultivars "Pasinler", "Granola" and "Caspar" by Kumlay and Ercisli (2015) with the addition of various concentrations of NAA and IBA with GA_3 in MS medium. Best rooting was obtained with 0.1 mg L^{-1} GA_3 + 1.0 mg L^{-1} IBA in Pasinler suggesting

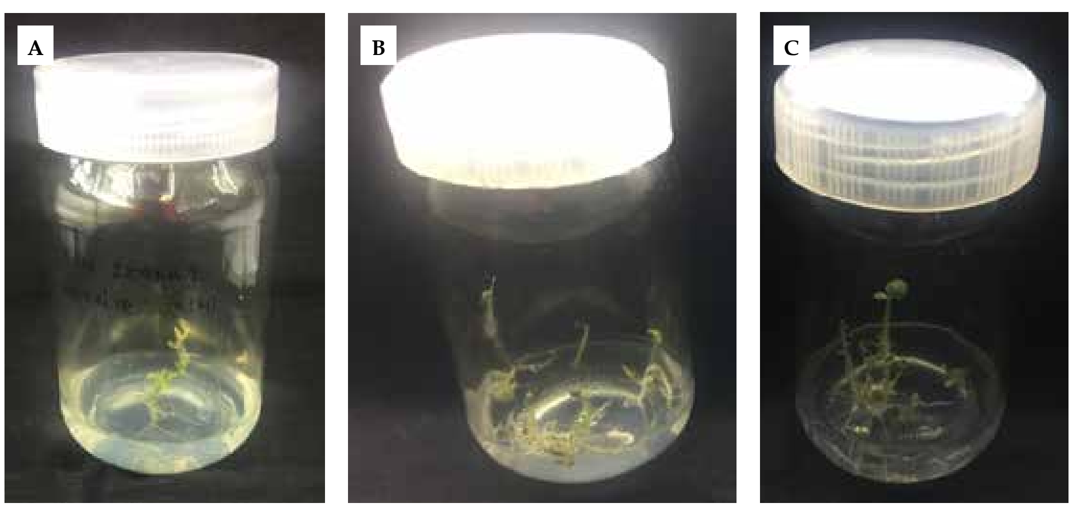

Fig.2. Standardisation of rooting medium for KCM transgenics; A: medium with composition (MS+ 50mg L-1 Kanamycin+ 0.2mg L^{-1} IAA); B: medium with composition MS+ 50mg L^{-1}Kanamycin+ 0.4mg L^{-1} IAA; C: The best rooting medium with concentration MS+ 50mg L^{-1}Kanamycin+ 0.3mg L^{-1} IAA

Table 3. Effect of medium composition for the root initiation and full-grown plantlets forpotato cultivar Kufri Chandramukhi.

S. No.	Treatment	Medium Composition	Number of days for rooting	Average Number of roots	Average root length after 15 days of initiation
1	RI	MS+ 50mg L^{-1} Kanamycin+ 0 IAA	-	0	0
2	R2	MS+ 50mg L^{-1} Kanamycin+ 0.2mg L^{-1} IAA	60	6.66 ±0.33	0.67 ±0.05
3	R3	MS+ 50mg L^{-1} Kanamycin+ 0.3mg L^{-1} IAA	15	31.33 ±2.02	2.62 ±0.10
4	R4	MS+ 50mg L^{-1} Kanamycin+ 0.4mg L^{-1} IAA	48	18.66 ±3.84	1.29 ± 0.03
		CD ±SE(m)		0.82 ± 0.24	0.06 ± 0.01

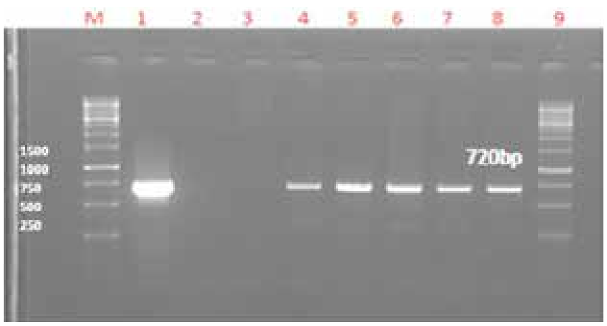

Fig. 3. Confirmation of the putative transgenics for presence of npt II gene; M 1kb ladder; 1: positive control as plasmid; 2: KCM negative control plant DNA; 3: water; 4-8: putative transgenic KCM lines showing integration of NptII gene; 9: ladder

efficacy of IBA in root induction. Proper root formation and root length in regenerated plants is crucial for the plants for their acclimatization and hardening. (Sanavy and Moeini; 2003)

Confirmation of transgene integration

To verify successful transformation, DNA was isolated from 52 transformants and was subjected to PCR analysis using *nptII* gene specific primers. Out of 52, 15 lines exhibited bands of expected size of 720 bp, corresponding to the *nptII* gene. There was no amplification in the non-transformed KCM plants used as control. A PCR reaction mix containing no DNA was also used as negative control whereas plasmid PRI 101 with full length annex in gene was used as a positive control. Thus successful integration of the gene was confirmed in potato lines The overall transformation efficiency was 28.8%

CONCLUSION

Kufri Chandramukhi (KCM) is a very popular and one of the earliest developed variety of potato. Though method for direct *in vitro* propagation of KCM is available to our knowledge, Agrobacterium mediated transformation and regeneration in KCM has not been reported previously. The callus induction and regeneration reponse in potato is highly genotype specific Efficient transformation and regeneration protocol is critical for developing transgenics gene editing and function studies. protocol the present study will help in the further improvement of KCM through genetic transformation ogin shortest period of time with minimum contamination.

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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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EVALUATION OF TRANSLAMINAR FUNGICIDES AND THEIR TANK MIXED APPLICATION WITH ECONOMICS FOR MANAGEMENT OF LATE BLIGHT OF POTATO (*PHYTOPHTHORA INFESTANS*) IN SUBTROPICAL PLAINS OF INDIA

Mehi Lal[1]*, Sorabh Chaudhary[2], Saurabh Yadav[1], Sanjeev Sharma[3], Manoj Kumar[1] and SK Chakrabarti[3]

ABSTRACT: Late blight, incited by *Phytophthora infestans* (Mont.) de Bary is the major disease of potato under the class of foliar diseases. Chemical methods are being used for the effective management of late blight. However, this pathogen is more vulnerable against specific mode of chemicals (systemic fungicides), which may develop resistant. The field efficacy of translaminar fungicides and their tank mixed application with economics were evaluated in two different experiments for managing late blight of potato during three consecutive years. In first experiment it was observed that dimethomorph 50%WP @ 0.2% showed least average terminal disease severity (14.54%) with highest disease controlled (84.15%) followed by ametoctradin 27% + dimethomorph 20.27% SC @ 0.2% and cymoxanil 8 + mancozeb 64%WP @ 0.3%. In second experiment, under the tank-mixed application dimethmorph 50%WP @ 0.1% + mancozeb 75%WP @ 0.2% showed less average terminal disease severity (22.67%) with highest disease controlled (75.97%) along with highest tuber yield (40.70 t/ha) and highest B:C ratio (2.16) followed dimethmorph 50%WP @ 0.1% + chlorothalonil 75% WP @ 0.2%, which was statistically significant. These treatments are also least affected by environmental factors like rainfall. These new fungicides and their tank-mixed sprays were found effective for managing the disease and moreover these tank-mixed sprays can be used to avoid development of resistance against pathogen.

KEYWORDS: Potato, Late blight, Fungicides, Spraying, Management

INTRODUCTION

Late blight incited by an oomycetes' *Phytophthora infestans* (Mont.) de Bary is the dreadful disease of potato in both fields and storage condition (Fry and Goodwin 1997). *P. infestans* has short asexual life cycle and sporulating foliar lesions develop in very short duration (3 to 7 days) after post infection under favorable weather conditions (Maltese *et al.*, 1995) causes quickly defoliation of plants in the field and can infect potato tubers under high disease pressure. In India, potato yield loss due to late blight disease was expected up to 10-15% during 2020 (Anonymous, 2020). The yield losses and cost for management of late blight of potato amounted up to 10.00 billion US dollar (Suo-Meng & Shao-qun, 2022).

Various management measures are being used for controlling the late blight disease. The cultural practices can be used to minimize the pathogen populations by decreasing its survivability, dispersal and reproduction. The resistant cultivars are the best option for economically and eco-friendly management of the disease (Lal *et al.,* 2018). However, whenever the resistant varieties became more widely adopted and

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prevailing of highly divers virulence nature of *P. infestans*, the host resistance breakdown occurred due to pathogen adaptation within a decade resulting in the emergence of new highly virulent strains (Fry 2008). Therefore, the last better option is remained the use of suitable fungicides for controlling the disease. Characterization and proper evaluation of fungicides are crucial steps for understanding better use of a new fungicide in effective late blight management program. Furthermore, successful disease management requires regular application of fungicides at high doses with short time intervals throughout the crop growing season (Lal *et al.,* 2015).

On the basis of mobility, late blight fungicides can be classified into three groups *i.e.* contact, translaminar and systemic. The contact fungicides are remained on surface of the plant while systemic fungicides moved inside the plant system, well known for plant disease management. In case of translaminar, fungicides enter into plant but not circulating in the plant and can cross the leaf surface thickness. The translaminar fungicides are more effective than contact fungicides and possess better tenacity on the plant surface, are being applied as combination with contact fungicides so that development of resistance can be avoid in pathogen. After introduction of metalaxyl (Phenylamide), within thirty-six months metalaxyl resistant isolates of *P. infestans* were observed on field grown potatoes in Ireland, The Netherlands and Switzerland (Gisi and Cohen 1996). The three fungicides *viz.,* mandipropamid, cymoxanil and mefenoxam were showed insensitivity against *P. infestans* clonal lineages of US11 and US8 (Saville *et al.,* 2015). During late 1980's for experimental purpose, metalaxyl based fungicides were introduced in India for management of late blight. However, its commercial application was started since 1994-95 and more than a decade developed high level of resistance against *P. infestans* thereby it failed to save the potato crop from the late blight in temperate highlands (Bhat *et al.,* 2009; Singh and Bhat 2007). The new fungicides with different mode of actions need to be evaluated regularly (Kamel *et al*.,2024) and pre-mixed two or more fungicides with different modes of action or tank mixed fungicides to be applied for management of late blight diseases, so that these modes of fungicides application can avoid to development of resistance in the *P. infestans*. Therefore, the aim of this study was to evaluate the translaminar fungicides and their tank-mixed applications along with economics against late blight to obtain maximum benefit from potatoes production.

MATERIALS AND METHODS

Two field experiments were conducted at ICAR-Central Potato Research Institute, Regional Station, Meerut, Uttar Pradesh during *rabi* season of the years 2015-16, 2016-17 and 2017-18. For each experiment seed tubers of *cv.* Kufri Bahar (Highly Susceptible) were planted in randomize block design (RBD) in 3×3 m^2 plot size and maintain 60×20 cm row to plant distance. The crop was planted in each year during second week of November. The crop was raised with the application of 180kg N, 80kg P_2O_5 and 100 kg K_2O/ha and other practices were followed as per recommendations for the region (Lal *et al.,* 2022). In experiment 1, eight treatments consist with translaminar and systemic fungicides and in experiment 2; six treatments with tank mixed application of translaminar & contact fungicides were included. In each treatment three sprays were scheduled for both the experiments. The first sprays were initiated just at the appearance of late blight disease and second and third sprays at 7-10 days interval after the first spraying. The treatments details are as follows:

Experiment 1

T1: Cymoxanil8 + Mancozeb 64% WP @ 0.3%

T2: Mandipropamid 23.4 % SC @ 0.1%

T3: Dimethomorph 50% WP @ 0.2%

T4: Phenomidon 10 + Mancozeb 50% WDG @ 0.3%

T5: Ametoctradin 27% + Dimethomorph 20.27 % SC @ 0.2%

T6: Metalaxyl- M 3.3% + Chlorothalonil 33% SC @ 0.1%

T7: Captan 70% + Hexaconazole 5%WP @ 0.2%

T8: Azoxystrobin 11% + Tebuconazole 18.3% WS @ 0.1%

T9: Control

Tank mixed application of translaminar fungicides (Experiment 2):

T1: Dimethomorph 50% WP @ 0.1% + Mancozeb 75% WP @ 0.2%

T2: Dimethomorph 50% WP @ 0.1% + Chlorothalonil 75% WP @ 0.2%

T3: Dimethomorph 50% WP @ 0.1% + Propineb 70% WP @ 0.2%

T4: Mandipropamid 23.4 SC @ 0.1% + Mancozeb 75% WP @ 0.2%

T5: Mandipropamid 23.4 SC @0.1% + Chlorothalonil 75% WP @ 0.2%

T6: Azoxystrobin 23 SC @ 0.1% + Mancozeb 75% WP @ 0.2%

T7: Control

Disease and yield assessment

The terminal disease severity was recorded as per method of Henfling (1987) after 10 days of final spray. The recorded experimental data was statistically analyzed using IRRISTAT software (version 4.4.20030719). The percentage disease control and yield (t/ha) were recorded at harvesting. The cost of fungicides (Rupees per Kg or L) and their spraying cost were calculated. The rate of harvested potato tubers (Rupees per ton) was taken as prevailing rate in the markets. Net return over the control and Benefit-Cost ratio (B: C) were calculated for each treatment.

Weather parameters

Weather parameters *i.e.* temperature, relative humidity and rainfall were recorded during all three cropping season years. In each year, cropping season was started from November to February. During these period weather parameters was recorded and calculated average weekly for each month.

RESULTS AND DISCUSSION

In experiment 1 it was recorded that on mean basis (63.30 - 84.15% disease controlled) all treatments were found effective against control (91.78% disease severity). The results revealed that treatment T3 showed least average terminal disease severity (14.54%) with highest average disease controlled (84.15%). The second best treatment was T5 with average terminal disease severity (17.35%) with disease controlled (81.10%) followed by T1 with 20.01% terminal disease severity along with disease controlled 78.20% (**Table 1**). These treatments were statistically at par to each other and significantly differed from the treatments T6 and T8. The lowest average field efficacy (63.30% disease controlled) was observed with treatment T7 when first sprays were initiated just at the appearance of late blight disease and second and third sprays at 7-10 days interval after first spraying. All treatments showed higher yield compared to control treatment (T9). The highest average tuber yield (39.95 t/ha) was recorded with T1 followed by T3 with 39.91 t/ha. The yield of both the treatments was statistically at par. The lowest average yield

Table 1. Evaluation of new fungicides for management of late blight of potato during 2015-16, 2016-17 and 2017-18.

Treatments	2015-16			2016-17			2017-18			Average		
	Terminal disease severity (%)	Disease controlled (%)	Yield (T/ ha)	Terminal disease severity (%)	Disease controlled (%)	Yield (T/ ha)	Terminal disease severity (%)	Disease controlled (%)	Yield (T/ ha)	Terminal disease severity (%)	Disease controlled (%)	Yield (T/ ha)
T1	10.70	86.67	43.76	26.00	72.54	33.68	23.33	75.95	42.40	20.01	78.20	39.95
T2	24.30	69.58	41.77	30.00	68.47	32.84	22.00	77.32	42.97	25.43	72.29	39.19
T3	8.30	89.58	42.98	23.00	75.59	33.42	12.33	87.29	43.34	14.54	84.15	39.91
T4	27.70	65.42	41.86	31.00	67.46	32.54	23.00	76.29	42.04	27.23	70.33	38.81
T5	10.70	86.67	43.00	26.67	71.86	33.22	14.67	84.88	43.24	17.35	81.10	39.82
T6	30.00	62.50	41.02	34.33	64.07	31.51	29.00	70.10	41.02	31.11	66.10	37.85
T7	32.70	59.17	41.02	36.67	61.69	31.44	31.67	67.35	41.30	33.68	63.30	37.92
T8	34.00	57.50	40.44	40.00	58.30	30.88	21.33	78.01	42.48	31.78	65.38	37.93
T9	80.00	0.00	38.44	98.33	0.00	29.39	97.00	0.00	37.64	91.78	0.00	35.16
CD (P 0.05)	8.05	–	0.99	4.64	–	1.45	3.24	–	1.68	9.50	–	0.86
SE	2.48		0.33	1.60		0.48	1.08		0.56	3.18		0.28

(37.85 t/ha) was observed with treatment T6 against control treatment (35.16 t/ha).

In experiment 2, three translaminar fungicides *viz,* Dimethmorph 50% WP, Mandipropamid 23.4 % SC, and Azoxystrobin 23%SC were evaluated as tank-mixed fungicides with three contact fungicides *i.e.* Mancozeb 75%WP, Chlorothalonil 75%WP & Propineb 70%WP, which are frequently used as prophylactic in late blight management. All treatments were found effective for managing the late blight. However, treatment T1 showed less average terminal disease severity (22.67%) with highest disease controlled (75.97%), which was significantly differed the T2 with average terminal disease severity of 30.83% along with disease controlled 67.31% as against control average terminal disease severity (94.33%). The next best tank-mixed spray was T3 which was statistically at par with T5 (**Table 2**). The

Table 2. Evaluation of tank mixed fungicides for management of late blight of potato during 2015-16, 2016-17 and 2017-18.

Treatments	2015-16		2016-17		2017-18		Average	
	Terminal disease severity (%)	Disease controlled (%)	Terminal disease severity (%)	Disease controlled (%)	Terminal disease severity (%)	Disease controlled (%)	Terminal disease severity (%)	Disease controlled (%)
T1	22.0	75.6	22.5	77.04	23.5	75.26	22.67	75.97
T2	35.0	61.1	27.5	71.94	30.0	68.42	30.83	67.31
T3	40.0	55.6	37.5	61.73	33.0	65.26	36.83	60.95
T4	42.5	52.8	40.0	59.18	32.5	65.79	38.33	59.36
T5	40.0	55.6	42.5	56.63	31.0	67.37	37.83	59.89
T6	55.0	38.9	47.5	51.53	36.0	62.11	46.17	51.06
T7	90.0	0.0	98.0	0.0	95.0	0.0	94.33	0.0
CD (P 0.05)	2.32	–	4.00	–	1.70	–	1.71	–
SE	0.75		1.40		0.55		0.55	

maximum average terminal disease severity (46.17%) was observed with treatment T6 when first spray was initiated just at the appearance of disease and second and third sprays at 7-10 days interval after first spraying. The maximum average tuber yield (40.70 t/ ha) was recorded with treatment T1 followed by T2 with 38.10 t/ha. Both treatments T1 & T2 were significantly differed from each other. The next best treatment was T5 which was statistically at par with T3 (**Table 3**). Among the treatments lowest average yield (35.50 t/ ha) was recorded in the treatment T6 against control (29.80 t/ha). Economics of the tank mixed fungicide were calculated and it was observed that treatment T1 gave 10.90 t/ha additional yield with Rs. 63,220.0 gross return and net return (Rs. 43,190.0) over control. The next best treatment was T2 that gave Rs. 22,830.0 net return over control. The highest B:C ratio (2.16) was calculated with treatment T1 followed by treatment T4. The least B:C ratio (1.91) was calculated in treatment T6 (1.90) against control.

During cropping season average weekly weather parameters *i.e.* temperature and relative humidity were varied within month. In the year 2015-16 the average weekly minimum temperature ranged from 6.0-16.93°C and maximum temperature ranged from 14.50 to 27.0°C. The average weekly minimum relative humidity ranged from 48.75 -76.57% and maximum relative humidity 82.71-91.43%. The total rainfall was only 7.95 mm (Fig.1a**)**. During 2016-17, the average weekly minimum temperature ranged from 5.14 -14.00°C and maximum temperature ranged was 18.29 to 28.86°C. The average weekly minimum relative humidity ranged from 34.29 -60.57% and maximum relative humidity 77.33-91.86%. The total rainfall was 73.50 mm (Fig.1b). In 2017-18, the average weekly minimum temperature ranged from 4.71 -14.57°C and maximum temperature ranged was 15.14 to 29.43°C. The average weekly minimum relative humidity ranged from 26.86 -61.57% and maximum relative humidity 77.14-91.00%. The total rainfall was 11.50 mm (Fig.1c).

Management of late blight is an important aspect for high quality potato production. Application of fungicides can be an important option for integrated crop management because resistant cultivars may be severely

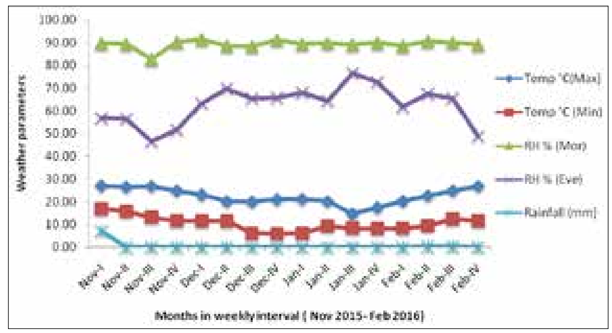

Fig.1a. Weather parameters during crop season 2015-16

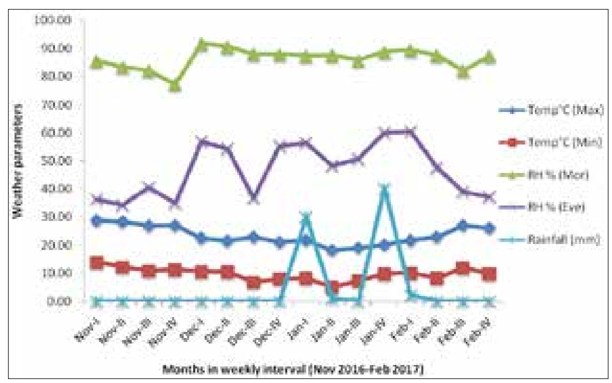

Fig.1b. Weather parameters during crop season 2016-17

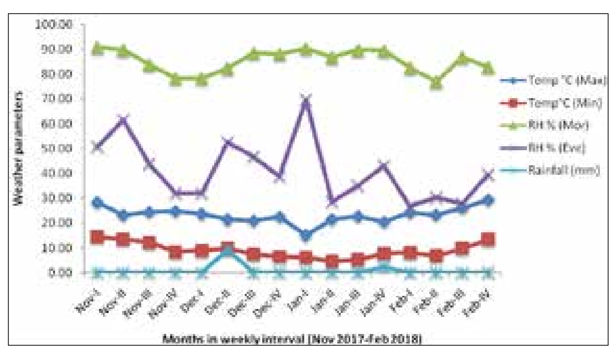

Fig.1c. Weather parameters during crop season 2017-18

Table 3. Economics of tank mixed fungicides for management of late blight of potato during 2015-16, 2016-17 and 2017-18.

