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Technological innovations for enhancing spices productivity and doubling farmers income

Spices have significantly shaped India's political and economic landscape through their flavour, preservative properties, and medicinal value. Formal spice research in India commenced in 1951 with the Spices Enquiry Committee, leading ICAR to oversee structured investigations. This paper traces the evolution of ICAR-IISR from its origins in the All India Coordinated Spices and Cashew Nut Improvement Project to its establishment as a regional CPCRI station in 1975, its elevation to NRC for Spices in 1986, and its transformation into ICAR-IISR in 1995. ICAR-IISR's mandate encompasses germplasm conservation, development of highyielding, stressresistant spice varieties, integrated crop management, biotechnology use, and farmer-centric technology transfer.

INDIA, often referred to as the "Land of Spices", cultivates approximately 70 different spice crops that are integral to its cultural, culinary, medicinal, and economic landscape. Spice cultivation occurs across various agroclimatic zones, with each state contributing to the diversity either through rainfed or irrigated farming systems. The production, processing, and trade of spices have a longstanding historical association with the Indian subcontinent, where traditional knowledge systems and practices are deeply embedded in the cultural and socioeconomic fabric. Despite this legacy, the spice sector is yet to fully realize its potential in terms of productivity enhancement and valuechain diversification. The recent decades have witnessed a gradual shift from traditional subsistence farming to commercially oriented spice agriculture, largely driven by institutional support, favourable policies, and the strategic adoption of modern technologies.

Spice exports are set for significant growth, driven by rising global demand across various industries. Key drivers include the increasing use of spice extracts, essential oils, and oleoresins in the food and beverage industry to enhance flavour and preservation. Beyond essential oils and oleoresins, products such as curry powders, pastes, sauces, and mixed condiments are gaining export prominence. The pharmaceutical and nutraceutical sectors are also enhancing demand, as spices are widely recognized for their medicinal properties and are used in supplements, herbal formulations, and functional foods. Additionally, the booming wellness industry is contributing to higher spice consumption, with growing consumer preference for natural and organic health products. Domestically, consumption of spices in their primarily processed form is declining, indicating a shift toward value addition–beneficial for both employment generation and economic returns.

Spices have demonstrated a significant role in the agricultural export sector, contributing substantially to both volume and value. During 2023, spices accounted for 26% of the total volume and 50% of the total export value of the country's horticultural exports, ranking fifth in terms of export value among agricultural commodities. In the fiscal year 2022–23 (estimated), spices were cultivated over an area of 4.43 million ha, yielding a production of 11.15 million tonnes. The export of spices and spice products during the same period reached 1.40 million tonnes, valued at approximately USD 3.95 billion. The technological and innovation ecosystem associated with

spice crops forms a critical foundation for enhancing production and sustaining the positive trajectory of spice trade. Strengthening and advancing technologies, agronomic practices, and innovations across the entire spice value chain is essential to address competitive challenges in the global spice market and to reinforce the country's leadership in meeting international demand.

The ICAR-Indian Institute of Spices Research (IISR) stands as a pioneer in transforming the spice sector through science, innovation, and sustainable practices. Established with the mission to enhance productivity, resilience, and the overall growth of the spice industry, the institute has played a crucial role in developing high-yielding and disea-seresistant spice varieties, cutting-edge agricultural technologies, and advanced farming methodologies. By integrating scientific advancements with traditional knowledge, ICAR-IISR has significantly improved spice cultivation practices, leading to increased yields, enhanced quality and better adaptability to changing climatic conditions. Its efforts have empowered farmers with improved practices and tools, promoting environmentally sustainable cultivation and ensuring economic growth and food security across the spice value chain. The institute also plays a vital role in nurturing spice-focused startups by offering technological guidance, value-addition approaches, and market-driven insights.

Technological innovations in spices

Key advancements include high-yielding varieties; production of quality seed and planting materials; enhanced cropping systems; site-specific nutrient and plant health management; innovative agro-input delivery mechanisms; crop-specific micronutrient formulations; and post-harvest processing and value-addition strategies. These interventions have led to yield improvements of approximately 25–30%, while also enhancing the quality and sustainability of spice production in India.

Innovative approaches in planting material production

Protocols for micropropagation, micro-rhizome production, and improved vegetative propagation techniques in spice crops have been standardized and widely promoted to enable the production of disease-free nucleus planting material of improved varieties across the country. One such advancement is the pro-tray-based transplanting technique in turmeric and ginger, which utilizes single-bud sprouts (5 g) raised in a soilless nursery medium. This method significantly reduces the seed-rhizome requirement to one-fourth of the conventional practice, thereby lowering seed-input costs, which typically account for up to 60% of the total production expenses. In addition to cost efficiency, this approach effectively mitigates seedling-stage disease incidence and is also applicable to black pepper for generating disease-free planting material.