Treatments	Yield (T/ha)			Average yield (T/ ha)	Additional yield over control (T/ha)	Gross return (Rs/ha)	*Cost of treatment (Rs/ha)	Net return over control (Rs/ha)	B:C
	2015- 16	2016- 17	2017- 18						
T1	44.13	32.77	45.20	40.70	10.90	63220.0	20030.0	43190.0	2.16
T2	41.41	31.50	41.39	38.10	8.30	48140.0	25310.0	22830.0	1.93
T3	40.92	30.62	40.56	37.37	7.57	43906.0	22310.0	21596.0	1.94
T4	40.84	30.44	38.31	36.53	6.73	39034.0	18830.0	20204.0	1.96
T5	41.14	30.76	40.47	37.46	7.66	44428.0	24110.0	20318.0	1.92
T6	39.49	29.01	37.99	35.50	5.70	33060.0	18530.0	14530.0	1.91
T7	30.8	28.18	30.43	29.80	0.00	0.00	0.00	0.00	1.90
CD (P 0.05)	1.72	1.49	1.06	1.06					
SE	0.56	0.48	0.34	0.34					

*Includes cost of fungicides, labour and other cost. Tubers yield @ Rs 5080.0/T, Mancozeb 75% WP @ Rs 380.0/kg, Chlorothalonil 75% @ Rs 1260.0/kg, Propineb 70% WP @ Rs 760.0/ kg, Azoxystrobin 23 % SC @ Rs 680.0/L, Mandipropamid 23.4% SC @ Rs 4500.0/L and Dimethmorph 50% WP @ Rs 4900.0/kg.

affected under high congenial climatic condition (Nelson, 2020). Although, various management strategies are also available for managing the late blight disease but their efficacy is not effective as chemical management. In India, about 44 molecules (fungicides) have been registered on CIB& RC (Central Insecticides Board and Registration Committee) for late blight management. Among them 23 are in as single and 21 are in combinations of two groups of fungicides (Subhash *et al*., 2025). In these fungicides, some of the fungicides were registered for both late blight and early blight diseases. In this study, Cymoxanil 8% + Mancozeb 64% @ 0.3%, Dimethmorph 50% @ 0.1% and Ametoctradin 27% + Dimethomorph 20.27% SC @ 0.2% found highly effective against *P. infestans*. The application of cymoxanil or dimethomorph based fungicides @ 0.3% at the early appearance of the disease along with one prophylactic and one post application spray of mancozeb, was found effective, these chemicals were also effective in sequential application as alone (Chakraborty and Mazumdar, 2012; Islam *et al*., 2022). Using a mixture of narrow specific and widely specific fungicides for managing late blight is one of the strategy (Ivanov *et al.,* 2021). The new fungicides *i.e.* Dimethmorph 50% WP @ 0.1%, Ametoctradin 27% + Dimethomorph 20.27% SC @ 0.2%, Azoxystrobin 11% + Tebuconazloe 18.3% WS @ 0.1%, Mandipropamid 23.4% SC @ 0.1% and Metalaxyl- M 3.3% + Chlorothalonil 33% SC @ 0.1% can be included at farmer practices for controlling the late blight. Among them few fungicides have dual mode of action that will avoid resistance development in *P. infestans* than single mode of action fungicides. Ametoctradin 27% + dimethomorph 20.27% SC found effective against late blight @ 0.08 & 0.1% (Lal *et al.,* 2017). The mixed formulations of fungicides were found effective in controlling late blight (Jha *et al.,* 2017) and spray schedules of contact fungicides followed by systemic/ translaminar + contact reduced late blight disease in Tripura (Dey *et al*., 2024). Recently, the Azoxystrobin 11% + Tebuconazloe 18.3% WS registered for late blight management. The application of tank-mixed fungicides was better than the rotational application of fungicides for managing *Botrytis* fruit rot of strawberry (Amiri *et al.,* 2019). In this study, the tank-mixed of Dimethmorph 50%WP @ 0.1% + Mancozeb 75% WP @ 0.2% and Dimethmorph 50%WP @ 0.1% + Chlorothalonil 75%WP @

0.2% were found highly effective. Because both translaminar and contact fungicides have synergistically actions to control the disease. Mancozeb and Chlorothalonil are well known to act as multisite activity and have less chance to develop resistance against *P. infestans* (Perez *et al.*, 2022). The assessment of benefit cost ratio (B: C) tells about economic benefit of the treatments at farmers' field, therefore, it is an important parameter for recommendation of any treatment for successful management of the disease. It is well known that severity of late blight disease is affected weather conditions. In this study, during year 2016-17 disease severity in control was higher than that of the other cropping years. This may be due to high rain fall and other weather factors during that year. Low temperature and higher relative humidity are the main climatic conditions responsible for appearance and spreading the disease. Further, rainfall is the crucial factor at management point of view, because it affects the efficacy of fungicides, spraying interval and disease severity. The fungicides efficacy is affected by intensity of rainfall in downy mildew of onion (Araújo *et al.*, 2020).

Therefore, it is be better to select rainfastness fungicides which have attribute to resist against rain. The contact fungicides are easily washed due to rain water than the systemic/translaminar. In this context, present study used translaminar fungicides *i.e.* Dimethmorph, Madipropamid, Cymoxnil and Fenamidone having rainfastness quality which can be more helpful in managing late blight disease of potato.

CONCLUSION

The new fungicides i.e. Dimethmorph 50% WP @ 0.1%, Ametoctradin 27% + Dimethomorph 20.27% SC @ 0.2%, Azoxystrobin 11% + Tebuconazloe 18.3% WS @ 0.1%, Mandipropamid 23.4% SC @ 0.1% and Metalaxyl- M 3.3% + Chlorothalonil 33% SC @ 0.1%, can be included at farmer practices for managing the late blight disease. The tank mixed of Dimethmorph 50% WP @ 0.1%+ Mancozeb 75% WP @ 0.2% and Dimethmorph 50% WP @ 0.1%+ Chlorothalonil 75% WP @ 0.2% was highly effective as tank mixed fungicides with high B:C ratio in managing late blight of potato.

AUTHORS' CONTRIBUTION

Conceptualization of research (Lal, M. Sharma S. and Chakrabarti SK); Designing of the experiments (Lal, M. Sharma S. and Kumar M); Execution of field/lab experiments and data collection (Lal, M. Yadav, S); Analysis of data and interpretation (Chaudhary S. Lal M. and Sharma S); Preparation of the manuscript Lal, M. Chaudhary, S and Sharma S).

DECLARATION

The authors declare no conflict of interest.

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DEGENERATION OF POTATO VARIETIES DUE TO VIRUS INCIDENCE IN NORTH GUJARAT

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ABSTRACT: The physiological causes and viral disease infections are the two main reasons for potato degeneration. The seed potato infected with viral diseases degenerate in the following successive generations therefore the investigation was carried out to evaluate the most popular potato varieties of Gujarat *i.e.* K. Badshah and K. Khyati against viruses (PLRV, mild mosaic & severe mosaic) and their subsequent degenerative effects on yield with comparison to fresh breeder seed. The three treatments *viz.*, T_1: Fresh breeder seed every year, T_2: Previous seed produce using seed plot technique, T_3: Previous seed produce without seed plot technique were evaluated. The studies were conducted for four consecutive years during *rabi* 2017-2021. The results revealed significantly higher per cent plant emergence at 40 DAP was recorded in T_1 (Fresh breeder seed every year) and T_2 (Previous seed produce using seed plot techniques) in all years as compared to T_3 (Previous seed produce without seed plot techniques). The per cent incidence of viral diseases at 75 DAP was recorded highest (mild mosaic:16.67 %, severe mosaic: 17.67 and PLRV 21.83 in last year) in T_3 *i.e.* Previous seed produce without seed plot techniques. Comparatively lower per cent incidence of viral diseases (mild mosaic:10.67 %, severe mosaic: 7.33 and PLRV 13.33 in last year) was recorded in T_2 *i.e.* Previous seed produce using seed plot techniques and the least incidence of viral diseases (Mild mosaic:1.83 %, Severe mosaic: 1.67 and PLRV 1.67 in last year) was recorded in T_1 *i.e.* Fresh breeder seed every year. The total tuber yield was higher in first two year in breeder as well as SPT raised seed. In Successive years the SPT raised seed tuber yield decrease. So, based on results it is concluded that seed producer can produce quality seed tuber from breeder seed up to three consecutive years by using "Seed Plot Technique".

KEYWORDS: Degeneration, potato, virus, PLRV, Mosaic, tuber yield

INTRODUCTION

Potato (*Solanum tuberosum*) is the third significantly valuable crop internationally and India is on second rank after china which produce 542.30. lakh tonnes (2021-22) potato annually. In the developing world the potato consumption reaches to tripling from 3.45 kg/capita year^{-1} in 1962 to 25 kg/capita year^{-1} in 2020 due to its per hectare production capacity, its significant nutritive value and great adaptability as vegetable purpose (fit with any other vegetables) and versatility in processing products (Faostat, 2021). Potato is known as hunger breaking crop as it has very short cropping period which fits easily in any cropping sequence. However, potato yield in developing countries is hindered by various factors, and one significant factor is seed degeneration which is mainly responsible for low production in per hectare area. (Fuglie, 2007, Gildemacher *et al.*, 2009 and Cromme *et al.*, 2010)

Tubers are the most common method of potato propagation due to their ability to produce genetically identical clones of the parent plant. However, sexual propagation through true potato seed allows for the introduction of genetic diversity, which can be advantageous in breeding new potato varieties with improved traits. This is due to the fact that asexual propagules, such as seed tubers, are clonal and genetically identical, providing a favourable environment for pathogens to thrive and spread. On the other hand, sexual propagules like True Potato Seeds (TPS) exhibit genetic diversity, making it more difficult for pathogens to establish and proliferate. Whitehead (1930)

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elaborate degeneration as increase in viral diseases incidence and decrease the total tuber yield in subsequent potato generations. According to Struik and Wiersema, 1999 many soil borne pathogen or many vector borne pathogen become seedborne. Dung *et al.*, 2012 reported that the pathogen which cause degeneration are seedborne in nature, but not all significantly contribute to degeneration as they don't upsurge in incidence or severity over generations. Potato viruses, spreading systemically from parent to progeny tubers, are the primary cause of degeneration in potato plants. (Salazar, 1996; Solomon-Blackburn and Barker, 2001). According to Scholthof *et al.*, 2011 *Potato virus Y* (PVY), *Potato leafroll virus* (PLRV) and *Potato virus X* (PVX) are the most vital in potato production systems worldwide. Seed potato degeneration, caused by pathogens and pests in planting material, is a global production challenge for potato growers due to reduced yield and quality. (Sharma *et al.*, 2016). The rate of degeneration varies from variety to variety, place to place and from cropping season to cropping season.

The "Seed Plot Technique (SPT)"-based conventional seed tuber production system has been used successfully in India for the past 50 years. After the development of SPT, SPT expands for indigenous quality seed production system from hills to plains in India. The seed plot techniques used in India is mainly based on agronomical practices such as to keep tuber seed disease free, planting the crop in area or in period when the sucking pest pressure is low with incorporation of IPM practices, rough out the virus infected or off type plants and cut the foliage on or before the vectors reaches on its ETL. When seed potato stocks are multiplied in more aphid vector-prone areas, insecticide application is also frequently used to stop the spreading of seed borne viral diseases from seed potato crops. Certified seed is always recommended as the main management tactic to avoid farm degeneration (Kreuze *et al.*, 2020).

Poor potato yield is linked to using virus-infected seed potatoes infected with PVY and PLRV, leading to degeneration in successive generations. (Sarker *et al.*, 2018). To evaluate denegation behaviour of potato varieties affected by PVY and PLRV infection is the notable problem for seed potato production. A study conducted in several nations revealed that the severe economic impact of PVY on potatoes was as high as 30–40% in India, 16.5% in Ireland, 34% in Canada, 37% in Kenya, 40–44% in Poland and the USA, and almost 50% in China (Gray *et al.*, 2010; Wang *et al.*, 2011; Were *et al.*, 2013; Hasiow-Jaroszewska *et al.*, 2014; Hutton *et al.*, 2015; Jailani *et al.*, 2017).

The cost of cultivation of potato is very high. In potato cost of cultivation, the 40-45% cost behind the seed cost which is main factor for crop profitability. Now a days “Potato Seed Plot Technique” is used for quality potato seed production. By adopting “Potato Seed Plot Technique” producers can produce their own seed but the information on how many times producers can produce their own seed from breeder seed through “Potato Seed Plot Technique” is lacking. Therefore, the present study was commenced for four successive years to find out the impact of degenerative viruses on produce and effect of rate of degeneration on potato crop during *rabi* season under North Gujrat agro-climatic condition.

MATERIALS AND METHODS

The field study was carried out at Potato Research Station, S. D. Agricultural University, Deesa to evaluate the rate of degeneration of potato varieties due to virus incidence in north Gujarat for four consecutive years from 2017-18 to 2020-21. Prior to experiment in the year 2016-17 (experiment conducted in one set) only the fresh breeder seed of two varieties *i.e.* K. Badshah and K. Khyati were raised by seed plot technique (SPT) and without using seed plot technique. From the first year onward, the experiment was conducted in two sets. In first set the seed production chain of two varieties *i.e.* Kufri Badshah and K. Khyati by using seed plot technique (SPT) and without using seed plot technique and the produce (seed produce through SPT and without SPT) were cold stored for next year use and process was continue in subsequent year (2016-17 to 2019-20). In the second set evaluation program of previous year seed produced seed was carried out and the process was continued in subsequent years (2017-18 to 2020-21). In evaluation program the experiment was laid out in a randomized block design with factorial concept by with two varieties *i.e.* Kufri Badshah and K. Khyati and three treatments *i.e.* T_1: Fresh breeder seed every year, T_2: Previous seed produced using seed plot technique, T_3: Previous seed produced without seed plot technique with 3.0 m × 2.0 m plot size and five replications. Planting was done at 50 cm row spacing and 20 cm plant-to-plant spacing in sandy loam soil, following recommended agronomic practices.

Seed plot technique:

- Planting in 1st calendar week of November.
- Place yellow sticky traps 60 per hectare at equidistance for mass trapping of white flies and aphids above canopy height.
- Three foliar sprays of label claim systemic insecticide (Imidacloprid 17.8 SL and Thaimethoxam 25 WG) at 15 days interval starting from 35-40 DAP.
- Cutting of haulm when aphids cross its critical level *i.e.,* 20 per 100 compound leaves.

Growth parameters:

Plant emergence (%) at 30 and 40 days after planting (DAP)

$$\text{Plant emergence (\%)} = \frac{\text{Total number of tuber germinated}}{\text{Total number of tubers planted}} \times 100$$

Yield attributes:

Out of total tubers obtained in each plot, all tubers were sorted in to four different grades based on their weight as I grade (>75 g. tuber), II grade (50-75 g. tuber), III grade (25-50 g. tuber) and IV grade (0-25 g. tuber) and transformed into tonnes per hectare.

Total tuber yield (t/ha): Total tuber yield was calculated by sum of all the grade *i.e.* I,II, III and IV grade.

Per cent incidence of Mosaic (Mild & severe) and PLRV were recorded at 45, 60 and 75 DAP.

Per cent disease incidence (PDI) of Mosaic and PLRV was carried out by using the following formula.

$$\text{PDI} = \frac{\text{Total number of virus infected plants}}{\text{Total number of plants observed}} \times 100$$

Statistical analysis:

The statistical analysis was carried out using the software OPSTAT developed by HAU, Hisar.

RESULTS AND DISCUSSION

Effect on emergence (2017-18, 2018-19, 2019-20 & 2020-21):

Significantly higher plant emergence at 40 DAP was recorded in T_1 (Fresh breeder seed every year) and T_2 (Previous seed produce using seed plot techniques) in three years as compared to T_3 (Previous seed produce without seed plot techniques) while there was non-significant difference in emergence between the two varieties. Shetty *et al.*,

(2021) studied on potato tuber degeneration in Karnataka and reported that the highest per cent plant germination of 88.98 per cent and 84.13 at 30 and 40 days after planting, respectively with previous seed produce using seed plot technique.

Effect incidence of viral diseases (2017-18, 2018-19, 2019-20 & 2020-21):

The incidence of mild mosaic, severe mosaic and PLRV at 75 DAP was noted significantly highest in T_3 *i.e.* Previous seed produce without seed plot technique (Mild mosaic- 6.50, 7.00, 15.50 & 16.67 per cent, Severe Mosaic- 4.50, 6.67, 15.33 & 17.67 per cent & PLRV- 6.00, 14.83, 21.50 & 21.83 per cent) in the year 2017-18, 2018-19, 2019-20 and 2020-21, respectively. Comparatively lower incidence was recorded in T_2 *i.e.* Previous seed produce using seed plot technique (Mild mosaic- 4.83, 4.83, 7.67 & 10.67 per cent, Severe mosaic- 2.63, 2.67, 5.83 & 7.33 per cent & PLRV- 4.00, 6.83, 10.66 & 13.33) in the year 2017-18, 2018-19, 2019-20 and 2020-21, respectively. The least mosaic incidence was recorded in T_1 *i.e.,* Fresh breeder seed every year (Mild mosaic- 3.67, 2.33, 2.50 & 1.83 per cent, Severe mosaic- 1.83, 1.50, 1.50 & 1.67 per cent & PLRV- 3.00, 4.83, 2.33 & 1.67) in the year 2017-18, 2018-19, 2019-20 and 2020-21, respectively (Table 1). The least incidence of viral disease (*i.e.* Severe Mosaic and PLRV) was noted in T_1 *i.e.* Fresh breeder seed every year and which was at par with T_2 *i.e.,* Previous seed produce using seed plot technique in the 2017-18 and 2018-19. In the subsequent years (2019-20 to 2020-21) the incidence of viral disease was increased in T_2 as compared to T_1. The incidence of mild mosaic was found minimum in T_1 *i.e.,* Fresh breeder seed every year and which was at par with T_2 *i.e.* Previous seed produce using seed plot technique in the 2017-18. In the subsequent year, least incidence was recorded in T_1 and which was followed by T_2 and T_3.

The disease incidence of viral diseases was found non-significant between the varieties *i.e.,* K. Badshah and K. Khyati. However, the minimum mild (9.11%) and severe mosaic (8.67%) virus was noted in K. Badshah variety as compared to K. Khyati (Mild Mosaic:10.33% and Severe mosaic: 9.11%) while minimum per cent PLRV was noted in K. Khyati (12.22%) as compared to K. Badshah (12.33%). (Table:2)

The interaction effect between various treatments and varieties had not exerted any significance influence on per cent incidence of viral diseases.

Tuber yield:

Significantly the highest total tuber yield was noted in treatment T_1 *i.e.,* Fresh breeder seed every year. Comparatively lower total tuber yield noted in T_2 *i.e.,* Previous seed produce using seed plot technique. The least total tuber yield was recorded in T_3 *i.e.* Previous seed produce without seed plot technique in the year 2017-18, 2018-19, 2019-20 as well as in 2020-21 in the both cultivars. Highest tuber yields 40.80, 52.75, 40.69, 47.93 t/ha was recorded in K. Khyati variety in the year 2017-18, 2018-19, 2019-20 and 2020-21 respectively as compared to K. Badshah variety (Table:3).

DISCUSSION

The results shows that the minimum viral disease (Mosaic & PLRV) incidence was noted in breeder seed as well as SPT raised seed in initial first two years. The results were corroborating the finding of Basu *et al.*, (2003) and Singh *et al.*, (2014). They concluded that SPT-raised potato crops had higher tuber yields and a lower incidence of viral diseases. Further Ali *et al.*, (2013) discovered that crops raised with high-quality seed production program hardly ever had any

Table 1. Per cent emergence at 30 and 40 DAP (2017-18, 2018-19, 2019-20 and 2020-21).

Year	Treatment	% Emergence at 30 DAP				% Emergence at 40 DAP			
		T_1	T_2	T_3	Mean	T_1	T_2	T_3	Mean
2017-18	K. Badshah	81.93	88.67	83.67	84.76	91.43	95.33	90.00	92.26
	K. Khyati	80.67	86.33	83.00	83.33	94.00	92.67	89.33	92.00
	Means	81.30	87.50	83.33		92.72	94.00	89.67	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		0.97		NS		0.68	
	Treatment	2.50		1.19		1.75		0.83	
	Variety × Treatment	NS		1.68		2.48		1.18	
2018-19	K. Badshah	80.67	87.67	73.33	80.56	91.00	92.33	79.00	87.45
	K. Khyati	83.33	89.33	75.67	82.78	90.00	93.00	78.00	87.00
	Means	82.00	88.50	74.50		90.50	92.67	78.50	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		1.86		NS		1.79	
	Treatment	4.79		2.28		4.61		2.20	
	Variety × Treatment	NS		3.22		NS		3.11	
2019-20	K. Badshah	83.33	91.00	81.33	85.22	91.000	94.000	84.332	89.777
	K. Khyati	88.33	91.33	85.00	88.22	92.666	94.334	87.334	91.445
	Means	85.83	91.17	83.17		91.833	94.167	85.833	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		2.10		NS		1.92	
	Treatment	5.41		2.57		4.94		2.35	
	Variety × Treatment	NS		3.64		NS		3.33	
2020-21	K. Badshah	87.00	89.66	86.00	87.55	91.00	91.33	89.34	90.56
	K. Khyati	85.00	90.33	87.66	87.67	90.67	92.00	90.00	90.89
	Means	86.00	89.99	86.83		90.83	91.67	89.67	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		1.20		NS		1.13	
	Treatment	3.09		1.47		NS		1.38	
	V × T	NS		2.08		NS		1.96	

vector-transmitted viruses, while ware crops ("Seed Plot Technique" not followed) were the only ones to have them in abundance.

The results are also conformity with the findings of Singh *et al*., (2014). They reported potato growers of North Gujarat are advised to maintain their seed stocks of cvs. K. Badshah, K. Pushkar and K. Surya up to three consecutive years adopting seed plot technique for maintaining assured quality seed and yield potential which also gives assurance against introduction of other tuber borne diseases like common scab, black scurf, brown rot etc. Shetty *et al*., (2021) also noted at 65 days after planting, that the treatment of previous seed products using the seed plot technique resulted in a lower percentage of mosaic and PLRV and higher tuber yield as compared to ware crop (seed plot techniques not used).

Table 2. Per cent incidence of Mild & Severe Mosaic and PLRV at 75 DAP (2017-18, 2018-19, 2019-20 and 2020-21).

Year	Treatment	Mild mosaic 75 DAP				Severe mosaic 75 DAP				PLRV 75 DAP			
		T_1	T_2	T_3	Mean	T_1	T_2	T_3	Mean	T_1	T_2	T_3	Mean
2017-18	K. Badshah	3.67	4.67	6.67	5.00	1.33	2.27	4.33	2.65	2.33	3.67	5.00	3.67
	K. Khyati	3.67	5.00	6.33	5.00	2.33	3.00	4.67	3.33	3.67	4.33	7.00	5.00
	Means	3.67	4.83	6.50		1.83	2.63	4.50		3.00	4.00	6.00	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		0.52		NS		0.42		1.32		0.63	
	Treatment	1.34		0.64		1.07		0.51		1.61		0.77	
	Variety × Treatment	NS		0.90		NS		0.72		NS		1.09	
2018-19	K. Badshah	3.00	5.00	7.00	5.00	1.33	2.00	6.33	3.22	3.33	6.33	17.67	9.11
	K. Khyati	1.67	4.67	7.00	4.44	1.67	3.33	7.00	4.00	6.33	7.33	12.00	8.56
	Means	2.33	4.83	7.00		1.50	2.67	6.67		4.83	6.83	14.83	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		0.75		NS		0.77		NS		0.93	
	Treatment	1.93		0.92		1.98		0.94		2.40		1.14	
	Variety × Treatment	NS		1.30		NS		1.33		3.39		1.62	
2019-20	K. Badshah	2.67	7.33	14.00	8.00	1.67	5.33	16.33	7.78	2.00	10.00	23.66	11.89
	K. Khyati	2.33	8.00	17.00	9.11	1.33	6.33	14.33	7.33	2.67	11.33	19.33	11.11
	Means	2.50	7.67	15.50		1.50	5.83	15.33		2.33	10.66	21.50	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		0.94		NS		0.72		NS		0.97	
	Treatment	2.43		1.15		1.85		0.88		2.49		1.18	
	Variety × Treatment	NS		1.64		NS		1.25		NS		1.68	
2020-21	K. Badshah	2.00	10.33	15.00	9.11	1.33	6.67	18.00	8.67	1.33	13.33	22.33	12.33
	K. Khyati	1.67	11.00	18.33	10.33	2.00	8.00	17.33	9.11	2.00	13.33	21.33	12.22
	Means	1.83	10.67	16.67		1.67	7.33	17.67		1.67	13.33	21.83	
		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
	Variety	NS		0.83		NS		0.86		NS		0.83	
	Treatment	2.13		1.01		2.22		1.05		2.13		1.01	
	Variety × Treatment	NS		1.44		NS		1.49		NS		1.44	

Table 3. Total tuber yield (t/ha) for the year 2017-18, 2018-19, 2019-20 and 2020-21.

Treatment	Total tuber yield (t/ha)															
	2017-18				2018-19				2019-20				2020-21			
	T_1	T_2	T_3	Mean	T_1	T_2	T_3	Mean	T_1	T_2	T_3	Mean	T_1	T_2	T_3	Mean
K. Badshah	45.29	38.36	29.16	37.61	56.63	52.62	22.38	44.87	45.68	38.17	12.62	32.15	53.40	32.31	21.65	35.79
K. Khyati	48.55	40.70	33.15	40.80	68.31	62.02	27.94	52.75	50.70	40.69	30.69	40.69	66.00	42.11	35.68	47.93
Mean	46.92	39.53	31.16		62.47	57.37	25.16		48.19	39.42	21.65		59.70	37.21	28.66	
	CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)		CD (0.05)		S.Ed. (±)	
V	2.23		1.06		5.94		2.83		2.86		1.36		4.21		2.01	
T	2.74		1.30		7.27		3.46		3.51		1.67		5.16		2.46	
VXT	NS		1.84		NS		4.89		4.96		2.36		NS		3.47	

CONCLUSION

The winter is very short in North Gujarat as compared to other Northern states of India. The aphid population is major concern for quality seed potato production. The seed producer must have to adopt "Seed Plot Technique" for quality seed production under North Gujarat condition. Based on degeneration study of potato varieties result revealed that the incidence of viral diseases increasing slowly up to three consecutive years then after the incidence increasing fast in the seed which produce through seed plot technique as compared to breeder seed. So, it is concluded that seed producer can produce quality seed tuber from breeder seed up to three consecutive years by adopting "Seed Plot Technique".

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CONFLICT OF INTEREST

All authors declare no conflict of interest with this article.

ETHICAL STATEMENT

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

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TECHNOLOGICAL IMPACT ON POTATO FARMERS' INCOME: INSIGHTS FROM A BIBLIOMETRIC ANALYSIS

Abhijit Das[1*], Sahin Aktar Munshi[2] and Bikram Barman[3]

ABSTRACT: This research encompassed a bibliometric analysis aimed at assessing the advancement of studies concerning the technological impact on potato farmers' income. The analysis employed Dimensions.ai data and involved querying keywords such as "Impact" and "Technology" and "Income" and "Potato" "Farmer" from 1974 to 2023, yielding 1329 pertinent documents in CSV format. To comprehend the intellectual framework, VOS viewer software (version 1.6.19) was utilized to visualize and analyze the collected data. The results unveiled the pre-eminence of human society in publications concerning the effects of technology on farmers' income, with 578 papers. Among these articles, a majority (613) were aligned with Sustainable Development Goal 2, focused on zero hunger. Investigation into co-authorship among countries highlighted the United States as a prominent and active contributor to present research, with other nations forming clusters around it. In terms of organizational citations, Wageningen University and Research, International Maize and Wheat Improvement Center and International Food Policy Research Institute as the leading entities, underscoring their substantial influence in the field. Notably, the "Agricultural Systems" and "Agricultural Economics" journals emerged as a prominent source for present research. The study advocates for collaborative research efforts to effectively investigate the technological impact of farmers' income, emphasizing the importance of cooperation over isolated endeavours.

KEYWORDS: Agriculture, potato farmers' income, sustainable development goal, technology

INTRODUCTION

In today's rapidly evolving agricultural landscape, modern technologies are becoming indispensable for farmers, including those cultivating staple crops like rice, wheat, and even specialized crops such as potatoes. Technologies like precision farming, digital platforms, and data-driven tools are reshaping how farmers approach agriculture, helping them address key challenges, optimize resource use, and unlock new growth opportunities. These innovations not only enhance productivity and reduce costs but also provide valuable market insights, allowing farmers to create more value from their efforts.

Numerous studies highlight the transformative impact of these technologies. For instance, research by the National Council of Applied Economic Research (NCAER) in India found that farmers, including potato growers, who adopted precision agriculture techniques experienced a rise in net income by as much as 35% (NCAER, 2020). Similarly, the World Economic Forum suggests that embracing modern agricultural technologies could boost incomes by 70% and potentially lift 150 million people out of poverty by 2030 (World Economic Forum, 2020).

Precision agriculture tools, such as soil sensors, drones, and advanced data analytics, have proven especially beneficial in improving farming practices. Studies show that these technologies can increase crop yields by up to 20% while reducing the use of water

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and fertilizers by 30% and 20%, respectively (UNCTAD, 2020). For potato farmers, in particular, this translates into more efficient water use, improved soil health, and higher yields per hectare.

Beyond boosting production, modern technologies also help farmers, including potato growers, reduce operational costs. Automation, robotics, and IoT systems streamline farm operations, reducing the reliance on manual labour and making farming more efficient. The Food and Agriculture Organization (FAO) found that using drones for pest control, for example, can cut pesticide usage by 30%, resulting in significant cost savings (FAO, 2019). These efficiencies directly translate into higher profitability.

Moreover, access to real-time market data through digital platforms is revolutionizing how farmers make decisions. Mobile phones and the internet allow farmers to monitor live market prices, weather conditions, and demand trends, enabling them to make informed choices on what to grow, when to harvest, and how to price their crops. The World Bank reports that such platforms have contributed to a 10% increase in income for farmers in some developing nations (World Bank, 2021).

The positive impact of technology on farmers' incomes is strongly linked to the United Nations Sustainable Development Goals (SDGs), particularly those aimed at eradicating poverty (SDG 1), ensuring food security (SDG 2), and promoting sustainable economic growth (SDG 8) (United Nations, 2015; World Bank, 2020).

This study conducts a bibliometric analysis to explore how technological advancements influence farmers' incomes, particularly for crops like potatoes. By examining scientific literature, this analysis seeks to uncover trends, research gaps, and opportunities for collaboration in this evolving field. The study is divided into two main sections: the first focuses on the research methods, outlining data collection and processing, while the second presents a comprehensive analysis of the findings.

MATERIALS AND METHODS

The Data

This research employed bibliometric analysis to explore the implications of technology on farmers' income. The term "bibliometric analysis" was coined by Groos and Pritchard to refer to a set of quantitative tools used for tracking and assessing literature related to a specific subject (Pritchard, 1969; Roemer and Borchardt, 2015). Our approach followed the procedural steps outlined in Fig. 1 for this investigation, covering the time span from 1974 to 2023.

For data collection, we relied on Dimensions. ai, a research information system provided by Digital Science. While standardized research publications were traditionally confined to the Web of Science (WoS) (Bass *et al.*, 2020), alternatives like Scopus and Google Scholar gained prominence, especially in regions with limited resources. Google Scholar became a preferred choice for researchers in developing nations due to accessibility despite financial constraints. The platform enabled convenient data access and concept development for stakeholders.

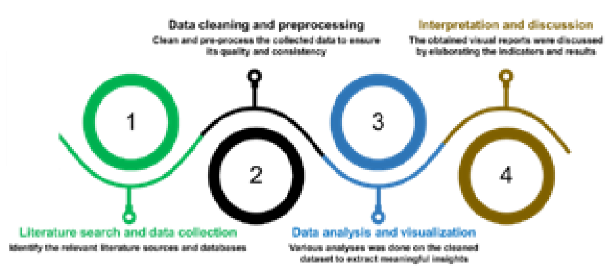

Fig.1. Steps in bibliometric analysis

The COVID-19 pandemic accelerated the pace of bibliometric studies, emphasizing the need for real-time trend analysis (Hook *et al.*, 2021, Das *et al.*, 2021). Dimensions, as a comprehensive platform, grants scholars access to a wide range of full-text data, including pre-prints, articles, conferences, and more, spanning different years. This expanded dataset offers new avenues for exploration. Machine learning techniques establish connections among scholarly items, while data enhancements like categorizations and disambiguation of entities provide additional context.

In this study, we relied on the Dimensions database to gather relevant information such as authors, article titles, affiliations, and other pertinent details. The Dimensions database, with its diverse analytical functions including citation and subject analysis, is well-suited for bibliometric research. Although no language restrictions were imposed during data extraction, we limited the collection to English language documents, as the search query specified English titles and abstracts. This approach enabled content evaluation of non-English documents through their titles and abstracts.

The efficacy of bibliometric analysis hinges on the precision of the search query. Hence, we crafted a meticulous query based on an extensive review of existing literature and the identification of research gaps. The aim was to create a comprehensive query that yields high-quality and reliable results

Selection of Database and Search Query

A focused query, tailored to our study's theme, was employed to ensure data accuracy. Our search terms included "Impact" and "Technology" and "Income" and "Potato" and "Farmer". The search was confined to titles and abstracts within the timeframe of 1974 to 2023. We excluded unpublished sources, pre-prints, and book chapters to ensure data reliability. Utilizing Dimensions.ai, we retrieved pertinent articles and filtered out irrelevant ones, resulting in 1329 documents presented in CSV format.

Subsequently, the retrieved data was subjected to analysis using VOS viewer software (version 1.6.19), a commonly used tool for visualizing and dissecting the intellectual landscape of a field (van Eck and Waltman, 2017). Additionally, we conducted trend analysis to unveil patterns and developments within the literature. By adhering to these steps, we amassed and scrutinized an extensive collection of pertinent documents, facilitating visualization of the intellectual framework and identification of trends within the studied domain.

Data Extraction and Analysis

For data analysis, we compiled the data in MS Excel CSV format to facilitate subsequent assessment. Tabular analysis was executed using Excel, while VOS Viewer software (version 1.6.19) was employed for constructing visual maps (van Eck and Waltman, 2017). Citation analysis gauged the scientific significance and impact of publications. To evaluate international research collaboration among participating countries, we introduced a metric called "connection strength," derived from visualized maps. This metric quantifies scientific collaboration between any two countries and is depicted by the thickness of connecting lines. A thicker line indicates greater collaboration and signifies higher connection strength.

RESULTS AND DISCUSSION

After a thorough examination of pertinent data, a comprehensive total of 1329 documents underwent meticulous scrutiny within the scope of the study. Fig. 2 visually portrays the distribution of articles that adhered to the

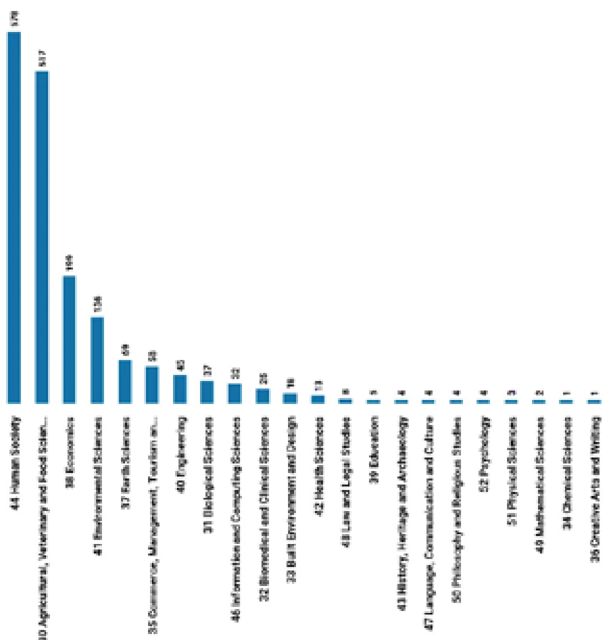

Fig.2. Number of publications in each research category

criteria encompassing the broader subject area under investigation. The findings unveiled that the domain of human society exhibited the highest volume of publications pertaining to the influence of technology on farmers' income, totalling 578 articles, closely followed by agricultural, veterinary, and food sciences with 517 publications. In a bid to delve deeper into the correlation between technological impact on farmers' income and the Sustainable Development Goals (SDGs), an analysis of the publication count associated with each SDG criterion was undertaken. The outcomes of this analysis are effectively presented in Fig. 3. Notably, the preponderance of articles was aligned with SDG 2, namely Zero hunger, amounting to 613 publications, trailed by SDG 13, Climate Change, with 174 publications.

Fig. 4 provides an overview of the cumulative count of publications throughout the study duration. The graph unmistakably delineates a prevailing ascending trajectory in such publications from 2005-06 to 2022. The significant surge in publications after

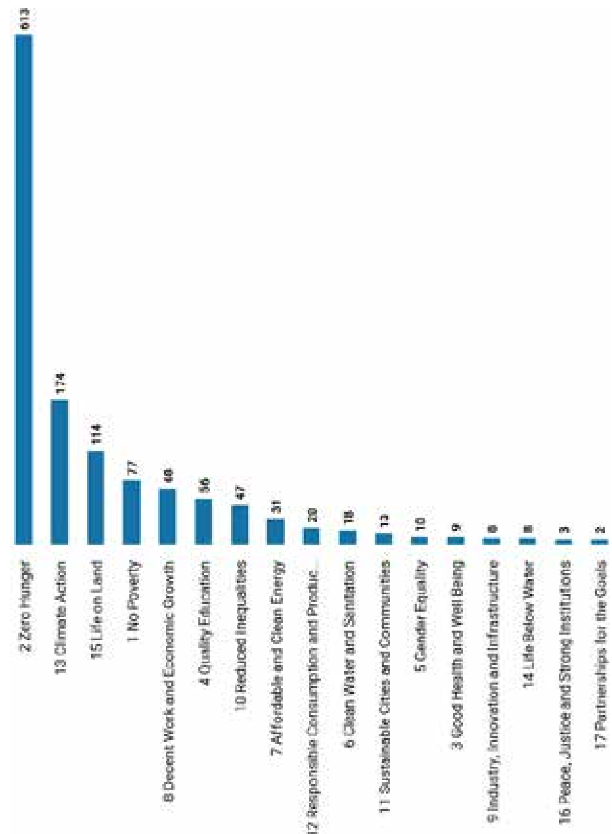

Fig.3. Number of publications on the SDG themes

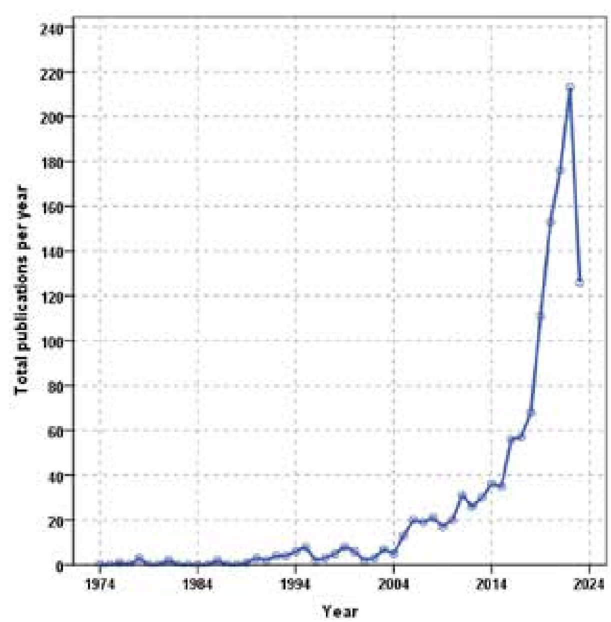

Fig.4. Growth of publications during the study period

2005 can be attributed to the confluence of several factors. Firstly, this period witnessed a notable advancement in technology, with the proliferation of digital tools, data analytics, and precision farming techniques. These innovations presented unprecedented opportunities for enhancing agricultural productivity and income, prompting researchers to delve into their implications. Moreover, the increasing availability and accessibility of data, coupled with the rise of open-access platforms and digital repositories, facilitated the dissemination of research findings, fuelling scholarly interest in the subject. Additionally, growing concerns about global food security, sustainability, and the need to uplift rural economies led to a heightened focus on leveraging technology to bolster farmers' incomes. Consequently, academia, policymakers, and agricultural practitioners recognized the urgent need to comprehensively study the multifaceted interactions between technology adoption and income generation, driving the exponential growth in publications on this vital nexus (Rosenzweig *et al.*, 2013; Wheeler and von Braun, 2013).

Performance Analysis

Top Author Analysis

Assessing an author's impact heavily relies on their contribution in terms of both the number of documents authored and citations received. Our study presents outcomes in both tabular and visual formats. Table 1 furnishes data about prolific authors, encompassing document count and average citations per document. Through scrutiny of co-authorship links, we quantify the extent of collaboration between individuals. The table analysis centres on the top 10 authors identified in our research. For a graphical depiction, refer to Fig. 5, illustrates the findings via visualization using VOS software.

Table 1. Authors analysis (Top 10).

Author's Name	Total Number of Documents	Citations	Citations (mean)
Bekele A Shiferaw	5	674	134.80
Matin Qaim	10	662	66.20
Graham Brookes	9	476	52.89
Peter Barfoot	7	442	63.14
Wanglin Ma	4	267	66.75
Victor M Manyong	5	121	24.20
Dil Bahadur Rahut	5	108	21.60
Yuansheng Jiang	5	70	14.00
Julius Manda	4	43	10.75
Camillus Abawiera Wongnaa	4	39	9.75

Fig.5. Visualization map of co-authorship analysis of the authors

This co-authorship scrutiny unveils authors' interconnectedness, spotlighting significant collaborative endeavours among them.

Employing the VOS viewer, we performed co-authorship analysis within specific parameters. We maintained a minimum of two documents per author and a maximum of twenty-five authors per document. Articles not meeting these criteria were automatically excluded. The outcomes of this analysis are depicted in Fig. 5, showcased in the VOS viewer's output interface.

Among the considered authors, 319 individuals met the stated requirements.

Yet, only 32 of them exhibited connections or associations with each other. The analysis unveiled 17 distinct clusters, each highlighting collaboration among authors within the respective cluster. Co-authorship stands as a highly quantifiable manifestation of scientific collaboration, well-documented and generating a "co-authorship network" through author interactions. Fig. 5 visually captures the robust networking within these nine clusters of authors. Noteworthy authors, such as Graham Brookes, Matin Qaim, and Yuansheng Jiang, among others, contributed significantly to collaborations within this context.

Co-Authorship Analysis of Countries

The analysis of country co-authorship within the same dataset was conducted to explore collaborative relationships between nations. To establish a robust collaboration network, specific criteria were applied to filter and obtain pertinent data. The requirement was set at a minimum of five documents per country, resulting in 44 countries out of the initial 91 meeting the criteria. Fig. 6 visually illustrates this network, presenting a map featuring labelled circles denoting individual countries. The size of each circle corresponds to the quantity of documents produced by that specific country. Larger circles and labels indicate a more substantial impact and contribution to the particular study. Significantly, the United States emerges as a prominent and active participant, while other countries cluster around it. This observation indicates a strong network of collaboration among these nations.

Citation Analysis

The collected data was employed for conducting a citation analysis, a widely adopted bibliometric method involving the scrutiny of citations within a paper to establish linkages with other researchers. Sandison emphasized that a citation transcends being a mere bibliographic reference appended to the end of a text, encompassing remarks, footnotes, or excerpts from a citation index (Sandison, 1989). Instead, it embodies an author's purposeful decision to forge a connection between their work and that of another researcher at a specific juncture. Likewise, Shaw asserted that citations create bonds among authors, signifying the degree of their indirect interaction through scholarly literature (Shaw, 1983). The citation analysis of organizations and sources is visually presented in Fig. 7 and 8, correspondingly.

To delve into inter-organizational citations, a minimum of five documents from each organization was set as a threshold.

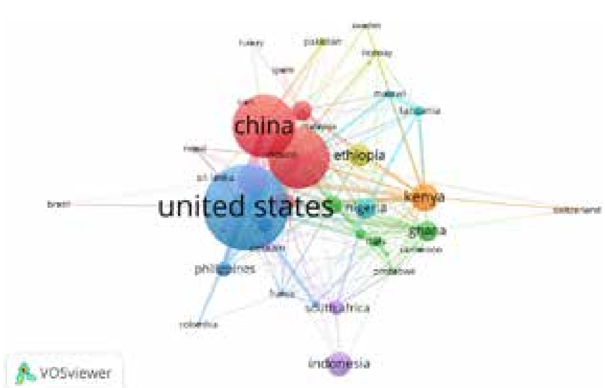

Fig.6. Visualization map of co-authorship analysis of the countries

Fig.7. Visualization map of the citation analysis by organization

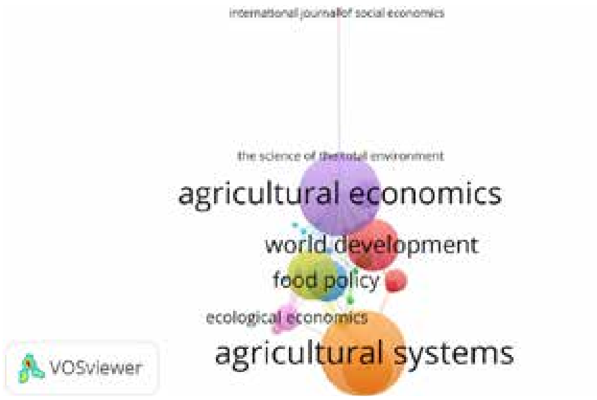

Fig.8. Visualization map of the citation analysis by source

The study identified a total of 54 relevant organizations and grouped them into 10 clusters based on predetermined criteria. Notably, Wageningen University and Research, International maize and wheat improvement center and International food policy research institute surfaced as the top three organizations, underscoring their substantial influence.