To meet the increasing demand for quality planting material, a novel propagation system was developed using vertical mesh columns filled with a mixture of composted cocopeat and vermicompost, enriched with biocontrol agents under protected cultivation conditions. This setup enables the simultaneous production of three types of planting material in large quantities: single-node cuttings, top shoots with lateral branches (which promote early fruiting by initiating bearing branches near the plant base), and reproductive branches (plagiotropes) suitable for bush pepper cultivation. This integrated method enhances propagation efficiency while ensuring the health and quality of planting materials.

Black pepper and nutmeg exhibit dimorphic branching, producing upright orthotropic and lateral plagiotropic shoots. Planting materials derived from plagiotropic branches form bush-like plants, suitable for high-density planting. While conventional black pepper is spaced at 2.5–3.0 × 2.5–3.0 m (approximately 1,100 plants/ha), bush pepper can be grown at 2 × 1 m spacing, increasing plant density to compensate for lower per-plant yields. These bush types are ideal for homesteads, terraces, bunds, and pots, offering both production and ornamental value.

The vertical-column method utilizes 10–12 ft plastic-coated wire mesh columns filled with a composted cocopeat and powdered dry cow-dung mixture (3:1) as rooting media for top shoots. This setup transforms clinging roots into absorbing roots, promoting faster growth. Under protected conditions with shade nets, sprinkler irrigation, fertigation, and regular plant protection, the vines can fully cover the column and begin fruiting within a year, making it suitable for cultivation in non-traditional and urban areas.

Harnessing next-generation tools for spice crop improvement

Recent advancements in spice crop research have emphasized molecular approaches for genotype characterization, genetic finger-printing, gene identification and cloning, marker-assisted selection (MAS), and association mapping of key quantitative traits. Molecular markers such as RAPD, AFLP, PCR-RFLP, and ICAR-ISSR have been utilized to assess genetic variability, characterize cultivars and related species, and study genetic relationships in black pepper, cardamom, ginger, and turmeric. In vanilla, RAPD and AFLP markers, along with morphological traits, have been used to examine genetic diversity, species relationships, and finger-printing of key genotypes.

Extensive genomic resources, SNPs, SSRs, Indels and CNVs developed from ESTs and genomic data of black pepper, turmeric, ginger and cardamom, have been widely employed in genotyping, varietal identification and DNA fingerprinting. Transcriptome-based identification of drought-responsive genes and transcription factors has been carried out and validated through expression profiling. In black pepper and cardamom, integrated approaches involving whole genome resequencing, transcriptomics, and SNP genotyping are being used to isolate genes linked to critical traits such as drought tolerance, yield, and quality. Genome-wide association studies (GWAS) have been initiated to identify significant marker–trait associations (MTAs), aiming to accelerate genetic improvement in these perennial spice crops.

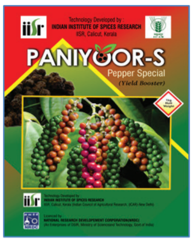
Candidate gene identification related to secondary metabolite biosynthesis has led to the isolation, cloning, and characterization of key genes involved in the curcumin and piperine pathways, using both *in silico* analyses and co-expression studies. In black pepper and ginger, several disease-resistance genes have been successfully cloned and validated. Notable achievements include the molecular cloning of a cDNA fragment encoding the defense-related protein β-1,3-glucanase in *Piper nigrum* and methyl glutaryl CoA reductase in *Piper colubrinum*. Additionally, the coat protein gene of cucumber mosaic virus (CMV) infecting black pepper was isolated and sequenced, and corresponding transgenic constructs were developed for potential disease resistance.

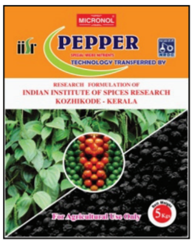
Recent initiatives have focused on genome editing in ginger and black pepper to develop genotypes resistant to bacterial wilt and *Phytophthora*, respectively. Key resistance-related genes have been identified through comparative transcriptomic analyses, with cloning and sequencing efforts currently underway.