Citation analysis was also conducted for the sources engaged in this study, employing a criterion of at least four documents per source. Consequently, 38 sources fulfilled this criterion and were categorized into 9 clusters. Of the sources scrutinized, only 12 exhibited a robust interconnection. The size of the bubble associated with each source mirrors its impact, with larger bubbles denoting greater influence. Two journals namely "Agricultural systems" and "Agricultural economics" showing greater influence on research related to technological impact on farmers' income.

Comprehensive research synthesis

Comprehensive research synthesis is essential for understanding how modern technology adoption affects the income of potato farmers. By reviewing various studies and findings, this review provides a broad perspective on how technological advancements influence potato farming practices and improve economic outcomes.

a. Harnessing technology to address the agrarian crisis in India

India's agriculture sector, including its significant potato farming community, faces challenges such as low incomes, rising debts, and farmer distress. Technology has become a critical tool for transforming potato farming, helping farmers increase yields, reduce costs, and enhance market access, which are crucial steps toward alleviating the agrarian crisis.

Remote sensing and satellite technology

Remote sensing technology, using satellite imagery and aerial surveys, provides potato farmers with crucial data on crop health, soil moisture levels, and pest infestations. This information allows farmers to address specific problem areas proactively, improving productivity and securing their income. The Indian Space Research Organisation (ISRO) supports this through services like the "Farmers' Portal," offering real-time information to help potato farmers make informed decisions.

Digital platforms and mobile applications

Digital platforms and mobile applications have become powerful tools for potato farmers, enabling them to access critical information, connect with markets, and secure financial support. Platforms like e-NAM (Electronic National Agriculture Market) enable potato farmers to trade directly with buyers, bypassing intermediaries and securing better prices. According to the Ministry of Agriculture, over 1.7 million farmers, including many potato growers, have benefited from e-NAM, leading to better incomes.

b. Importance of crop breeding in enhancing potato farmers' income

Crop breeding is crucial for potato farmers in developing varieties that yield more, resist diseases, and adapt to challenging environmental conditions (Nkonya *et al.*, 2004). This section explores how advances in crop breeding enhance the income potential of potato farmers.

High-Yielding Varieties (HYVs)

The development of high-yielding potato varieties (HYVs) has significantly increased productivity per unit of land. These varieties are specifically bred for traits like disease resistance, high yield potential, and adaptability to different climates (Eberhart, 1989; Nkonya *et al.*, 2004). HYVs help potato farmers improve their output and income by ensuring stable and increased yields.

Resistance to pests and diseases

Pest- and disease-resistant potato varieties are vital in reducing crop losses and boosting income. Research has shown that improving resistance in potato crops can significantly increase yields, helping farmers maintain consistent production even in the face of pest outbreaks (Sitch *et al.*, 1996).

Stress tolerance and market-preferred traits

Breeding stress-tolerant potato varieties allows farmers to maintain production levels in difficult growing conditions, such as drought or poor soil quality. Additionally, breeding potatoes with traits preferred by the market, such as improved quality or nutritional value (Das and Das, 2023), increases the prices potato farmers can command, directly impacting their income.

c. Agronomic practices and their role in improving potato farmers' income

Agronomic practices are critical for optimizing resource use, improving farm productivity, and minimizing risks for potato farmers. Techniques like crop rotation, soil management, water-efficient technologies, and integrated pest management (IPM) are key contributors to income growth (Mwania *et al.*, 1989).

Crop rotation

Crop rotation, where potato farmers alternate crops in a planned sequence, helps break pest and disease cycles, improve soil fertility, and reduce weed issues (Bisanda and Mwangi, 1996). This practice improves soil health and contributes to yield increases, ultimately raising farm profits.

Soil management

Effective soil management, such as balanced nutrient application and soil conservation, is crucial for maintaining high potato yields (Mwania *et al.*, 1989). A report by the International Plant Nutrition Institute (IPNI) found that proper nutrient management can improve incomes by up to 30%, as it ensures sustainable soil productivity and minimizes nutrient loss (Das *et al.*, 2024)

Water-efficient technologies

Water-efficient technologies are essential for potato farmers, particularly in areas facing water scarcity. Techniques like drip irrigation reduce water wastage and improve efficiency. A study in the Journal of Agricultural Science showed that drip irrigation in potato farming can lead to a 47% increase in income (Yang *et al.*, 2023).

Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is an environment friendly approach that combines biological control, cultural practices, and careful pesticide use to manage pests effectively. The FAO estimates that IPM can increase potato farmers' incomes by up to 50% by reducing crop losses and cutting chemical input costs.

d. Factors influencing potato farmers' adoption of technology

The decision to adopt modern technologies in potato farming is influenced by several factors, including farmers' assets, vulnerability, institutional support, and other considerations.

Assets

Farmers’ access to resources such as land, capital, and labour significantly impacts their ability to adopt new technologies (Meinzen-Dick *et al.*, 2004). Potato farmers with larger landholdings or better access to credit are more likely to adopt advanced technologies, as they can manage the associated costs and risks (Adesina and Baidu-Forson, 1995). For instance, access to credit has been a key factor in the adoption of improved potato varieties in India (Krishna and Qaim, 2007).

Vulnerability

Potato farmers' exposure to risks, such as climate variability and market price fluctuations, affects their willingness to invest in new technologies. Vulnerable farmers, especially those in drought-prone regions, may hesitate to adopt water-saving technologies due to uncertainty (Mazonde, 1993). A study in Uganda revealed that risk-averse farmers were less likely to adopt better agricultural practices (Kassie *et al.*, 2018).

Institutions

Institutional support, such as agricultural extension services and farmer cooperatives, plays a crucial role in encouraging technology adoption. Extension services offer potato farmers the technical training needed to implement new methods effectively (Meinzen-Dick *et al.*, 2004). Studies in Kenya and Nigeria show that access to extension services increases farmers' likelihood of adopting improved crop varieties (Adesina and Zinnah, 1993; Feder *et al.*, 1985).

Other Factors

Other factors influencing technology adoption include the perceived benefits, costs, and ease of use of the new technologies, as well as the influence of social networks and peers (Mwania *et al.*, 1989). Potato farmers are more likely to adopt new technologies if they see others in their community benefiting from them (Manda *et al.*, 2018).

e. Traditional agriculture vs. Modern agriculture: Impact on potato farmers' income

The shift from traditional to modern agricultural practices has profound implications for potato farmers’ incomes. While traditional farming methods are still in practice, modern techniques offer substantial advantages in terms of productivity and profitability.

Merits of traditional agriculture

Traditional agriculture, often practiced on a small scale, relies on local knowledge and is well-adapted to specific ecosystems (Altieri and Toledo, 2011). Potato farmers in traditional systems often save seeds from their harvests, reducing input costs and maintaining crop diversity, which can contribute to income stability (Pretty, 2007).

Demerits of traditional agriculture

However, traditional farming methods are generally less productive and more labour-intensive, limiting their income potential (Hazell and Wood, 2007). Potato farmers who rely on traditional methods may also struggle with limited market access, making it difficult to achieve higher incomes. Additionally, traditional systems are often less resilient to climate change compared to modern farming techniques, which are better suited to withstand extreme weather events (Clarke, 1990).

CONCLUSION

Based on the bibliometric analysis concerning the effects of technology on potato farmers' income, it was found that 44 nations displayed a robust collaborative network. Notably, the United States stood out due to its significant research contributions and impact in this field. Regarding the participating organizations, a total of 54 were identified and categorized into 10 distinct clusters. The top three influential organizations, as determined by their research impact, were the Wageningen University and Research, International maize and wheat improvement center and international food policy research institute. Among the various sources scrutinized, the agricultural systems and agricultural economics journals exhibited a noteworthy influence on technological impact of farmers' income research. In summary, technological impact of farmers' income studying the remains a crucial subject warranting continuous research and exploration. Further research in the realm of technological impact on farmers' income is imperative to unravel nuanced insights, optimize agricultural practices, and foster sustainable economic growth in farming communities worldwide. As technology continues to evolve, a deeper understanding of its implications holds the key to enhancing livelihoods and ensuring food security for generations to come. Robust investigation in this area will empower farmers with innovative tools and strategies, paving the way for resilient and prosperous agricultural systems.

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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 animal performed by any of the authors.

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EVALUATION OF ADVANCED POTATO (*SOLANUM TUBEROSUM* L.) GENOTYPES FOR SALINITY TOLERANCE BASED ON YIELD AND AGRONOMIC TRAITS

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ABSTRACT: Salinity stress is a major constraint on potato (*Solanum tuberosum* L.) production, particularly in salinity-prone regions such as the Indo-Gangetic plains. This study evaluated 58 potato genotypes, including 54 advanced breeding lines and 4 released varieties, under control (ECe < 1 dS/m) and saline (ECe ~ 6.8-7.05 dS/m) environments. Genotypes were assessed for key agronomic traits, including marketable tuber yield (MTY), non-marketable tuber yield (NMTY), total tuber yield (TTY), marketable and non-marketable tuber no. and dry matter content (DM%). Salinity stress significantly reduced MTY and TTY, with yield reductions ranging from 1.86% to 65.74% and an average reduction of 31.70%. Genotypes such as WS/19-911 (yield reduction – 1.86%), WS/17-321 (2.39%) and WS/18-407 (3.16%) demonstrated superior tolerance, exhibiting minimal yield reductions, while others, including WS/17-717 (65.74%), WS/19-701 (63.64%) and WS/17-813 (60.43%), showed high susceptibility. Among released varieties, Kufri Bahar exhibited the lowest yield reduction (7.32%) in the current investigation. The Stress susceptibility index (SSI) varied across genotypes, with tolerant lines maintaining stable yields under stress. These findings highlight the potential of salinity-tolerant genotypes for breeding programs aimed at improving potato productivity in saline environments. This research underscores the importance of selecting genotypes that combine high marketable yields with resilience to salinity stress for sustainable cultivation.

KEYWORDS: Salinity, marketable yield, stress susceptibility index, yield reduction.

INTRODUCTION

The potato is the third most important food crop in the world after rice and wheat in terms of human consumption. It is a vital contributor to food security and nutrition due to its adaptability and high nutritional value. It thrives in diverse environments, ranging from the Arctic Circle to tropical regions, at altitudes from sea level to over 4000 meters, and under extreme weather and soil conditions (Ramirez *et al.*, 2019). Its tuber yield depends on sucrose synthesis via photosynthesis, its translocation, and starch conversion in stolons, processes that are highly sensitive to abiotic stress during tuber initiation, affecting yield and quality (Sanwal *et al.*, 2022). For potatoes, which are moderately sensitive to salinity (Abu Zeid *et al.*, 2021), even low salinity levels (1.7–3.5 dS/m) can cause substantial yield reductions, making it a critical constraint in many regions (Chourasia *et al.*, 2021).

Salinity stress disrupts plant growth and tuber development by inducing ionic imbalance, osmotic stress, and oxidative damage, leading to significant yield losses (Li *et al.*, 2022). Plant growth is suppressed, tuber yield declines and alterations are observed in the levels of dry matter, soluble solids, and secondary metabolites within the tubers (Levy and Tai, 2013). Along with this it also restricts water uptake by roots, accelerates

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plant senescence, and leads to browning and cracking of the tuber surface (Levy *et al.*, 2013). Physiological and biochemical traits, including Na^+/K^+ homeostasis, osmotic adjustment through proline accumulation, and antioxidant defence mechanisms, are critical determinants of salinity tolerance in potatoes. Recent advancements in molecular and physiological research have identified many key genes which regulate salt tolerance pathways in potatoes (Li *et al.*, 2022).

The Indo-Gangetic plains and coastal regions, such as the Ganges Delta, are particularly vulnerable to salinity stress due to unsustainable agricultural practices and increasing soil salinization caused by climate change (Sarangi *et al.*, 2020). In these areas, salinity not only limits crop productivity but also exacerbates challenges in resource use efficiency and soil health. Salinity-induced yield losses vary significantly among potato genotypes, with reductions of up to 60% reported under severe stress conditions (Sanwal *et al.*, 2022). Genetic variability among cultivars offers opportunities for breeding salt-tolerant varieties that can sustain high yields and quality under adverse conditions (Han *et al.*, 2023). Genotypes that exhibit high marketable yield and low non-marketable yield under saline stress are particularly desirable for breeding programs and commercial cultivation.

This study evaluates the performance of diverse potato genotypes under natural saline conditions, focusing on their marketable and non-marketable yields. By identifying genotypes with superior salinity tolerance and yield stability, the findings contribute to breeding efforts for developing stress-resilient potato varieties, ensuring sustainable production in salinity-affected regions.

MATERIAL AND METHODS

This study evaluated 58 potato genotypes (Table 1), comprising of 54 advanced breeding lines and 4 released varieties, derived from various breeding programs. The parental lineages of potato genotypes represented a diverse genetic base, including released varieties, HT series clones (heat-tolerant clones), and exotic accessions, ensuring a wide range of traits for salinity tolerance studies. Only genotypes that had demonstrated superior performance in prior breeding evaluations were selected for this study. The check varieties included Kufri Thar-2, derived from CIP397006.18 (Luthra *et al.*, 2020); Kufri Surya, recognized for its heat tolerance (Minhas *et al.*, 2006); Kufri Daksh, known for water-use efficiency (Kumar *et al.*, 2024); and Kufri Bahar, a leading and widely cultivated variety due to its adaptability.

All the genotypes were planted in saline and control (normal) environments replicated thrice in a randomized complete block design (RCBD) in 2nd week of November 2023. Five sprouted tubers of size 30–40 mm of each genotype was planted at a distance of 60 cm × 30 cm in ICAR-IIWBR farm Hisar, Haryana. Salinity stress was created by applying natural saline ground water (ECiw ~ 6 dS m^{-1}) while for the control treatment, the best available water of ECiw ~ 0.72 dS m^{-1} was used. The treatment-wise irrigation was started just after planting and a total of 6 irrigations were applied during the whole cropping period based on 100% evapotranspiration (ET). As per standard recommendation, half a dose of nitrogen and a full dose of phosphorus and potassium were applied at the time of planting and the remaining dose of nitrogen was applied at the earthing up stage (30 days after planting). Dehaulming was performed

Table 1. List of potato genotypes and their parental lineages used in the study.

S.No.	Genotype	Parents	S.No.	Genotype	Parents
1	WS/19-728	HT/10-1559 × Kufri Mohan	30	WS/17-712	HT/12-932 × HT/7-220
2	WS/19-701	HT/10-1559 × Kufri Mohan	31	WS/17-209	MOP/11-147 × HT/7-804
3	WS/19-439	NA	32	WS/19-2008	Innovator × Kufri Pukhraj
4	WS/19-1715	Innovator × JEX/A-122	33	WS/17-1009	HT/10-1907 × HT/7-804
5	WS/19-720	HT/10-1559× Kufri Mohan	34	WS/17-814	Kufri Lalit × HT/7-804
6	WS/19-911	NA	35	WS/14-10-6	NA
7	WS/18-602	CP4197 × Kufri Mohan	36	WS/16-904	NA
8	WS/17-717	HT/12-932 × HT/7-220	37	WS/17-802	Kufri Lalit × HT/7-804
9	WS/18-432	Kufri Jawahar × HT/7-321	38	Kufri Daksh	CP1748 × LT-1
10	WS/19-733	HT/10-1559 × Kufri Mohan	39	WS/18-622	CP4197 × Kufri Mohan
11	WS/17-813	Kufri Lalit × HT/7-804	40	WS/17-1727	NA
12	WS/19-2012	Innovator × Kufri Pukhraj	41	SL/20-519	Kufri Frysona × Kufri Sutlej
13	WS/19-1907	Innovator × CP4242	42	SL/20-1001	UDS60 × Kufri Sutlej
14	Kufri Thar 2	CIP397006.18 (CP4175)	43	SL/20-410	Kufri Himsona × Kufri Jyoti
15	WS/19-1706	Innovator × JEX/A-122	44	SL/20-801	CP4517 × Kufri Sutlej
16	WS/19-1914	Innovator × CP4242	45	SL/20-206	Kufri Kuber × Kufri Sutlej
17	Kufri Surya	Kufri Lauvkar × LT-1	46	SL/20-607	Kufri Mohan × Kufri Jawahar
18	WS/18-1619	NA	47	SL/20-705	Kufri Swarna × Kufri Sutlej
19	WS/19-102	CP4512 × Kufri Mohan	48	SL/20-1502	CP4496 × CP3486
20	WS/19-502	CP3379 × HT/7-321	49	SL/20-707	Kufri Swarna × Kufri Sutlej
21	WS/18-407	Kufri Jawahar × HT/7-321	50	SL/20-511	Kufri Frysona × Kufri Sutlej
22	WS/18-403	Kufri Jawahar × HT/7-321	51	SL/20-412	Kufri Himsona × Kufri Jyoti
23	WS/19-512	CP3379 × HT/7-321	52	SL/20-720	Kufri Swarna × Kufri Sutlej
24	WS/17-321	Kufri Jawahar × HT/7-804	53	SL/20-207	Kufri Kuber × Kufri Sutlej
25	WS/18-412	Kufri Jawahar × HT/7-321	54	SL/20-111	CP4175 × Kufri Sutlej
26	WS/18-405	Kufri Jawahar × HT/7-321	55	SL/20-406	Kufri Himsona × Kufri Jyoti
27	WS/19-721	HT/10-1559 × Kufri Mohan	56	SL/20-1009	UDS60 × Kufri Sutlej
28	WS/17-806	Kufri Lalit × HT/7-804	57	SL/20-408	Kufri Himsona × Kufri Jyoti
29	WS/18-618	CP4197 × Kufri Mohan	58	Kufri Bahar	Kufri Red × Gineke

*NA - Information not available

90 days after planting and harvesting was performed after one week to ensure proper curing. Treatment-wise soil samples were collected just after harvesting to measure the soil salinity build-up and it was found that the final salinity was found in the range of 6.8-7.05 dS m^{-1} in saline treatment.

Traits measured

Data were collected from three plants of each genotype under both conditions, and mean values were used for analysis. The traits measured included marketable tuber yield (MTY), the weight of tubers over 20 g meeting market standards (MTN), and non-marketable tuber yield (NMTY), the weight of tubers under 20 g (NMTN). Total tuber yield (TTY) was the sum of marketable and non-marketable yields. Dry matter content (DM%) was calculated as the percentage of dry weight in tubers after drying at 70°C to constant weight, providing insights into tuber quality.

Statistical analysis

A paired t-test was conducted to determine the significance of differences in traits between control and saline treatments, with a significance threshold set at $p<0.001$. Statistical analysis and data visualization were performed using the R programming environment (R Core Team, 2020).

Stress Susceptibility Index (SSI)

The Stress Susceptibility Index (SSI) was calculated to assess the sensitivity of each genotype to salinity stress using the formula:

$$SSI = 1 - (Yws/Yns) \;/\; DII$$

Where:

Yws: Yield of a genotype under saline treatments.

Yns: Yield of a genotype under control treatments.

DII (Stress Intensity Index): Calculated as:

$$DII = 1 - (\text{Mean } Yws \;/\; \text{Mean } Yns)$$

RESULTS

The yield parameters of 58 potato genotypes, including four check varieties, were evaluated under natural field conditions in both control (non-saline) and saline treatments.

Marketable tuber number per plant (MTNPP)

The mean MTNPP under control treatments was 3.95, while under saline, it was lower at 2.66. The ranges for this trait were 0.90 to 6.13 in control and 0.40 to 4.87 in saline treatments. The coefficient of variation (CV) was 30.04% under control and 38.11% under saline treatments, indicating higher relative variability under saline stress (Table 2). The genotype SL/20-206 recorded the minimum MTNPP under control (0.90), while WS/17-814 exhibited the maximum (6.13) followed by WS/19-1907 (5.93) and WS/19-2012 (5.73) (Table 3). Under saline treatments, the minimum MTNPP was observed in genotype SL/20-801 (0.40), and the maximum in WS/19-2012 (4.87) followed by WS/19-911 (4.80) and WS/17-1009 (4.33). Most of the genotypes exhibited reduced tuber numbers under saline treatments except WS/19-911 and SL/20-1001 where more tuber numbers were observed. Maximum tuber number reduction was observed in genotype SL/20-801 (66.67%), WS/17-717 (65.28%), WS/19-701 (64.10%) and WS/19-102 (61.11%). Statistical analysis revealed a highly significant difference between control and saline treatments ($t = 11.40$, $p < 0.001$) (Fig 1).

Marketable tuber yield (MTY)

The mean MTY under control treatments was 175.6 g/plant, while under saline treatments, it was significantly lower at 106.20 g/plant. The ranges of MTY were 22.80 to 305.20 g/plant in control and 9.60

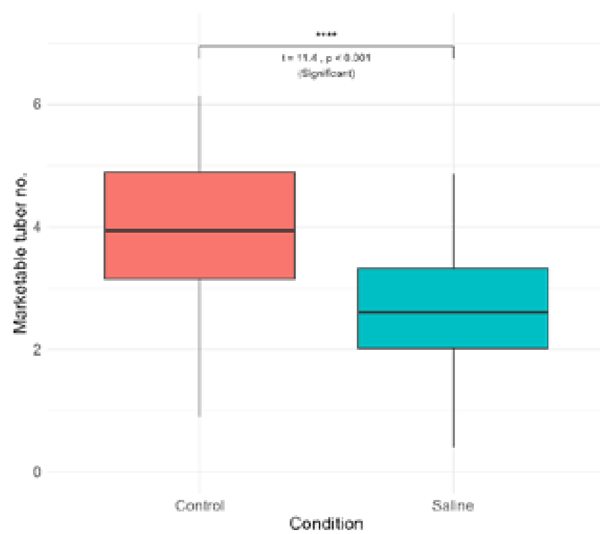

Fig. 1. Variation in marketable tuber no. of potato genotypes under control and saline treatments

Table 2. Comparative Analysis of Traits in Potato Genotypes Under Control and Saline treatments.

Trait	Control						Saline						Paired t-test (t-value)	P value
	Range	Min.	Max.	SD	SE	CV (%)	Range	Min.	Max.	SD	SE	CV (%)		
DM (%)	14.74 – 20.32	WS/19-733	K Thar-2	1.31	0.17	7.55	14.48 – 21.22	SL/20-720	SL/20-408	1.51	0.20	8.63	-0.51	0.611
MTN	0.90 – 6.13	SL/20-206	WS/17-814	1.19	0.16	30.04	0.40 – 4.87	SL/20-801	WS/19-2012	1.02	0.13	38.11	11.39	<0.001
MTY (g)	22.8 – 305.2	SL/20-206	K Thar-2	63.30	8.31	36.05	9.60 – 208.60	SL/20-801	Kufri Thar-2	45.30	5.95	42.66	13.58	<0.001
NMTN	2 – 10.2	WS/19-2012 & WS/19-102	WS/17-813 & WS/18-403	1.92	0.25	41.14	1.8 – 9.67	SL/20-707	WS/17-1009	1.82	0.24	39.69	0.316	0.753
NMTY	19.73 - 104	SL/20-1001	WS/18-403	18.88	2.48	38.97	17.27 – 84.20	WS/19-701	WS/16-904	15.99	2.10	35.94	1.47	0.146
TTY (g)	75.3 – 343.8	SL/20-801	Kufri Thar-2	66.74	8.76	29.79	51.2 – 241.3	WS/19-701	WS/19-2008	49.66	6.52	32.95	11.88	<0.001

to 208.60 g/plant in saline treatments (Table 2). The genotype SL/20-206 recorded the minimum MTY under control treatments (22.80 g/plant), while Kufri Thar-2 exhibited the maximum (305.20 g/plant) followed by WS/19-2008 (301.13 g/plant) and WS/19-1907 (299.73 g/plant). Under saline treatments, the minimum MTY was observed in SL/20-801 (9.60 g/plant), and the maximum in Kufri Thar-2 (208.60 g/plant) followed by WS/19-2008 (205.80 g/plant) and WS/19-1907 (128.33 g/plant). The SD under control (63.30) and under saline treatments (45.30), reflects higher variability in the control environment. The CV (36.05% under control and 42.66% under saline) also indicate greater relative variability under saline stress. Statistical analysis using a paired t-test revealed a highly significant difference between control and saline conditions ($t=13.58$, $p<0.001$) (Fig. 2). This indicated that salinity stress significantly reduced the marketable tuber yield. Most of the genotypes exhibited MTY reduction under saline conditions except one genotype i.e. WS/17-321 which exhibited a 3.12% yield advantage under saline conditions. Maximum yield reduction was

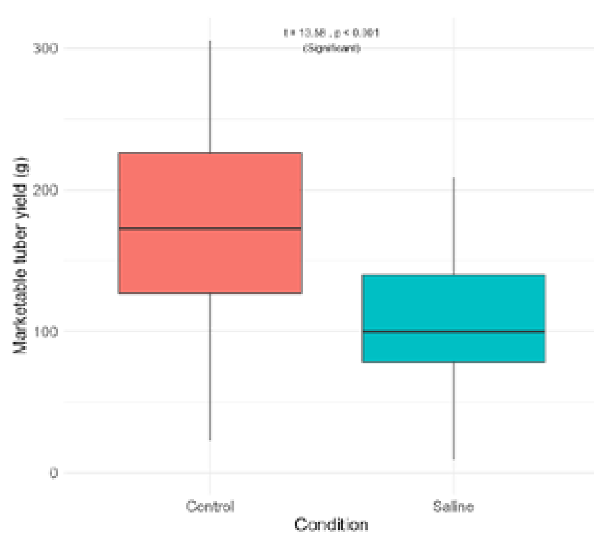

Fig. 2. Variation in marketable tuber yield of potato genotypes under control and saline treatments

Table 3. Performance of different potato genotypes under control and saline treatments.

Genotype	DM (%)		NMTN (No./plant)		NMTY (g/plant)		MTN (No./plant)		MTY (g/plant)		TTY (g/plant)	
	Control	Saline	Control	Saline	Control	Saline	Control	Saline	Control	Saline	Control	Saline
WS/19-728	16.04	17.93	5.27	4.40	58.80	45.13	4.90	2.60	191.40	101.00	250.20	146.13
WS/19-701	15.97	16.46	3.73	2.07	35.87	17.27	2.60	0.93	104.93	33.93	140.80	51.20
WS/19-439	17.66	16.73	4.87	3.80	49.07	36.60	3.13	2.00	152.73	76.33	201.80	112.93
WS/19-1751	17.30	18.18	4.13	3.60	48.53	41.00	5.20	4.20	236.27	166.20	284.80	207.20
WS/19-720	17.47	17.37	5.60	3.93	56.07	45.27	3.73	2.60	148.07	98.13	204.13	143.40
WS/19-911	19.33	18.67	3.87	5.40	41.87	49.07	4.27	4.80	166.27	155.20	208.13	204.27
WS/18-602	16.49	17.96	6.13	4.80	70.20	49.40	5.27	2.73	221.00	119.00	291.20	168.40
WS/17-717	17.12	15.95	6.00	1.87	58.87	17.40	4.80	1.67	225.27	79.93	284.13	97.33
WS/18-432	17.10	15.52	6.07	6.13	63.07	61.00	3.93	3.20	178.00	117.13	241.07	178.13
WS/19-733	14.74	14.61	5.80	4.33	69.47	45.80	5.33	2.47	229.40	92.53	298.87	138.33
WS/17-813	16.56	14.85	10.20	4.13	88.93	33.60	5.27	2.27	226.13	91.07	315.07	124.67
WS/19-2012	16.36	16.46	2.00	5.00	21.40	47.93	5.73	4.87	247.27	187.53	268.67	235.47
WS/19-1907	18.80	20.16	3.47	5.07	39.53	50.67	5.93	3.27	299.73	128.33	339.27	179.00
Kufri Thar 2	20.32	20.15	3.13	3.00	38.60	30.27	5.47	3.33	305.20	208.60	343.80	238.87
WS/19-1706	16.60	16.98	6.00	6.80	62.67	64.47	3.80	2.20	138.00	77.93	200.67	142.40
WS/19-1914	16.15	16.32	3.47	1.93	38.07	24.00	3.07	1.33	150.60	72.53	188.67	96.53
Kufri Surya	18.21	18.69	3.40	2.40	35.73	28.87	3.93	3.07	171.33	131.87	207.07	160.73
WS/18-1619	17.69	17.37	3.60	3.47	45.33	27.80	3.13	2.00	164.33	95.13	209.67	122.93
WS/19-102	17.71	16.75	2.00	2.27	22.53	22.80	3.60	1.40	164.07	65.73	186.60	88.53
WS/19-502	17.56	16.8	3.60	3.47	37.67	31.40	2.73	1.67	110.40	50.20	148.07	81.60
WS/18-407	18.91	18.33	5.80	7.40	59.67	60.73	3.20	2.87	115.60	109.00	175.27	169.73
WS/18-403	16.14	17.24	10.20	4.50	104.00	48.80	5.40	3.00	207.87	119.50	311.87	168.30
WS/19-512	20.03	18.54	2.33	2.20	27.07	27.07	3.87	2.87	262.67	165.27	289.73	192.33
WS/17-321	17.51	18.83	6.47	5.47	59.73	52.53	2.80	2.70	104.73	108.00	164.47	160.53
WS/18-412	18.03	16.81	4.47	3.13	43.93	32.07	3.33	2.27	163.47	89.73	207.40	121.80
WS/18-405	16.22	15.9	4.47	4.47	45.67	45.13	4.33	2.13	215.20	83.27	260.87	128.40
WS/19-721	16.89	15.42	4.00	5.00	49.40	51.20	5.33	3.80	197.67	163.47	247.07	214.67
WS/17-806	19.12	17.13	4.33	4.07	39.93	43.07	4.27	3.40	241.67	169.80	281.60	212.87
WS/18-618	16.36	18.78	3.00	2.53	30.60	26.33	3.93	2.00	225.60	89.90	256.20	116.23
WS/17-712	18.48	19.02	4.60	5.67	54.27	59.20	4.33	4.07	194.07	166.33	248.33	225.53
WS/17-209	15.81	16.14	4.07	4.53	42.87	51.53	4.60	4.20	230.27	141.67	273.13	193.20
WS/19-2008	17.03	17.52	2.93	3.40	35.47	35.53	5.07	3.87	301.13	205.80	336.60	241.33
WS/17-1009	17.25	17.95	4.53	9.67	50.40	67.13	5.47	4.33	228.33	170.13	278.73	237.27
WS/17-814	17.42	18.41	5.60	3.80	65.13	36.73	6.13	3.67	268.73	162.73	333.87	199.47
WS/14-10-6	15.20	17.3	3.73	3.67	40.93	33.00	5.73	3.53	256.80	148.47	297.73	181.47
WS/16-904	15.30	15.25	8.80	9.00	93.93	84.20	4.60	2.40	187.60	87.60	281.53	171.80
WS/17-802	18.84	17.36	6.53	5.73	69.93	59.00	4.87	3.67	268.27	144.67	338.20	203.67
Kufri Daksh	17.38	16.92	5.07	6.13	41.73	57.20	4.33	3.13	185.20	109.20	226.93	166.40
WS/18-622	17.04	15.2	4.40	3.87	48.73	37.13	3.60	3.00	181.47	104.07	230.20	141.20

Genotype	DM (%)		NMTN (No./plant)		NMTY (g/plant)		MTN (No./plant)		MTY (g/plant)		TTY (g/plant)	
	Control	Saline	Control	Saline	Control	Saline	Control	Saline	Control	Saline	Control	Saline
WS/17-1727	16.98	18.66	8.80	5.13	93.07	55.60	3.80	3.80	177.53	121.70	270.60	177.30
SL/20-519	19.70	19.54	2.53	2.47	23.93	23.00	2.10	1.27	117.30	43.53	141.23	66.53
SL/20-1001	16.93	18.53	2.33	9.00	19.73	79.30	2.00	2.50	173.50	86.10	193.23	165.40
SL/20-410	17.98	18.88	5.47	7.73	44.87	74.60	4.07	2.40	131.07	89.87	175.93	164.47
SL/20-801	16.78	17.2	4.40	5.20	39.60	49.53	1.20	0.40	35.70	9.60	75.30	59.13
SL/20-206	18.70	19.88	7.60	5.53	71.00	34.87	0.90	0.80	22.80	21.00	93.80	55.87
SL/20-607	15.19	15.71	2.80	5.53	22.73	58.47	4.40	3.10	152.50	90.00	175.23	148.47
SL/20-705	17.08	17.96	4.00	2.60	52.80	28.60	3.20	2.87	152.60	134.20	205.40	162.80
SL/20-1502	18.22	19.42	2.80	4.87	31.70	44.47	3.80	1.67	111.90	66.27	143.60	110.73
SL/20-707	16.65	17.9	3.07	1.80	30.27	20.33	3.00	2.60	125.27	110.20	155.53	130.53
SL/20-511	18.97	19.42	3.40	3.67	31.20	37.67	3.00	1.33	114.90	40.80	146.10	78.47
SL/20-412	19.72	17.42	4.50	3.73	51.20	28.53	2.40	1.60	92.30	51.40	143.50	79.93
SL/20-720	15.50	14.48	3.33	3.67	30.13	33.27	2.47	1.20	87.80	45.40	117.93	78.67
SL/20-207	17.81	16.62	2.20	2.73	27.33	29.07	3.27	2.33	170.80	119.40	198.13	148.47
SL/20-111	18.99	19.24	4.53	6.53	43.13	64.27	4.20	2.07	167.20	78.47	210.33	142.73
SL/20-406	18.02	15.67	6.73	6.60	65.20	64.73	3.27	2.47	101.47	81.07	166.67	145.80
SL/20-1009	16.27	17.43	7.87	6.60	71.67	66.53	2.33	2.13	78.73	66.67	150.40	133.20
SL/20-408	19.32	21.22	3.20	4.53	33.30	49.93	3.60	2.33	124.70	74.40	158.00	124.33
Kufri Bahar	16.23	16.66	3.40	5.53	40.93	61.47	5.13	4.20	179.40	142.73	220.33	204.20

exhibited by genotype SL/20-801 (73.11%) followed by WS/19-701 (67.66%), WS/17-717 (64.52%) and SL/20-511 (64.50%). Out of 4 check varieties minimum MTY reduction was observed by variety Kufri Bahar (20.44%) and maximum reduction by variety Kufri Daksh (41.04%). Ten genotypes were found that exhibited lower yield reduction under saline treatments as compared to check Kufri Bahar.

Non-marketable tuber number per plant (NMTNPP)

The mean NMTNPP under control treatments was 4.67, while under saline treatments, it was 4.58. The ranges of NMTNPP were 2.00 to 10.20 in control and 1.80 to 9.67 in saline treatments (Table 2). The genotype WS/19-2012 exhibited the minimum under control treatments (2.0), while WS/17-813 recorded the highest (10.2) NMTNPP. Under saline treatments, the minimum NMTNPP was observed in SL/20-707 (1.8), and the maximum in WS/17-1009 (9.67). The box plot visually represents the distribution of NMTNPP under control and saline treatments. Statistical analysis revealed no significant difference between control and saline treatments ($t = 0.317$, $p = 0.753$). This result suggests that salinity had no significant impact on the number of non-marketable tubers per plant (Fig 3).

Non-marketable tuber yield (NMTY)

The mean NMTY under control treatments was 48.44 g/plant, while under saline treatments, it was slightly lower at 44.51 g/plant. The ranges of NMTY were 19.73 to 104.00 g/plant in control and 17.27 to 84.20 g/plant in saline treatments (Table 2). The genotype SL/20-1001 recorded the minimum NMTY under control treatments (19.73 g/plant), while WS/18-403 exhibited

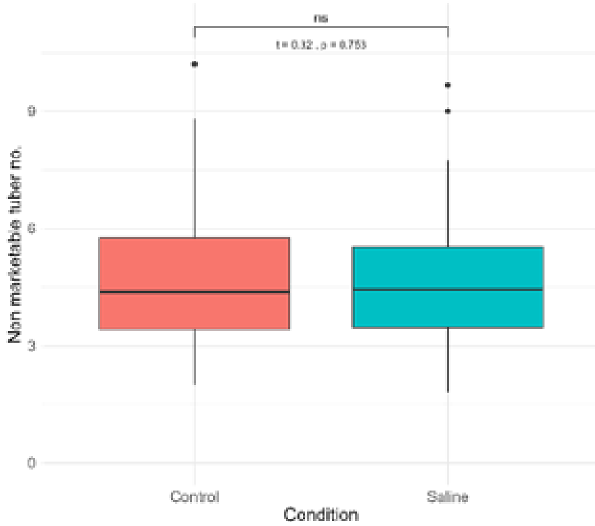

Fig. 3. Variation in non-marketable tuber no. of potato genotypes under control and saline treatments

the maximum (104.00 g/plant). Under saline treatments, the minimum NMTY was observed in WS/19-701 (17.27 g/plant), and the maximum in WS/16-904 (84.20 g/plant). Statistical analysis revealed no significant difference between control and saline treatments ($t = 1.474$, $p = 0.146$) (Fig. 4). This result suggests that salinity did not significantly impact the non-marketable tuber yield.

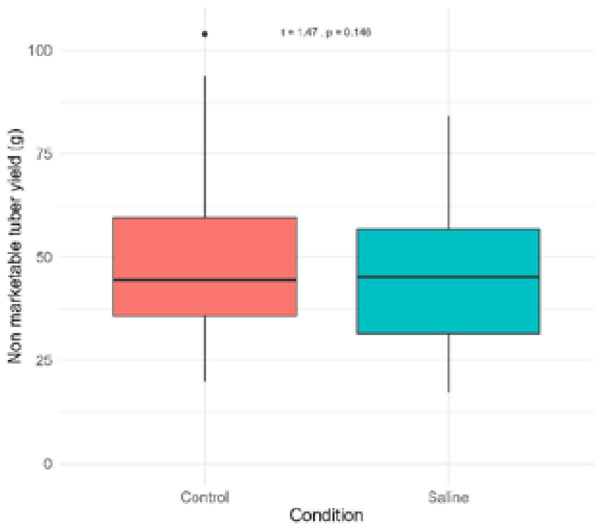

Fig. 4. Variation in non-marketable tuber yield of potato genotypes under control and saline treatments

Total tuber yield (TTY)

The total tuber yield (TTY) was significantly affected by salinity stress, as evident from the statistical analysis conducted on potato genotypes. Under control treatments, the mean TTY was 224.00 g/plant, with an SD of 66.74, SE of 8.76, and a CV of 29.79%. The range of TTY under control varied from 75.30 g/plant (SL/20-801) to 343.80 g/plant (K. Thar-2) (Table 2). After Kufri Thar-2 maximum TTY under control treatments was exhibited by genotype WS/19-1907 (339.27 g) followed by WS/17-802 (338.20 g) and WS/19-2008 (336.60 g) (Table 3). In comparison, under saline treatments, the mean TTY decreased significantly to 150.70 g/plant, with an SD of 49.66 g/plant, SE of 6.52 g/plant, and a CV of 32.95%. The range under saline treatments spanned from 51.20 g/plant (WS/19-701) to 241.30 g/plant (WS/19-2008). Under saline treatments after WS/19-2008 maximum TTY was shown by Kufri Thar-2 (238.87 g), WS/17-1009 (237.27 g) and WS/19-2012 (235.47 g). So out of all check varieties, Kufri Thar-2 performed better under both the control and saline treatments. The paired t-test revealed a highly significant difference between control and saline treatments ($t=11.881$, $p<0.001$), confirming the adverse impact of salinity on TTY (Fig 5).

Dry Matter Content (DM)

The results showed that the mean dry matter under control treatment was 17.40%, while under saline treatments, it was slightly higher at 17.48%. The genotype WS/19-733 recorded the minimum dry matter under control (14.74%), whereas variety Kufri Thar-2 exhibited the highest (20.32%) followed by WS/19-512 (20.03%) and SL/20-412 (19.72). Under saline treatments, the minimum DM was observed in SL/20-720 (14.48%), and the maximum in SL/20-408 (21.22%) followed by WS/19-1907 (20.16%) and Kufri Thar-2

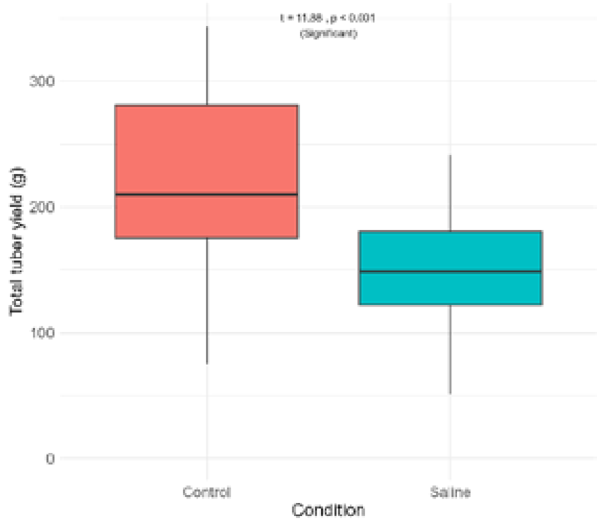

Fig. 5. Variation in total tuber yield of potato genotypes under control and saline treatments

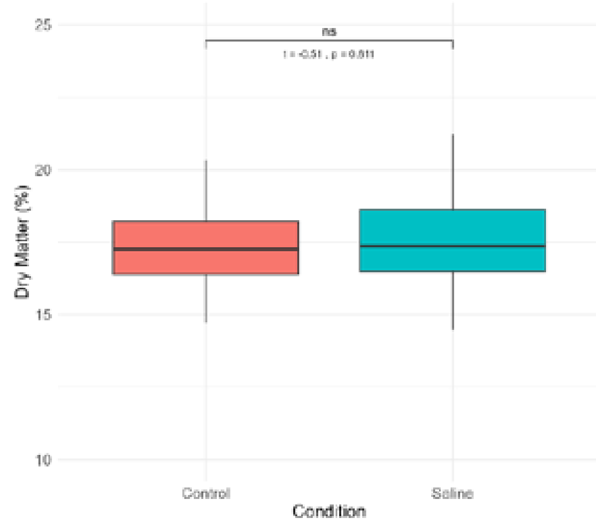

Fig. 6. Variation in dry matter (%) of potato genotypes under control and saline treatments

(20.15%). Statistical analysis using a paired t-test (t = -0.51, p = 0.611) indicated no significant difference between the DM content under control and saline treatments. The variability parameter (SD of 1.31 for control and 1.51 for saline) also suggested minor fluctuations in response to salinity. A comparison across the genotypes revealed that certain genotypes, such as WS/19-720, WS/19-733, WS/19-2012, Kufri Thar-2, WS/16-904 and SL/20-519 maintained almost stable DM content across both conditions, highlighting potential tolerance to salinity-induced stress. The box plot visually represents the distribution and variability of dry matter content under control and saline treatments, showing comparable medians and ranges (Fig 6).

Stress Susceptibility Index (SSI)

The analysis of the Stress susceptibility index (SSI) revealed significant variation among the potato genotypes, highlighting their differing responses to salinity stress (Fig 7). Genotypes with SSI values less than 1 were identified as tolerant, demonstrating smaller yield reductions under stress. Notable tolerant genotypes included WS/19-911 (0.06), WS/19-2012 (0.37), WS/17-712 (0.28), Kufri Bahar (0.22), and SL/20-1502 (0.69), which maintained stable yields despite the stress conditions. Genotypes with SSI values close to 1, such as WS/19-720 (0.90), WS/17-209 (0.89) and WS/19-2008 (0.86) exhibited moderate tolerance by experiencing yield reductions proportional to the overall stress intensity. Conversely, genotypes with SSI values greater than 1 were classified as sensitive, indicating higher susceptibility to salinity stress. Highly sensitive genotypes included WS/17-717 (1.99), WS/19-733 (1.63), SL/20-519 (1.60), and SL/20-720 (1.01), which showed significant yield declines under stress. These findings underscore the potential of tolerant genotypes, such as WS/19-911 and WS/18-407 (0.10), for cultivation in saline environments, while sensitive genotypes may require targeted breeding efforts or improved management practices to enhance their performance under stress.