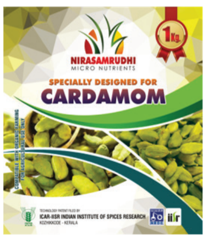
Cutting-edge innovations in plant and soil health management

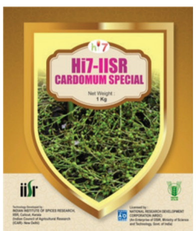
Crop specific micronutrient formulations

Soils in many spice-growing regions face declining fertility due to acidity, nutrient imbalances, and deficiencies in secondary and micronutrients, which limit crop yields. To address these issues, crop-specific and pH-based micronutrient formulations for foliar application have been developed, resulting in a 10–25% increase in yield and improved product quality. By using these micronutrient formulations, farmers can improve their soil fertility, increase crop productivity, and reduce dependency on chemical fertilizers. These formulations are also compatible with organic farming, making them environmentally sustainable. To promote widespread adoption, the micronutrient mixtures have been licensed to 31 entrepreneurs, enabling commercial production and distribution, now covering over 10% of the total cropped area.









Decision support system for soil test-based fertilizer recommendation (Spice FeRT)

The software for soil test and crop response-based fertilizer (NPK) recommendation model for different yield targets (q/ha) in black pepper, ginger, turmeric and cardamom. This software was developed with different input parameters (soil test values for N, P and K, pH), crop yield targeted (as fresh/ dry yield in q/ha) and per ha recommendations for lime, N, P2O5 and K2O were calculated using the designed STCR models for the crops and the results were expressed in per bed (for ginger and turmeric) and per plant (for pepper and cardamom) basis for different fertilizer inputs.

Lime-based microbial formulations

Granular lime and gypsum-based formulations were developed to correct soil pH imbalances and enable efficient delivery of beneficial microbes. After successful trials under greenhouse and field conditions, the product development process was submitted for patenting. This formulation also benefits the crop by improving the physical condition of the soil, enhancing secondary nutrient availability and boosting soil microbial activity. The formulations released were:

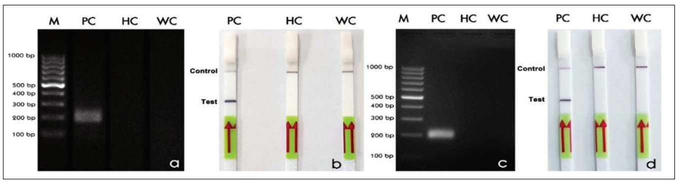
- **Tricholime:** A lime-based formulation enriched with *Trichoderma*, designed to neutralize soil acidity, promote plant growth, and suppress soil-borne pathogens in a single application.
- **Bactolime:** Combines lime with plant-beneficial bacteria, improving acidic soils while simultaneously delivering microbial inoculants.
- **Bactogypsum:** Formulated for alkaline soils, this product integrates gypsum with beneficial bacteria to improve soil conditions and microbial activity
- **Trichogypsum:** A gypsum-based formulation containing *Trichoderma*, aimed at managing high pH soils and promoting beneficial fungal colonization to support plant health.

Encapsulation technology for delivery of beneficial micro-organisms

ICAR-IISR has developed and patented the world's first encapsulation technology for the smart delivery of beneficial microorganisms to crops, offering a sustainable alternative to conventional talc and liquid-based biofertilizers. This technology allows encapsulation of agriculturally important microbes such as *Trichoderma*, nitrogen fixers and phosphorus solubilizers, enabling targeted delivery for enhanced nutrient mobilization, plant growth, and biocontrol. The biocapsules, with extended shelf life and storage at ambient temperatures, have improved the efficiency and reach of microbial inoculants, currently covering about 10% of spice-growing areas. This innovation has significantly advanced organic farming by reducing dependence on chemical inputs while maintaining high productivity. The technology has been licensed to ten Indian firms and internationally to M/s Lysterra LLC, Russia, highlighting its global relevance. As adoption grows, it is poised to play a key role in promoting environmentally sustainable agriculture.

Diagnostics

Advanced molecular diagnostic tools have been developed for the rapid and sensitive detection of pathogens affecting spice crops. Loop-mediated isothermal amplification (LAMP), real-time LAMP, and RPA-LFA (recombinase polymerase amplification–lateral flow assay) have been standardized for virus detection in black pepper, cardamom, and ginger. These tools facilitate the certification of virus-free planting material, particularly in black pepper, and offer potential applicability across crops. Protocols for conventional PCR, RPA, and LAMP have also been established for identifying key fungal pathogens such as *Phytophthora*, *Pythium*, and *Fusarium*, including a multiplex PCR assay for their simultaneous detection. In ginger, single and duplex RPA assays provide efficient pathogen identification. A strain-specific real-time LAMP assay has been developed for detecting race 4 of *Ralstonia solanacearum*, the causative agent of bacterial wilt in ginger. This tool allows indexing of soil, water, and rhizomes, supporting field-level applications for pathogen-free site and seed selection.