DISCUSSION

The observed similarity in dry matter content between control and saline conditions

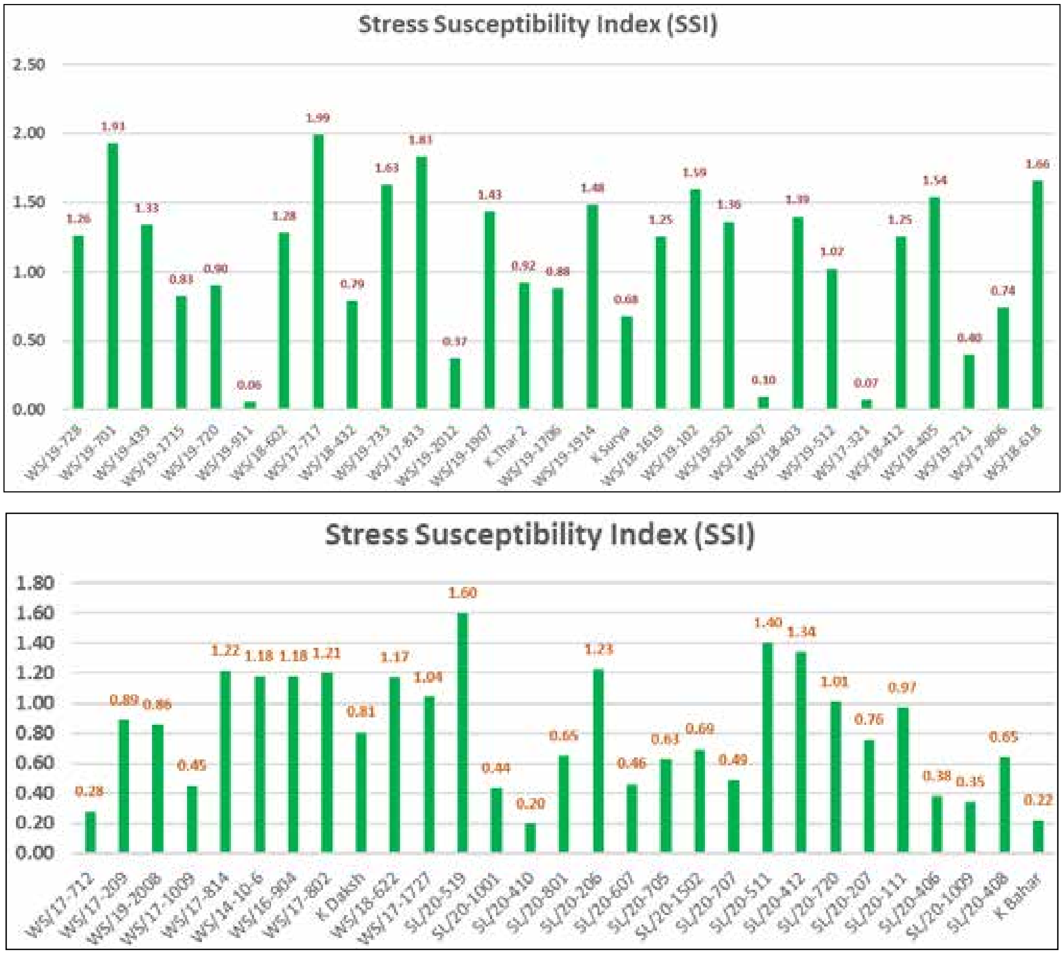

Fig. 7. Stress Susceptibility Index (SSI) of potato genotypes under salinity stress treatments

indicates that salinity did not significantly impact this trait across the evaluated genotypes. This stability in DM might suggest inherent physiological mechanisms enabling these genotypes to maintain carbohydrate synthesis and storage even under saline stress. Genotypes showing consistent dry matter content under saline treatments could be prioritized for further breeding programs targeting salinity resilience. For example, SL/20-408 and Kufri Thar-2 showed high dry matter content under both control and saline treatments, making them potential candidates for breeding. Conversely, genotypes like WS/19-733 and SL/20-720, which exhibited lower dry matter content, could be considered less tolerant. The findings align with previous studies that reported varying impacts of salinity on dry matter content, depending on the genetic background and environmental factors.

The results of the present investigation demonstrated that salinity stress had a significant negative impact on the MTNPP trait. The reduction in mean MTNPP under saline treatments, coupled with a higher CV, suggests that genotypes exhibit diverse responses to salinity stress. This highlights the need for targeted selection of genotypes with stable performance under saline environments. Genotypes such as WS/19-2012 and WS/17-814, which recorded high

MTNPP under saline and control treatments, respectively, could be prioritized for breeding programs aimed at improving marketable tuber yield under stress. Conversely, genotypes like SL/20-206 and SL/20-801, which exhibited low MTNPP, may be less suitable for such programs. The observed variability and significant reduction in MTNPP under saline treatments align with previous studies indicating that salinity adversely affects tuber development and marketability. Future studies should focus on identifying physiological and molecular mechanisms that enable certain genotypes to maintain higher MTNPP under saline stress, which could facilitate the development of stress-resilient potato varieties.

The results demonstrated that salinity stress had a pronounced negative impact on the MTY trait. The reduction in mean MTY under saline treatments, coupled with a higher CV, suggests that genotypes exhibit diverse responses to salinity. This diversity highlights the importance of selecting genotypes with stable and high yields under saline environments. Kufri Thar 2, which exhibited the highest MTY under both control and saline treatments, emerges as a promising candidate for breeding programs aimed at improving yield under salinity stress. Conversely, genotypes like SL/20-206 and SL/20-801, which showed consistently low MTY, may be less suitable for saline environments. These findings align with prior research, underscoring salinity detrimental effects on potato yield. Future research should focus on identifying the physiological and molecular mechanisms that enable salinity tolerance in high-performing genotypes, such as Kufri Thar 2, to facilitate the development of resilient potato cultivars.

The results indicated that salinity stress had no significant influence on the non-marketable tuber no and yield, as evidenced by the non-significant p-value from the paired t-test. Genotypes that exhibit high marketable yield and low non-marketable yield under saline treatments are highly desirable, as they ensure both economic viability and quality, even in stress-prone environments.

The reduction in mean TTY, along with the higher CV under saline treatments, underscores the variability in genotype performance under stress. Kufri Thar 2, which exhibited the highest TTY under control treatments, and WS/19-2008, which performed best under saline treatments, are robust candidates for breeding programs focused on salinity tolerance. Conversely, genotypes such as SL/20-801 and WS/19-701, which consistently showed low TTY, may be less suitable for saline environments. These findings align with previous studies highlighting salinity detrimental effects on potato tuber yield. In their study, Levy and Tai (2013), showed significant genotypic differences in response to salinity, with varieties such as Vivaldi and Almera demonstrating better adaptation under high salinity treatments compared to Mondial and Charlotte. They also reported that salinity reduced tuber yield but increased dry matter and soluble solids across all genotypes, underscoring the differential impact of saline conditions on potato traits. Rahman *et al*. (2013) evaluated CIP germplasm in saline conditions and observed that CIP-112 recorded the highest yield (21.07 t/ha), followed by CIP-111 (18.72 t/ha) and CIP-102 (17.55 t/ha), all of which outperformed local variety Diamant (15.78 t/ha). The range under saline conditions in our study spanned from 51.20 to 241.30 g/plant. In comparison, Ramírez *et al*. (2019) reported that despite extreme salinity, 40% of the genotypes survived, yielding between 0.3–5.2 g of fresh tuber per plant. The observed variability among genotypes provides opportunities for selecting high-performing genotypes to enhance resilience under salinity stress. Further research is warranted to understand the physiological and molecular mechanisms underlying salinity tolerance in promising genotypes like K. Thar 2 and WS/19-2008.

Yield reduction percentage and comparison with check varieties

The analysis of yield reduction percentage revealed significant differences in the responses of genotypes under saline treatments. The yield reduction in the present study ranged from 1.86% to 65.74%, with an average reduction of 31.70%, highlighting significant variability in genotypic responses to salinity stress. Among the check varieties, Kufri Bahar exhibited the lowest yield reduction of 7.32%, showcasing salinity tolerance and yield stability under stress treatments. Similarly, Kufri Surya, Kufri Daksh and Kufri Thar-2 showed yield reductions of 22.38%, 26.67% and 30.52%, respectively. These results highlight the variability in salinity responses among check varieties. When compared to the genotypes, several promising genotypes demonstrated better performance than some of the check varieties. Notably, WS/19-2008 recorded the highest yield under saline treatments (241.30 g/plant) with a yield reduction of 28.30%, surpassing even Kufri Thar-2. Similarly, genotypes such as WS/19-911 (yield reduction- 1.86%), WS/17-321 (2.39%), WS/18-407 (3.16%) and SL/20-410 (6.52%) exhibited lower yield reduction, outperforming Kufri Bahar (7.32% yield reduction). These genotypes, with minimal reductions and consistent performance under stress, represent excellent candidates for breeding programs targeting salinity tolerance. In contrast, genotypes like WS/17-717 (65.74%), WS/19-701 (63.64%) and WS/17-813 (60.43%) displayed the highest yield reductions, highlighting their susceptibility to salinity stress. It is well known that salinity is a major abiotic stress which affects plant growth and yield drastically by disrupting physiological, biochemical and metabolic processes. In this study, yield reductions under saline treatments can be caused by multiple factors. It may be due to osmotic stress, which limits water uptake, reduced cell expansion, tuber initiation and bulking. Additionally, ion toxicity, due to excessive accumulation of Na^+ and Cl^- ions, can disrupt nutrient homeostasis which impacts the uptake of essential macronutrients like K^+, Ca^{2+}, and Mg^{2+}, thereby impairing enzymatic activities and plant metabolism. Furthermore, it can affect photosynthetic efficiency of potato plant which impacts biomass accumulation and tuber development. Salinity triggers oxidative stress through reactive oxygen species (ROS), responsible for cellular damage and disruption of metabolic pathways. So, all of these physiological constraints could be responsible for decline in tuber yield under saline treatments compared to the control treatment.

Ramírez *et al*. (2019) observed CIP 397099.4, CIP 396311.1, and CIP 390478.9 demonstrated the highest tolerance, with 9.3%, 8.9%, and 5.8% yield relative to control conditions, respectively. Levy (1992) reported yield reductions of 0–17% under moderate salinity and 21–79% under high salinity, with early-maturing cultivars like Atica and Desirée performing better. Salinity affected tuber growth more than haulm growth, delaying emergence and accelerating senescence. Munira *et al*. (2015) analyzed the response of ten potato varieties to different salinity levels (0.5 to 8.90 dS/m) and observed Sagita and Felsina as the top-performing varieties, achieving the highest yields of 363.3 g at 0.5 dS/m and 121.7 g/118.3 g at 8.90 dS/m. Lady Rosetta and Provento showed moderate tolerance, while Shilbilati and Lalpakri were the most affected, displaying the lowest yields and severe membrane damage. Across all varieties, yield reductions surpassed 60% under 8.90 dS/m salinity. Shaterian *et al*. (2008) evaluated the effects of salinity (100–150 mM NaCl) on tuber yield in 22 diploid potato clones and revealed significant variability in yield under salinity, with clones 9506-04 and 9788-03 showing the highest relative yields, demonstrating strong tolerance. Sanwal *et al*. (2022) assessed 53 potato genotypes under saline (6 dS/m) and control conditions, observing an average tuber yield reduction of 38.75% due to salinity stress. The highest yield under saline conditions was recorded in Kufri Lalit (428.27 g/plant), while Kufri Sheetman (60.93 g/plant) had the lowest. Abdullah-Al-Mahmud *et al*. (2018) assessed five CIP potato clones and two check varieties under salinity levels of 0 to 16 dS/m. At 0 dS/m, tuber yields ranged from 276 to 366.75 g/plant, with Diamant yielding the highest. At 16 dS/m, yields dropped to 14.25–48 g/plant, with CIP-139 showing the best performance. Yield reductions at 8 dS/m were 50.64% for CIP-139, 55.25% for CIP-112, and 59.51% for CIP-102.

The comparison underscores the importance of selecting genotypes that combine high yields with minimal yield reductions under saline conditions. While Kufri Bahar and Kufri Thar-2 serve as reliable standards for evaluating salinity tolerance in our study, the outstanding performance of WS/19-2008, WS/19-911, and WS/17-321 demonstrates the potential of these genotypes for breeding programs. The variability in yield reduction percentages across genotypes emphasizes the need for further research to understand the physiological and molecular mechanisms of salinity tolerance, particularly in high-performing genotypes like WS/19-2008, to develop stress-resilient potato cultivars. Figure 9 shows the yield of potato genotypes under control and saline conditions, with consistent reductions observed across all genotypes under salinity stress. Genotypes exhibiting minimal yield differences, such as WS/19-911 and WS/17-321, indicate potential tolerance, while others like WS/17-717 showed pronounced sensitivity. Figure 8 shows the percentage yield reduction under saline conditions across potato genotypes, with substantial variability observed among genotypes.

CONCLUSION

This study highlighted the remarkable diversity among advanced potato genotypes

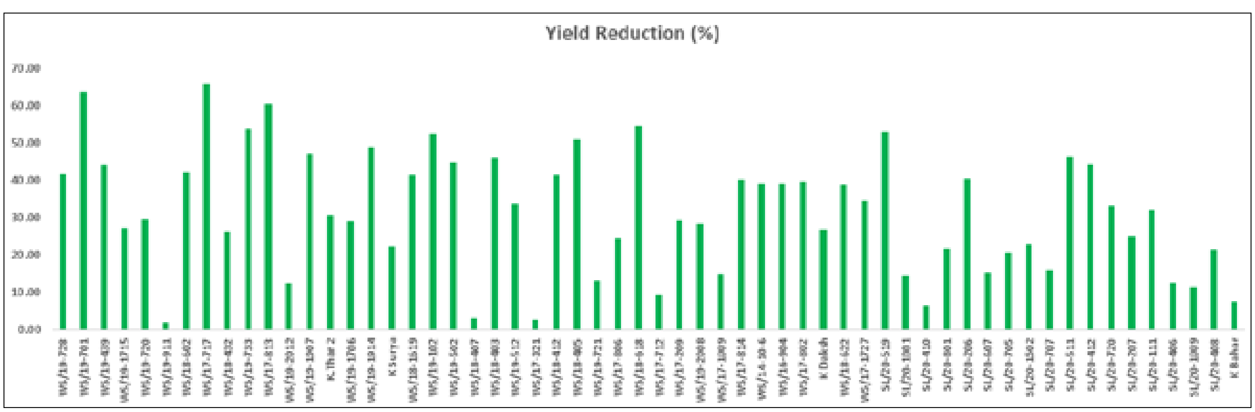

Fig. 8. Yield reduction (%) of potato genotypes under saline treatments

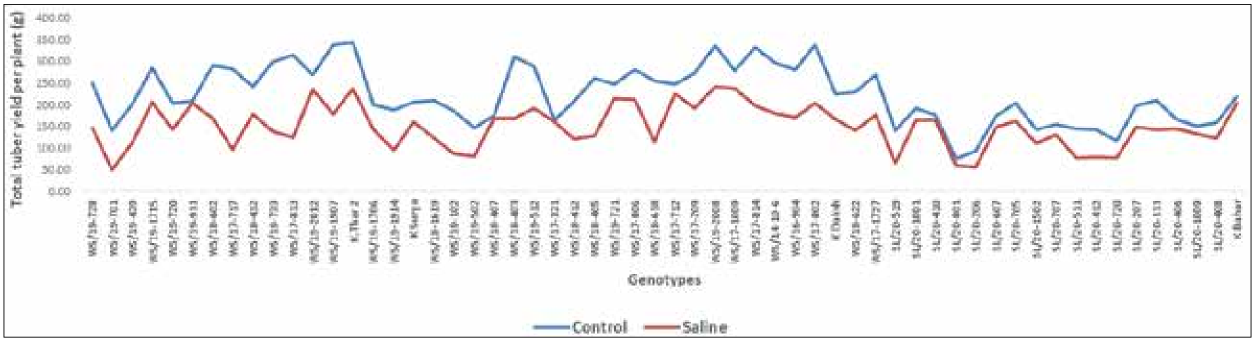

Fig. 9. Total tuber yield (g/plant) of potato genotypes under control and saline treatments

in their ability to tolerate salinity stress under natural field conditions. Genotypes such as WS/19-911 and WS/17-321, along with the variety Kufri Bahar, stood out for their resilience, maintaining high yields even under saline conditions. These genotypes were found superior for breeding efforts aimed at improving potato productivity in saline-prone areas. The results emphasize the importance of identifying and utilizing such robust genotypes to ensure sustainable cultivation and food security. Moving forward, a deeper understanding of the mechanisms driving salinity tolerance will be key to developing even more resilient potato varieties.

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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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PERFORMANCE OF DIFFERENT MULCHING MATERIALS WITH FERTILIZER LEVELS ON MORPHOLOGICAL GROWTH AND YIELD OF POTATO IN THE CENTRAL PLAINS OF INDIA

Bharti Choudhary[1*], Rahul Dongre[2], Sandhya Bakode[3] and VK Paradkar[4]

ABSTRACT: Mulching is essential for sustainable horticulture practices in this region as it helps reduce soil moisture loss, regulate soil temperature and minimize erosion. Examining different types of mulch in this specific climate can aid in developing adaptive strategies to mitigate the adverse effects of climate variability and enhance horticultural resilience. In the experiment, two factors were considered: five types of mulching materials—maize straw, polythene (25 microns), woven mulch, and silver mulch—and two fertilizer levels—75 % and 100 % of the RDF (120:100:100 NPK kg/ha). The experiment was conducted under the All India Coordinated Research Project on Potato at JNKVV, Chhindwara. Results revealed that all mulched treatments significantly outperformed the control (without mulch). The highest yield was recorded with polythene sheet mulch (31.73 t/ha), followed by maize straw mulch (30.13 t/ha). Maize straw mulch provided an additional yield of 10.24 t/ha over the control. Among fertilizer levels, 100% RDF (120:100:100 kg/ha NPK) produced the highest yield (31.73 t/ha). The combined effect of mulch and fertilizer showed that the highest yield (30.93 t/ha) was obtained in the F2M2 treatment (100% RDF with polythene mulch), whereas the lowest yield (18.73 t/ha) was recorded in the F1M0 treatment (75% RDF without mulch). These results highlight the importance of mulching and optimized fertilization in enhancing potato yield in the central plains of India.

KEYWORDS: Fertilizer, morphological growth, mulches, potato

INTRODUCTION

Potato (*Solanum tuberosum* L.) is the third most important food crop globally after rice and wheat in terms of human consumption. It originated in the Peruvian-Bolivian Andes Mountains of South America and belongs to the Solanaceae family. Currently, potatoes are cultivated in more than 160 countries and are recognized as one of the four major agronomic crops (Donnelly and Kubow, 2011). Potatoes are vegetatively propagated, with each plant capable of producing 5–20 new tubers that are genetic clones of the mother plant. Potatoes are highly efficient food crops, producing substantial dry matter, edible protein, and essential minerals. They are rich in vital nutrients, including vitamins C and B6, as well as minerals such as potassium, magnesium, and iron. Additionally, they contain B vitamins like riboflavin, thiamine, and folate, making them a valuable dietary source of vitamin B6. Due to their short growing cycle and flexibility in planting and harvesting, potatoes integrate well into multiple cropping systems and hold significant commercial value (Choudhary (2021).

Conventional potato production methods face several challenges. While fertilization and irrigation are commonly used to enhance yield, other crucial factors often receive less attention. Soil moisture fluctuations have

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been reported to adversely impact seed germination, crop emergence, and overall production (Ahmed *et al*., 2017). Balancing productivity, profitability and environmental health is a key challenge for agricultural sustainability (Singh *et al*., 2021). Potato cultivation requires a moderate temperature range for optimal growth. Extreme heat or cold can significantly reduce yield, with the ideal temperature for potato production being between 15–20°C. Growth declines when temperatures drop below 15°C or exceed 20°C (Gautam *et al*., 2025). Additionally, weed infestation poses a major challenge, as weeds compete with potato plants for nutrients, water, and sunlight, ultimately reducing yield (Ferdous *et al*., 2017).

Mulching is an effective agronomic practice that modifies the plant micro-environment to enhance crop yield. Based on the type of materials used, mulching can be broadly categorized into three types: organic mulching (e.g., crop straw, leaves, geotextiles), inorganic mulching (e.g., plastic films, biodegradable films), and mixed mulching (e.g., combinations of plastic, straw, grass, and gravel) (Kader *et al*., 2017). Mulching practices have both direct and indirect benefits on microclimatic conditions and crop productivity. It effectively prevents soil erosion and reduces water loss from arable lands (Prosdocimi *et al*., 2016). Soil characteristics and climatic conditions might have influenced growth in addition to mulches (Karangwa *et al*., 2023). Additionally, mulching minimizes nitrogen leaching, enhances nutrient availability and improves overall soil quality (Haraguchi *et al*., 2004). Plastic mulching significantly influences soil hydrothermal conditions by increasing soil temperature and reducing moisture loss through evaporation (Wang *et al*., 2005). Among the various mulching techniques, plastic and straw mulching are widely adopted in potato cultivation. Straw mulching, in particular, is a practical and sustainable approach in regions where straw is readily available (Tang *et al*., 2015). It plays a crucial role in reducing soil evaporation and erosion, improving soil moisture retention, regulating temperature, increasing soil enzymatic activity, and suppressing weed growth (Akhtar *et al*., 2018). Furthermore, straw mulching enhances soil nutrient availability, boosts crop productivity, and mitigates environmental pollution caused by straw burning, contributing to both agronomic and ecological sustainability (Pengfei Li *et al*., 2025). The Central Plains of India, including Madhya Pradesh, experience a combination of semi-arid and sub-humid climatic conditions, making soil moisture conservation a critical factor for sustainable agriculture.

Straw mulch is particularly beneficial in regions where organic residues are readily available. In the Central Plains of India, especially in Madhya Pradesh, maize straw is abundantly produced, making it a cost-effective and sustainable mulching option. Utilizing maize straw as mulch can significantly reduce production costs while improving soil moisture retention, suppressing weeds, and enhancing soil fertility. Despite the well-documented benefits of mulching, limited studies have evaluated its effectiveness in the Central Plains of India. This study investigates the impact of different mulching materials in combination with varying fertilizer levels on the morphological growth and yield of potatoes in this region. Unlike previous research, this study provides a comprehensive evaluation of the agronomic and economic viability of different mulch types, particularly emphasizing maize straw as a locally available and sustainable alternative. The findings will help optimize mulching practices for improved potato productivity in the central plains of India.

MATERIAL AND METHOD

Experimental site

The experiment was conducted during the 2020-21 and 2021-22 cropping seasons under the All India Coordinated Research Project on Potato at JNKVV, Chhindwara, Madhya Pradesh, India. The experimental site is situated at 22°3′26.77″ N latitude and 78°56′17.42″ E longitude, at an altitude of 675 meters above mean sea level. The region has a semi-arid to sub-tropical climate, with an average annual rainfall of 1350 mm. The soil of the experimental site was sandy loam in texture with a neutral pH of 7.33. It was rich in organic carbon (1.52%) and contains available nitrogen (332 kg/ha), phosphorus (35 kg/ha), and potassium (157 kg/ha).

To ensure relevance, the study incorporates average seasonal data on rainfall, relative humidity, and temperature during the potato-growing period for both years. Total rainfall received during the crop growth period was 1.23 mm. The average maximum and minimum temperatures during the season were 29.9°C and 11.4°C, respectively. Relative humidity ranged from 23.5% to 80.7%, influencing crop growth and development. These climatic conditions played a crucial role in influencing potato growth and yield during the study period.

Experimental Design and Treatments-

The gross plot size measured 4.8 m x 4.0 m, while the net plot size was 3.6 m x 3.6 m. The experiment was laid out in a Split-Plot Design with three replications. The study involved two factors: five different mulching materials and two fertilizer levels, leading to 10 treatment combinations. The treatments were as follows: - Mulching Materials: - M0: No mulch (control), M1: Maize straw mulch, M2: Polythene mulch (25 microns), M3: Woven mulch, M4: Silver mulch, Fertilizer Levels are as F1: 75% of Recommended Dose of Fertilizers (RDF) (90:75:75 kg NPK/ha), F2: 100% of RDF (120:100:100 kg NPK/ha). Woven mulches are landscaping fabrics typically made from woven or knitted polypropylene, as well as blends of cotton, jute, coir, and polyester. They are characterized by a medium texture and thickness, high tear resistance, good elongation, and lightweight properties. The potato variety *Kufri Chipsona-3* was used for the experiment. The crop was planted at a spacing of 60 × 20 cm (row to row and plant to plant) in the first week of November each year. The nitrogen was applied in three split doses—basal, 30 days after planting (DAP), and 45 DAP—as per the treatment requirements. Haulms were cut at 100 DAP, and harvesting was done 15 days after haulm cutting.

Mulch Application and Irrigation Details

Mulches were applied immediately after planting. Organic mulch (maize straw) was applied at a rate of 5 t/ha, while synthetic mulches were laid over the ridges. Ridge and furrow irrigation method was used at the intervals of 8 to 10 days to maintain optimal soil moisture levels based on crop water requirements and prevailing weather conditions. Agronomic practices and fertilizer application followed the recommended guidelines for the region, with reference to standard soil fertility recommendations.

Observations Recorded

The following parameters were recorded to assess the impact of treatments: Growth parameters: Emergence percentage (30 DAP), plant height (50 DAP), number of shoots per plant (50 DAP), and number of compound leaves per plant (50 DAP). Yield parameters**:** Grade-wise tuber yield, total tuber yield (t/ha), total tuber number (000′/ha). Quality parameters: Dry matter content of tubers and haulms (%). Economic analysis: Gross and net returns, benefit-cost (B:C) ratio for different treatments.

Statistical data analysis

The data were subjected to analysis of variance (ANOVA) appropriate to the Split Plot Design using OPSTAT software. Treatment means were compared using the Least Significant Difference (LSD) test at a 5% level of significance ($P < 0.05$) to determine significant differences among treatments.

RESULT AND DISCUSSION

The average of two-year data, results of the present investigation show that different growth and yield parameter such emergence percentage, plant height and number of shoots, leaves, grade wise total yield, grade wise tuber at harvesting and economics were influenced by different mulches and fertilizer's levels.

Effect of different mulches on plant growth & yield parameters

The percentage of plant emergence ranged from 93.50% to 94.63%, while plant height varied between 44.13 cm and 46.41 cm. The data are presented in Table 1, 2 and 3. The pictorial view of differents mulches are given in Fig. 1, 2, 3 and 4. The highest emergence percentage (94.63%) and maximum plant height (46.41 cm) were recorded with polythene mulch (M2), which was statistically comparable to all other treatments. In contrast, the lowest values for both parameters were observed in the control group. Among the treatments, the highest number of shoots per plant (7 shoots per plant) was observed with woven mulch, whereas the control and straw mulch treatments recorded the lowest shoot count (5.38 shoots per plant). Compared to unmulched conditions, mulching significantly improved grade-wise and total tuber yield, as well as the total tuber count. The highest grade-wise tuber yields recorded under polythene mulch were: 0–25 g tubers at 2.22 t/ha, 25–50 g tubers at 9.56 t/ha, 50–75 g tubers at 7.55 t/ha, and tubers over 75 g at 9.14 t/ha, resulting in a total tuber yield of 30.93 t/ha. Both maize straw and polythene sheet mulches demonstrated the highest yields, producing 27.36 t/ha and 30.93 t/ha, respectively. Notably, maize straw mulch yielded an additional 6.67 t/ha compared to the no-mulch condition.

The total tuber count was significantly higher under mulched conditions than in unmulched plots, as mulching helps regulate soil temperature and maintain optimal environmental conditions, which aligns with the findings of Hochmuth (2018). Generally, the increased yield observed with plastic mulches is associated with lower weed incidence, reduced insect pest damage, and decreased soil water evaporation, as reported by Orzolek *et al*. (1993). Similar yield improvements due to mulching have also been documented by Bharati (2020).

Effect of fertilizer on plant growth parameters

The study found that the maximum plant emergence percentage was 95.50%, with an average plant height of 47.10 cm and an average of 6.60 shoots per plant (Table 1, 2 and 3) when applying the full recommended dose of fertilizer, which is 120:100:100 kg of N:P:K per hectare. In terms of yield, the highest grade-wise tuber yields were recorded as follows: 2.24 t/ha for the 0-25 g grade, 8.64 t/ha for the 25-50 g grade, 8.09 t/ha for the 50-75 g grade, and 7.73 t/ha for the >75 g grade. The total tuber yield reached 26.69 t/ha with the application of 100% of the recommended dose of N:P:K. This dosage also resulted in the highest number of tubers per hectare.

Table 1. Effect of Mulches and fertilizer levels on emergence%, plant ht. (cm) & number of shoots/plant.

Treatment	Emergence %						Plant height (cm)						Number of shoots/plant					
	M0	M1	M2	M3	M4	Mean A	M0	M1	M2	M3	M4	Mean A	M0	M1	M2	M3	M4	Mean A
F1	91.75	92.75	92.50	93.00	92.00	92.40	42.95	43.95	42.73	44.63	43.98	43.65	4.75	4.50	6.75	5.75	6.75	5.70
F2	95.25	96.50	95.50	95.50	94.75	95.50	45.30	47.33	47.78	48.20	46.90	47.10	6.00	6.25	6.50	7.00	7.25	6.60
Mean B	93.50	94.63	94.00	94.25	93.38		44.13	45.64	45.25	46.41	45.44		5.38	5.38	6.63	6.38	7.00	
LSD (5%)																		
F				1.03						0.99						NS		
M				NS						NS						1.04		
Mulch at same level of A				NS						NS						NS		
Fertilizer at same level of B				NS						NS						NS		

Table 2. Effect of Mulches and fertilizer levels on Grade wise yield.

Treatment	Yield of tuber 0-25 g (t/ha)						Yield of tuber 25-50 g (t/ha)						Yield of tuber 50-75 g (t/ha)					
	M0	M1	M2	M3	M4	Mean A	M0	M1	M2	M3	M4	Mean A	M0	M1	M2	M3	M4	Mean A
F1	1.07	1.53	1.87	1.28	1.58	1.46	5.34	8.91	9.90	5.40	7.44	7.40	4.78	7.32	8.38	6.97	9.13	7.31
F2	1.42	2.70	2.57	1.99	2.51	2.24	7.91	9.33	9.21	9.65	7.09	8.64	7.88	7.77	9.91	6.50	8.37	8.09
Mean B	1.24	2.11	2.22	1.64	2.05		6.62	9.12	9.56	7.53	7.26		6.33	7.55	9.14	6.73	8.75	
LSD (5%)																		
F				0.26						0.95						NS		
M				0.30						0.63						1.56		
Mulch at same level of A				NS						1.08						NS		
Fertilizer at same level of B				NS						1.21						NS		

Table 3. Effect of Mulches and fertilizer levels on Grade wise, total yield & total number of tubers.

Treatment	Yield of tuber > 75 g (t/ha)						Total yield of tuber (t/ha)						Total no. of tuber (000'/ha)					
	M0	M1	M2	M3	M4	Mean A	M0	M1	M2	M3	M4	Mean A	M0	M1	M2	M3	M4	Mean A
F1	7.54	6.93	9.98	7.64	5.02	7.42	18.73	24.68	30.13	21.29	23.16	23.60	231.79	331.00	435.79	342.00	313.82	330.88
F2	5.45	10.24	10.05	5.59	7.33	7.73	22.65	30.04	31.73	23.73	25.30	26.69	324.24	382.14	502.38	430.20	379.25	403.64
Mean B	6.49	8.58	10.01	6.62	6.17		20.69	27.36	30.93	22.51	24.23		278.02	356.57	469.09	386.10	346.53	
LSD (5%)																		
F			NS				2.54						5.32					
M			0.86				1.90						7.90					
Mulch at same level of A			1.27				NS						11.84					
Fertilizer at same level of B			1.18				NS						11.17					

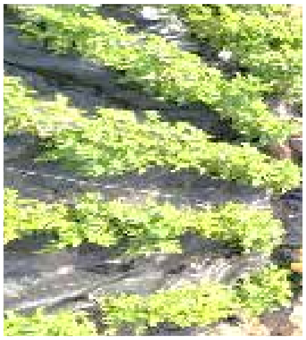

Fig. 1. Polythene mulch

Fig. 2. Woven mulch

Fig. 3. Maize Straw mulch

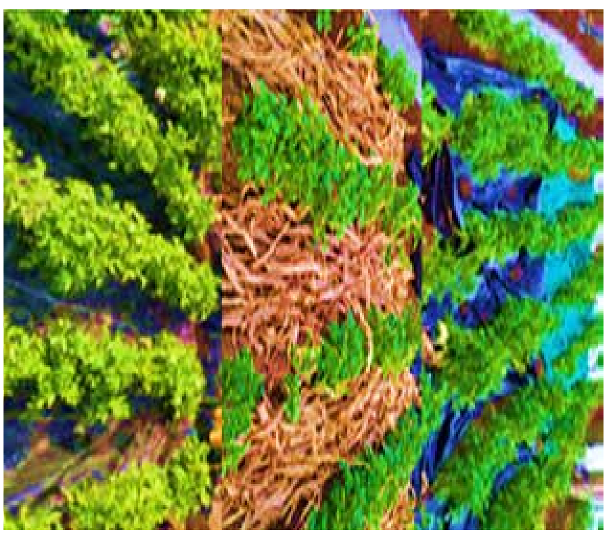

Fig. 4. Combined view of different mulches

Different levels of N:P:K fertilizers demonstrated varying effects on crop growth, yield attributes, and overall potato yield. However, the study by Choudhary *et al*., (2021) noted that there were no significant differences in total tuber yield and benefit-cost ratio between the 150% dose (180:150:150 kg N:P:K per hectare) and the 100% dose (120:100:100 kg N:P:K per hectare). Similar findings were reported by Kumar *et al.* (2008). Additionally, Sinha (2007) concluded that the optimal application of nitrogen was 225 kg/ha to achieve higher tuberization efficiency and both marketable and total tuber yields and Sadawarti *et al.,* 2013) found higher tuber yield with Mulching over no mulching in all grades tubers of potato.

Interaction

In the case of the combined effect of fertilizer and mulch, the maximum plant emergence of 96.50 percent was recorded with 100% RDF of N:P:K when using straw and polythene mulch. The maximum plant height was 48.20 cm, with an average of 7.00 shoots, and a tuber yield of 8.64 tons per hectare for the 25-50 gram grade, all achieved with 100% RDF of N:P:K combined with woven mulch. The highest yield of 31.73 tons per hectare was noted in treatment F2M2, which involved the application of 100% RDF with plastic mulch. Conversely, the lowest yield of 18.73 tons per hectare was recorded in treatment F1MO, which used 75% RDF without any mulch.

Nitrogen and phosphorus content, as well as nutrient uptake, were significantly higher in mulched plots compared to un mulched ones, which is essential for the proper vegetative growth of plants (Hundal *et al.,* 2000). Woven mulch is a fabric that promotes vegetative growth, while plastic mulch maintains optimum root temperatures for plant growth, resulting in improved nitrogen utilization efficiency and greater tuber yield. Additionally, the residue from straw contributes to the organic matter content of the soil and enhances its physico-chemical properties (Mahmood *et al.,* 2002).

Dry matter content of tubers (%)

The dry matter content of tubers per 100 g of fresh weight was assessed under different

Table 4. Effect of Mulches and fertilizer levels on Dry matter content of tuber (%) & haulm (%).

Treatment	Dry matter content of tubers (%)						Dry matter content of haulm (%)					
	M0	M1	M2	M3	M4	Mean A	M0	M1	M2	M3	M4	Mean A
F1	18.45	18.78	19.38	18.90	18.70	18.84	7.63	8.34	9.37	9.41	9.23	8.80
F2	19.55	19.80	19.83	19.88	19.53	19.72	9.13	9.82	9.61	9.40	9.41	9.47
Mean B	19.00	19.29	19.60	19.39	19.11		8.38	9.08	9.49	9.40	9.32	
LSD (5%)												
F				0.24						0.14		
M				0.32						0.17		
Mulch at same level of A				NS						0.26		
Fertilizer at same level of B				NS						0.25		

treatments and the interaction effects are presented in Table 4. The highest dry matter content was recorded at the 100% fertility level, with values of 19.72% for tubers and 9.47% for haulms. In contrast, the lowest dry matter content was observed at the 75% fertility level, measuring 18.74% for tubers and 8.80% for haulms. Among the mulching treatments, the white polythene mulch resulted in the highest dry matter content, with 19.60% for tubers and 9.49% for haulms. Conversely, the lowest dry matter content was recorded in the no-mulch treatment, with values of 19.00% for tubers and 8.38% for haulms. Although the interaction between fertility levels and mulching treatments was not statistically significant, the highest dry matter content was observed in the 100% N, P, K + white polythene mulch treatment, achieving 19.88% for tubers and 9.61% for haulms. In contrast, the lowest dry matter content was recorded under the 75% N, P, K + no mulch treatment, with 18.45% for tubers and 7.63% for haulms. These findings align with Nizam et al. (2017), who reported that mulching significantly increases dry matter content compared to unmulched conditions.

Economic analysis

The economic evaluation of different fertilizer levels and mulching treatments revealed (Table 5) that F2M1 (100% RDF +

Table 5. Economics affected by different treatments.

Treat.	Yield (t/ha)	Cost of cultivation (Rs/ha)			Cost (Rs/ha)		Sale price (Rs/t)	Net returns (Rs/ha)	B:C Ratio
		Seed	Fertilizer	Cultivation	Inputs	Produce			
T_1	18.73	45000	7095	45000	97095	187300	10000	90205	0.93
T_2	24.68	45000	7095	53000	105095	246800	10000	141705	1.35
T_3	30.13	45000	7095	75000	127095	301300	10000	174205	1.37
T_4	21.29	45000	7095	70000	122095	212900	10000	90805	0.74
T_5	23.16	45000	7095	65000	117095	231600	10000	114505	0.98
T_6	22.65	45000	9210	45000	99210	226500	10000	127290	1.28
T_7	30.04	45000	9210	53000	107210	300400	10000	193190	1.80
T_8	31.73	45000	9210	75000	129210	317300	10000	188090	1.46
T_9	23.73	45000	9210	70000	124210	237300	10000	113090	0.91
T_{10}	25.30	45000	9210	65000	119210	253000	10000	133790	1.12

Maize Straw Mulch) achieved the highest net return of Rs1,93,190 per hectare with a benefit-cost (BC) ratio of 1.80. In comparison, the same fertility level (100% RDF) without mulch resulted in a net return of ₹1,27,290 per hectare with a BC ratio of 1.28, yielding 22.65 t/ha.

Furthermore, the application of maize straw mulch led to an additional yield of 7.38 t/ha compared to the non-mulched condition, highlighting its economic advantage in improving crop productivity and profitability. Maize straw mulch increased profitability by reducing input costs and improving yield, making it a sustainable alternative for farmers. Similar economic benefits of mulching in potato cultivation were reported by Bharati (2020).

CONCLUSION

The study demonstrated that 100% RDF (120:100:100 NPK kg/ha) significantly improved potato growth and yield. Among mulching treatments, polythene mulch recorded the highest yield, while maize straw mulch provided the best economic returns. The combined application of 100% RDF with polythene or maize straw mulch proved to be the most effective strategy for maximizing potato productivity in the central plains of India. These findings highlight the importance of integrating optimal mulching techniques with balanced fertilization to achieve higher yields, improved quality, and greater economic returns in potato production.

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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ADVANCEMENTS IN POTATO SCIENCE: AGRONOMY, GENETICS, AND BIOTECHNOLOGY FOR SUSTAINABLE FOOD SECURITY

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ABSTRACT: Irish potato (*Solanum tuberosum* L.) is a globally significant crop, valued for its high nutritional content, adaptability, and contribution to food security. This study explores its role in addressing global challenges such as malnutrition, poverty, and climate change. Despite its importance, knowledge gaps persist regarding its full nutritional potential, bioavailability of nutrients, and sustainable production practices. By employing a multidisciplinary approach, this research evaluates the potato's nutritional value, its potential to combat micronutrient deficiencies, and strategies for enhancing productivity under changing environmental conditions. Key findings highlight the potato's pivotal role in improving diet quality, supporting livelihoods, and promoting sustainable agriculture. However, challenges such as pest susceptibility, production variability, and cultural barriers to dietary integration remain. Addressing these limitations through improved breeding, biofortification, and targeted education campaigns can further optimize the potato's impact. This article reviews the agronomical aspects of the Irish potato and its taxonomy nomenclature. Together, these findings highlight the importance of potatoes in providing food security to the international community, alongside the global fight against malnutrition. The aim of this study is to underscore the need for renewed focus on the Irish potato as a tool for global food security and sustainable development, offering a foundation for future research and policy innovation.

KEYWORDS: Agronomy, Climate change resilience, Pest control, Plant breeding, Potato biotechnology, *Solanum tuberosum* L.

INTRODUCTION

The Irish potato (*Solanum tuberosum* L.) is one of the most important staple crops worldwide, renowned for its high productivity, adaptability, and substantial role in global food security. It is the most produced crop after maize and ranks fourth in terms of universal tonnage, with wheat, maize and rice in the top three positions globally (Muthoni & Shimelis, 2023). Potatoes fall under the family Solanaceae and belong to the genus Solanum; they have a standard set of twelve chromosomes [x = 12] (Gaiero *et al.*, 2021). Potatoes are versatile crops that serve not only as staple vegetables but also as key ingredients in various processed foods (Devaux *et al.*, 2021). Additionally, they are utilized in industrial applications, such as starch production and the manufacture of alcoholic beverages (Zięba *et al.*, 2020). One of the significant challenges facing potato breeders is the development of varieties that possess desirable agronomic traits and excellent storage quality (Seid & Tessema, 2021). A crucial step in any crop improvement program is the assessment of genetic diversity, which enables the selection of suitable parents for successful hybridization and ultimately leads to the development of enhanced potato varieties.

As a nutritionally dense food, it is an excellent source of carbohydrates, vitamins, minerals, and dietary fiber, making it a crucial dietary component for millions, particularly in regions where malnutrition and scarcity persist. Its significance extends beyond human consumption, contributing to the livelihoods of farmers and the global

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agricultural economy (Giampiccoli *et al.*, 2023). However, despite its historical and present-day importance, there remain considerable gaps in research concerning its full nutritional potential, its role in diverse diets, and its capacity to combat emerging food security challenges (Devaux *et al.*, 2021). Food systems globally are under pressure from a range of factors, including population growth, climate change, and shifts in dietary patterns. Potatoes offer a unique opportunity to address these challenges due to its relatively short growth cycle, high yields per unit area, and adaptability to different climatic conditions (Devaux *et al.*, 2021). Yet, its potential remains underutilized, particularly in developing regions where its cultivation and consumption could significantly alleviate hunger and poverty. Furthermore, the lack of comprehensive data on the potato's contribution to diet quality, nutrient bioavailability, and its integration into diverse food systems poses a barrier to maximizing its benefits (Lizana *et al.*, 2021).

While its importance in the Andean region, Australia, Europe (Salmensuu, 2021), North America, and the Union of Soviet Socialist Republics (Osipov & Zeldner, 2023) is well known, large-scale production and rapid development are less common in low- and middle-income countries (Lindqvist-Kreuze *et al.*, 2024). According to the Food and Agriculture Organization (FAO) statistics, potato production in developing market economy countries has increased drastically, surpassing the growth rates of other roots and tubers (44%) together with cereals (47%) (Lizana *et al.*, 2021). Potatoes offer a wide range of importance (Dolničar, 2021); they convert the raw material of tubers into finished ready-to-consume high-quality food products such as table chips and crisps (Pavlista & Ojala, 2023). Potatoes are not only substantial in terms of food security and nutrition but also in the job market (Giampiccoli *et al.*, 2023), consequently creating an economically stable society. Additionally, they offer several advantages, including higher yields on less land and in harsher climates than most major crops do, and they are also quick to mature because of their rapid growth rate (Jennings *et al.*, 2020). The edible material is harvested in just sixty days, depending on the variety. Similarly, potatoes have a greater nutritional value per unit of land and resources (Šulc *et al.*, 2021).

Despite occupying smaller areas in most developing countries, the increasing popularity of potatoes has prompted policymakers to reevaluate their role in national food production systems (Ohanenye *et al.*, 2021). Recent efforts have focused on improving potato production, storage (Gikundi *et al.*, 2023), and marketing, as well as understanding and enhancing their nutritional contributions. However, balancing production improvements with nutritional quality is crucial (Koch *et al.*, 2020; Naumann *et al.*, 2020). While breeding for higher yields and disease resistance is essential, neglecting nutritional quality can compromise food security. This study seeks to bridge these gaps by exploring the nutritional and functional properties of the Irish potato and its role in global food security. Specifically, the research aims to (i) assess the nutritional value of potatoes in comparison to other staple crops, (ii) evaluate their potential for addressing micronutrient deficiencies, and (iii) investigate sustainable production practices that enhance yield and quality under changing environmental conditions. A multidisciplinary methodological approach was employed, encompassing nutritional analysis, agronomic evaluation, and an assessment of consumer perceptions and dietary integration.

The findings of this research highlight the pivotal role of the potato in meeting nutritional needs and promoting sustainable agricultural practices. By addressing existing knowledge gaps, this study provides a foundation for future research and policy development, enabling the potato to play an even more critical role in combating global food insecurity. The broader implications underscore the need for a renewed focus on underutilized crops like the potato to build resilient food systems, inspire innovation in crop research, and contribute to achieving global development goals (Stark *et al*., 2020).

Brief History of Irish potatoes

Potatoes are ancient crop plants whose sole purpose of cultivation is food (Earle, 2023); they are referred to by the name Mama Jatha as the mother of growth. The first wild potatoes presented traits of disease and insect resistance due to the presence of glycoalkaloid (Musita *et al*., 2020) (α-chaconine and α-solanine) compounds (Ordoñez-Araque *et al*., 2024). Different colors, sizes and shapes of tubers are presented. They were harvested and eaten almost 10,000 years ago in the humid plains of coastal South America. However, their taste is bitter (Martínez *et al*., 2022), as they contain toxicity levels that are unsafe for humans (Burgos *et al*., 2020). Thus, to qualify potatoes for human consumption, it is critical to choose and cultivate potatoes that are consumer-friendly (Timpanaro *et al*., 2021). To domesticate and preserve potato plants in the Andes, a biological technique known as freeze-drying was employed (Merivaara *et al*., 2021), which was principally to extract the unpleasant attributes from potato plants and retain only non-harsh characteristics for propagation.

Potatoes first gained significant intercontinental recognition during the first half of the 16th century, when Spanish explorers were gold-hunting (Vilardaga, 2021) in Peru. During their adventure to Europe in the late 1500s (Ríos *et al*., 2023), they took some potato tubers with them. However, some Europeans did not regard potato tubers as appropriate for consumption by elite members of society ab initio (Griffin *et al*., 2022). Rather, they conceived them as prime food for the impoverished and/or for farm animals. Furthermore, potatoes are considered toxic (Sookhtanlou *et al*., 2022) and are inedible by irrational agricultural laborers. Potatoes became among the most cultivated food sources worldwide around the 20th century, with the USA being the last major region to adopt the plant (Stark *et al*., 2020). Today, it is produced globally in more than 150 countries from regions such as North America, Europe, Africa, and some countries from the former Soviet Union (Dereje & Chibuzo, 2021). The inhabitants of the Andes view potatoes beyond food; they also use them as medicinal plants (Parra-Rondinel *et al*., 2021) that have various functions, traditionally as well.

The breeding of potato varieties that have a short maturity period commenced in South America; the newly bred varieties have excellent performance and growth due to favorable agricultural practices (Bolsheshapova *et al*., 2021). That was around the same time that the European continent was battling severe famine (Ljungqvist *et al*., 2024), when suddenly the European farmers were intrigued to delve into potato cultivation (Van Loon *et al*., 2024) to combat the food insecurities they were facing. Potatoes are quite affordable to grow and mature very early; thus, venturing into potato cultivation liberated the whole continent from famine (Earle, 2020). Additionally, potato's bountiful nutritional benefits nourished the increasing population of working-class settlers in urban areas, alongside the emancipation of factory workers from the 19th century, who came from rural areas (Devaux *et al.*, 2021). There are a few varieties that have shown genetic similarity (Tang *et al.*, 2022) with tubers cultivated and cloned in both Europe and North America, such as in South America (Caldiz, 2023). In addition, in 1845, late blight (Majeed *et al.*, 2022), a devastating plant disease caused by *Phytophthora infestans* (Guha Roy *et al.*, 2021), a fungus, attacked potatoes and wiped out crops.

This resulted in an eight-year period of famine and, consequently, the tragic death of more than a million people; the few survivors were constrained and had no option but to emigrate in search of greener pastures. The Irish calamity (Gray, 2021) prompted the implementation of management strategies such as practicing crop rotation, the use of fungicides (Kassaw *et al.*, 2021) and the development of disease-resistant yet still fruitful varieties. Most potato varieties produced in Chile are germplasm (Jansky *et al.*, 2021) drawn by plant breeders from Canada, the United States of America (Barrett *et al.*, 2023) and Eastern Europe.

Research Methodology

The study included various related research of scientific studies, and the information was organized into specific groups of the data collected (Table 1).

RESULTS AND DISCUSSION

Solanum tuberosum

Approximately 375 million tons of potatoes were produced in 2022 worldwide and were planted on 17,788,408 hectares of land. At present, China is the major producer of potatoes, with up to 95,631,400 tons, whereas India ranks second, with 56,176,000 tons produced as reported by the FAOSTAT in the December 2023 issue (Figure 1). Together, China and India generate more than one third of the total potatoes yield worldwide. Egypt (6.1 million tons) and South Africa (2.5 million

Table 1. Overview of thematic groups and related scholarly literature for Irish potato research.

Thematic Group	Research Topic	References
Nutritional profile	– Nutritional components: carbohydrates, proteins, fiber, vitamins (C, B-complex), minerals (potassium, magnesium). – Bioactive compounds: phenolics, antioxidants.	(Dereje & Chibuzo, 2021; Franková *et al.*, 2022)
Role in Food Security	– Contribution to global food security: high yield potential, adaptability. – Economic accessibility. – Reducing hunger and malnutrition in vulnerable populations.	(Osuji *et al.*, 2023; Rashid *et al.*, 2024)
Agricultural sustainability	– Resilience of varieties to climate change. – Disease resistance, pest management. – Modern agricultural technologies: biofortification, precision farming.	(Jennings *et al.*, 2020; Rashid *et al.*, 2024)
Socioeconomic importance	– Economic value in markets. – Role in rural employment and livelihoods. – Gender dimensions in farming and production chains.	(Mickiewicz *et al.*, 2022; Tadesse *et al.*, 2020)
Innovation in food products	– Development of processed products (chips, flour, starch). – Use in functional foods and nutraceuticals – Consumer perceptions and market trends.	(Pavlista & Ojala, 2023; Zięba *et al.*, 2020)
Prospects and challenges	– Impacts of climate change. – Breeding strategies for improved varieties. – Policies promoting Irish potato as a staple food	(Dolničar, 2021; Lindqvist-Kreuze *et al.*, 2024)

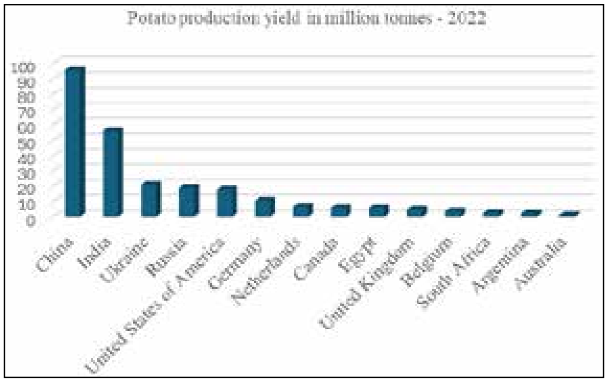

Fig.1. Top 14 potato-producing countries worldwide (FAOSTAT, 2022)

tons) ranked 9th and 12th – respectively. The two African countries produced the most potatoes that year.

In Africa, potatoes were domesticated toward the end of the 17th century, after Christian missionaries established petite plantations on the continent (Muthoni & Shimelis, 2023). Potato production has continued to expand drastically, increasing to 20 million tons in 2017 from only approximately 2 million tons during the last half of the 20th century. A total of 1.9 million hectares of harvested land were recorded in Africa in 2017, accounting for up to 10% of the world's cultivated area that year. The FAOSTAT 2018 reported a double increase in potato production on the African continent, with nearly three quarters of the growth rate being from East Africa. In contrast, 21% of potato production is from southern Africa, and West Africa accounts for 8% of the total potato production in Sub-Saharan Africa (Muthoni & Shimelis, 2023).

In Kenya, for instance, Irish potato is chiefly grown by small-scale farmers, mostly women. However, commercial production is conducted by larger-scale growers, who cultivate only areas above sea level, ranging between 1,200 and 3,000 m high (Makau *et al*., 2023). A vast majority of potatoes grown in Kenya are locally consumed (Gikundi *et al*., 2021): approximately 25 kg per capita per year. Viazi (meaning potatoes in Swahili, one of the official languages of the African Union) is cultivated by local communities (Kwambai *et al*., 2024; Musita *et al*., 2020) and is a delicacy enjoyed by many people in Kenya (Gikundi *et al*., 2021).

Potato Agronomy: Enhancing Cultivation Practices for Optimal Yield

Potatoes perform well in diverse crop science systems, such as intercropping and multiple setups, together with laterite, alluvial, red, hill and black soils (Hemkemeyer *et al*., 2024) at pH values ranging from 4–7.5 (Atanaw, 2021; Mugo *et al*., 2020). Stolons, roots and tubers can also grow in loamy soils as well as sandy or coarse soils (C. Wang *et al*., 2022), as these soils are able to supply ample oxygen and sufficient organic matter for good plant health (Gavrilescu, 2021). Potatoes grow better during cooler nights and slightly sunny days with temperatures below 24°C or 75.2°F. Between the 20th and 25th days of post planting, tuber formation commences, and the plants develop better at 20°C (68°F) during the day and at 14°C (57.2°F) at night (Gutiérrez-Quequezana *et al*., 2020). Hence, settlers in mountainous regions grow their potatoes more in autumn or summer. However, those in plains cultivate potatoes mainly during spring or winter and sometimes autumn.

While these agronomic features are true for most potato varieties, the exact duration differs from cultivar to cultivar, with the conditions of the environment playing a large role in the turnaround time (Li *et al*., 2021). Before planting, farmers breakdown clods and plough fields up to 30 cm deep (Stark & Thornton, 2020) to facilitate the management of perennial weeds (Jabran *et al*., 2023) and pathogens found in the soil (Tsror, 2023). The famous ridge-and-furrow planting method is commonly used for potato farming (Bhardwaj & Sharma, 2020). Potato tubers are cut in preparation for propagation, and the farmer's preferred seeds for sowing are usually those having at least three healthy eyes, also known as true potato seeds (Kacheyo *et al*., 2021). Between 30 and 40 grams with a diameter of more than 3 cm were weighed. One month after planting, soil turning is conducted by a plough with a two-way moldboard to enable total and fair shielding of the tubers by the soil (Jin *et al*., 2023).

Depending on the maturity period, weather conditions and soil type, approximately 350–550 mm of water should typically be provided to plants (Dietz *et al*., 2021). To prevent fungal infections, water on the leaves of the plants should be avoided, and drip irrigation should be used to reach the base of the plants (Abd Elhady *et al*., 2021). Do not overwater the plants (Jabran *et al*., 2023), and mulch around the plants (Sekhon *et al*., 2020) to retain moisture and suppress weeds (Jabran *et al*., 2023). The harvest of potato plants is variety dependent; that is, it can be initiated after two months for early maturing plants (Bolsheshapova *et al*., 2021; Ma *et al*., 2024) and after two and a half months for medium-maturing plants (Githieya *et al*., 2021), and late-maturation varieties can mature for up to three months (Ma et al., 2024). At maturity, the plants grow as high as 1 m or 3.5 feet, and the tubers are unearthed when the temperature is below 30°C (86°F) (Czerko *et al*., 2023). In most cases, it is a fortnight following the last irrigation. Importantly, the yield percentage is not uniform for all potato varieties (Silva *et al*., 2020). The production per hectare is estimated to be between 20–25, 25–30 and 30–35 for the early, medium and late varieties, respectively (Franková *et al*., 2022).

Botany of potato: Morphological Diversity

Irish potato is generally an autogenous plant; nonetheless, it experiences a handful of cross-pollination events, usually bumblebee insects. Potato plants are yearly herbaceous crops (Sharma *et al*., 2021), and they have threadlike roots because of the fibers around them (Dixon & Fitch, 2022). Stolons constitute another vital part of the potato; they are broad stems that grow inside the soil and are responsible for the formation of the starchy edible tubers that are chiefly used as vegetables (Abeytilakarathna, 2022). The leaves are usually green in color and grow close to 30 cm, one after the other, on angular stems branching from the main plant with flowers of different colors (Maiti & Singh, 2022), including pink, purple, yellow, red or white.

Overall, potato varieties with white flowers form tubers that have white skins; on the other hand, pink-like tubers are formed from varieties with colored flowers (Salunkhe *et al*., 2021). Stamens are rare in potato plants because of weather conditions, but when they are present, they appear in a light shade of yellow and are fixed on corolla tubes that are short in length (Aksoy *et al*., 2021).

Evolutionary Insights of Potato Taxonomy

Irish potato is a dicotyledonous plant (Naeem *et al*., 2023), and it is part of the Solanacea*e* family (Mallia *et al*., 2021). Additionally, it belongs to the *Solanum* genus, which comprises over 2,000 species and ranks as the most populated genus of angiosperms (Kaunda & Zhang, 2019). According to the newest classification, *Leptostemonum* (Aubriot & Knapp, 2022) and *Pachystemonum* are two subdivisions of the *Solanum* genus (Verma *et al*., 2021). The tuber-bearing species mostly fall under the *Petota* section, which has been split further into two parts: *Potatoe* and *Estolonifera* (Tang *et al*., 2022). *Potatoe* is the umbrella subsection for closely related and largely cultivated potato species belonging to the *Tuberosa* series (Maiti & Singh, 2022). Based on recent classification, only four recognized species are predominant and cultivated largely: *S. ajanhuiri*, *S. curtilobum*, *S. juzepczukii* and the famous *S. tuberosum* (Rodríguez *et al*., 2010). Approximately one-quarter of these species are tetraploid (2n = 48), nearly three-quarters are diploid (2n = 24), and the remaining half are hexaploid (2n = 72), pentaploid (2n = 60) or triploid (2n = 36) (Sharma *et al*., 2021).

Potato and Food Security: Ensuring Sustainable Production for a Growing Population

Malnutrition and a complete lack of food are very common in most developing countries; according to the FAO, more than one billion people are underfed worldwide. Potatoes are highly valued by many households in developing countries, mainly because of their stable and bountiful yield production, alongside their beneficial nutritional value, such as dietary energy (Rashid *et al*., 2024). It is more cultivated than other crops because it thrives in brutal climatic conditions (Jennings *et al*., 2020; Koch *et al*., 2020) in which most major plants do not, making it an essential source of nourishment for sustainability (Naumann *et al*., 2020). Furthermore, over 85% of potato plants are fit for human consumption, whereas only 50% of whole cereal plants are edible.

There has been an exponential rise in the nutritional supply of potato to developing countries (Rahim *et al*., 2023), and the yearly per capita kilograms have increased exponentially between 2000 and 2020 (Çalışkan *et al*., 2023). The versatility of potatoes enables mankind to prepare them in diverse forms, such as frying, boiling, mashing, steaming, baking and grilling. Potatoes can be eaten by people of all age groups and under most diet regimens (Tadesse *et al*., 2020). Approximately 20%–25% of a newly harvested potato is composed of dry matter, whereas the remaining percentage contains water (Czerko *et al*., 2023). The protein composition of dry potato is greater than that of roots and other tuberous plants; however, the protein composition is the same as that of cereal crops (Dolničar, 2021). Additionally, potatoes are rich in carbohydrates and other micronutrients, but it has a low-fat content (Ohanenye *et al*., 2021). The body of an adult human needs approximately 100 mg of ascorbic acid in a day (Gutiérrez-Quequezana *et al*., 2020), and a potato weighing 150 g is said to be of medium size and can provide close to 50 mg of vitamin C when eaten unpeeled (Burgos *et al*., 2020).

Nutritional Benefits of Potato: A Key Staple for Global Health and Nutrition

Potatoes increase the absorption of iron and provide vitamin B complexes alongside magnesium, potassium and phosphorus to humans. In addition to these minerals, they are good sources of dietary antioxidants that help reduce the possibility of developing chronic infections (Ohanenye *et al*., 2021). By 2030, the demand for potatoes globally is estimated to be approximately 440 million tons (Mickiewicz *et al*., 2022). Because potatoes are rich in nutrients, it has the potential to enhance various diets, in turn increasing nutrition, increasing health, and ultimately combating food insecurity threats worldwide, especially in developing countries (Burgos *et al*., 2020).

Potatoes have a cascade of dietary benefits, with freshly uprooted tubers containing water levels close to 75%, approximately 15% carbohydrates, 3% crude protein, 1.5%

minerals, 1% crude fats, 0.6% crude fiber and some vitamins. The nutritional quality of potatoes is better than that of cereals, despite potatoes containing minimal amounts of protein (Lutaladio & Castaldi, 2009). Potatoes also contain a reasonable quantity of principal amino acids, namely, tryptophan, isoleucine and leucine (Naumann & Pawelzik, 2023). Antioxidants that have significant roles in disease prevention are equally common in potatoes, and they are similarly employed to treat hepatic and gastrointestinal infections medically.

Plant Biotechnology in Potato: Genetic Engineering and Molecular Advancements

Advances in molecular biology and plant cell culture have revolutionized potato research, enabling scientists to gain a deeper understanding of potato plants (Beenzu *et al*., 2025). These breakthroughs have the potential to increase yield in potato farming, ameliorate nutritional value, and lead to new non-food applications for potato starch, i.e., the manufacture of biodegradable plastics (Verma *et al*., 2021) and the development of potato-based edible vaccines (Beenzu *et al*., 2024). Furthermore, techniques of micropropagation and those of plant tissue culture are being used to eliminate bacterial, parasitic and viral infections (Bakhsh *et al*., 2023). By rapidly multiplying disease-free potato plants, robust seed tubers can be produced. Significant progress has been made in the potato genome sequencing consortium, with successful mapping of the whole DNA sequence of the potato genome (Tang *et al*., 2022). This groundbreaking project has greatly expanded people's knowledge with respect to the functional traits of potato (Gaiero *et al*., 2021), as well as plant genes and proteins. Paving the way for further innovations in potato research and applications.

Genetic diversity and climate change resilience

Genetic diversity is paramount to crop growth and development, as it allows plant breeders to improve varieties by knocking down unwanted features or knocking in desired traits (Marhadour & Prodhomme, 2023), including disease resistance (Onditi *et al*., 2021; Singh *et al*., 2020). Abiotic stress resistance is another feature that can be developed in potato plants (Demirel, 2023). Since the commencement of agriculture, crop species have been exploited for genetic variability to obtain the substantial amount of food needed for human consumption. With time, however, the production of excess food has taken the focal point, mainly to curb food insecurity threats for the ever-growing population (Bradshaw, 2024). Currently, efforts are being made to concentrate on both the excellence and yield of staple foods to provide a balanced diet to the increasing population, aiming at both quality and quantity (Osuji *et al*., 2023).

Consequently, alterations in climatic conditions have prompted plant breeders to develop varieties that can endure climatic changes (Jennings *et al*., 2020). Owing to genetic diversity, desirable alleles can be sourced from mutant lines to develop varieties that are resilient to climate change, extreme temperatures and different pollutants. Furthermore, it is important to note that breeding objectives continue evolving (Jansky *et al*., 2021); therefore, it is important to reserve various genes in the germplasm (Saeed *et al*., 2023). In potatoes, to increase the diversity of breeding varieties, introgression of genes between cultivated species and wild ones is needed (Marhadour & Prodhomme, 2023). Prior to obtaining transgressive segregants, it is important to note the genetic diversity between two parents; to achieve heterosis, it is pertinent to choose parents with outstanding traits (Seid & Tessema, 2021). In agricultural practices, selecting strategic techniques to design substantial crosses spears the growth of novel lines to be used in non-traditional applications such as the production of biofuels.

Disease resistance in Potato: Strategies for Combating Pathogens and Pests

Irish potato is an herbaceous plant that is cultivated annually under tropical as well as subtropical conditions. The optimized soil temperatures ranged from 16°C to 20°C and were coupled with adequate soil aeration (Stark & Thornton, 2020). Furthermore, it is an ideal crop for water-scarce areas because of its water use efficiency (Ierna, 2023). To promote drought tolerance in potatoes, breeders have developed drought-resistant varieties with properties such as longer roots that help bind soil and have high water holding capacity to minimize the need for water (Demirel, 2023). Integrated pest management (IPM) systems have been developed to reduce the use of chemicals made from cultivated potatoes. IPM is an ecofriendly and environmentally conducive method to protect crops from pests (Abrantes *et al*., 2023; Naqqash, 2023) and diseases (Chikh-Ali & Karasev, 2023; Tsror, 2023). This intensive management approach has proven to be efficient in increasing public health safety by reducing environmental pollution. It is a multifaceted strategy that combines genetic tools and chemical, physical, cultural, and biological aspects to produce high-quality crops.

IPM is a plant production scheme that is acknowledged and approved by both the FAO and the CIP for pest and disease prevention. Farmer Field Schools (FFS), an initiative of the FAO, has recommended IPM in many low-resource settings, enabling farmers to examine the method via diverse techniques (Naqqash, 2023). Some experiments have included specific applications of pesticides with low levels of toxins applied to various strains of potato (Naqqash, 2023). In Carchi, Ecuador, FFSs significantly reduce highly toxic pesticide use—up to 75% in potato fields—without affecting productivity. Potatoes mostly grow nearly 3.5 feet high, and tubers begin to form 25 days after planting (DAP), whereas flowering varieties require a long duration of daytime; hence, depending on the conditions to which they are subjected in the field, they may or may not produce flowers. The maturity period differs from one cultivar to another, but generally, potatoes may be harvested 60–70 days post planting (Struik, 2023).

Potato breeding: Innovations in Genetic Improvement for Yield and Quality

In 2008, during the international year of potato production, the need to use, protect, and preserve potato diversity was highlighted (Lutaladio & Castaldi, 2009). Novel strains of potatoes were sourced from the gene pool to address the fight against pests and diseases that affect the plant; these strains increase production yield on marginal lands and increase the nutritional content of the potato. Thus, a continued supply of modern potato-based agricultural practices is essential. Although potato diversity is threat, most varieties from the Andes have gone extinct, while climate change affects the wild type, risking up to 70% of their natural habitats. Breeders prioritize special traits for propagation (Seid & Tessema, 2021); commercial potato varieties, for example, have a limited ability to flower, and when they do, they attract pollinators.

However, natural pollination remains vital for maintaining diversity, and farmers prefer varieties adapted to local conditions (Makau *et al*., 2022). Similarly, the farming systems of smallholder farmers in the Andes promote cross-pollination through various flowering plants, augmenting the production of seeds alongside diversity preservation (de los Angeles Bohórquez-Quintero *et al*., 2022). To further conserve potato biodiversity and ensure that its benefits are shared equitably, the CIP has industrialized resilient cultivars fit for the conditions of subsistence farmers, who are now cultivating these potato varieties across several developing countries of Latin America, Asia (J. Wang *et al*., 2023) and Africa (Muthoni & Shimelis, 2023).

CONCLUSION

The Irish potato remains a cornerstone of global food security, offering immense potential to address nutritional deficiencies, improve livelihoods, and enhance sustainable agricultural systems. This study reaffirms the potato's role as a nutrient-dense, climate-resilient crop with significant contributions to global diets and economies. By exploring its nutritional value, agronomic adaptability, and integration into food systems, the findings underscore its potential as a key resource in tackling challenges such as malnutrition, poverty, and climate change. However, several limitations should be noted. Despite its versatility, the potato faces challenges such as susceptibility to pests, diseases, and climate variability, which can limit production in certain regions. Additionally, while this research highlights the potato's nutritional contributions, its bioavailability of micronutrients and potential synergies with other dietary components require further investigation. Furthermore, consumer acceptance and dietary integration vary widely across cultures, presenting a barrier to maximizing its impact in regions where it is not a traditional staple. Future research should focus on addressing these limitations by advancing breeding programs for pest-resistant and climate-resilient potato varieties, exploring biofortification to enhance nutrient content, and promoting awareness campaigns to increase dietary acceptance. By addressing these gaps, the Irish potato can be further optimized as a cornerstone of global food security and a key player in achieving sustainable development goals.

AUTHOR CONTRIBUTION

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this article.

ETHICAL STATEMENT

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

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Gram	g	Minute	min
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Mega gram	Mg	Tonne	t

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