RPA-LFA for the detection of piper yellow mottle virus in black pepper

Green solutions for crop protection

The institute has developed several innovative technologies to enhance seed germination, vigour, and disease resistance in spice crops. Seed coating with efficient strains of plant growth-promoting rhizobacteria (PGPR) and seed priming using *Trichoderma* formulations have been introduced to improve and standardize germination, particularly in rhizomatous crops, while reducing storage losses. A PGPR consortium specifically formulated for black pepper was also developed to support nutrient mobilization, plant growth, and biocontrol, and has been commercialized through non-exclusive licensing.

An integrated technology was designed to manage bacterial wilt in ginger, involving soil solarization followed by drenching with 3% calcium chloride at planting and at 30-day intervals, along with seed rhizome treatment using *Bacillus licheniformis* (Bacillich 2%).

In cardamom, an IPM strategy for thrips control has been developed, combining the entomopathogenic fungus *Lecanicillium psalliotae*, spinosad (a reduced-risk insecticide), and existing chemical and cultural methods. Additionally, a promising entomopathogenic fungus, *Metarhizium pingshaense*, was isolated from *Conogethes punctiferalis*, with potential for development into a mycoinsecticide.

A liquid culture-based process for large-scale multiplication of resting spores of *Pochonia chlamydosporia* was formulated to ensure viable delivery for effective biocontrol. Furthermore, rhizome priming with *Trichoderma* was developed to accelerate bud sprouting, improve vigour, and prevent rot during storage and early crop stages. A novel PGPR strain, *Bacillus safensis*, has also been identified for its multifaceted benefits in plant growth promotion, soil nutrient solubilization, and disease suppression.

Advancements in post-harvest technologies and value-addition

Innovative post-harvest technologies have been developed and adopted by farmers and entrepreneurs to improve spice processing and value addition, ultimately boosting their income. Spice extracts have demonstrated strong antioxidant properties and show promise as nutraceuticals and potential anti-cancer agents.

Three spice-infused formulations, intended as functional additives for milk and dairy products, have been successfully commercialized through MILMA–the Kerala Co-operative Milk Marketing Federation. In another achievement, a process was standardized to produce ginger-lime juice powder using advanced dehydration methods that preserve the natural flavour, aroma, and bioactive components of the ingredients. This product offers a longer shelf life, making it suitable for commercial distribution and convenient consumer use.

Additionally, a unique spice-flavoured ice-cream has been developed, blending toned milk, cream, sugar, and skim milk powder with black pepper oleoresin. Another innovative product is a dairy-free ice-cream enriched with spice oleoresin and fortified finger millet milk, catering to health-conscious consumers seeking functional foods.

A pilot-scale vacuum impregnation system has also been designed to infuse spice extracts into food products effectively. This technology allows for the integration of bioactive spice compounds into various food matrices, improving their nutritional and functional attributes while preserving flavour and antioxidant content. This approach is ideal for the development of value-added products with enhanced health benefits.

To improve the efficiency of the drying process for food and agricultural products, a hybrid hot air-assisted infrared dryer has been engineered. The system can operate using infrared heating alone or in combination with hot air, providing adaptable drying solutions based on specific needs. This advanced drying method increases energy efficiency, shortens processing time, and better preserves the nutritional quality, colour, and aroma of the dried materials. Both vacuum impregnation and hybrid drying technologies offer significant commercial opportunities for entrepreneurs and startups in the food processing industry.

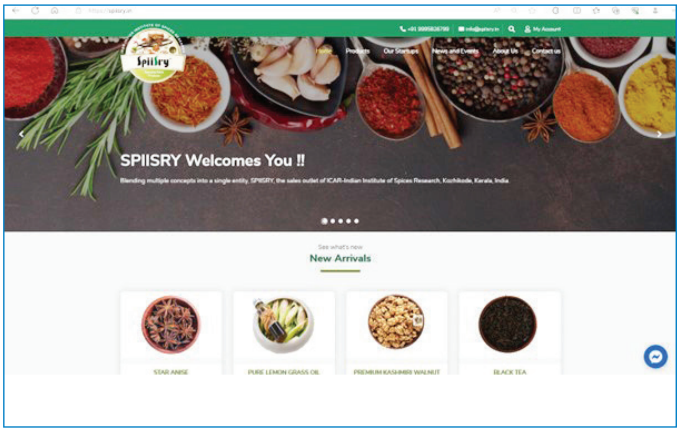
In the area of quality assurance, DNA barcoding techniques have been implemented at ICAR-IISR to identify plant-based adulterants in commercial spice products like black pepper powder, cinnamon, nutmeg, and turmeric. Notably, this method successfully detected chili adulteration in traded black pepper for the first time, demonstrating its effectiveness in ensuring spice authenticity.

Science for success: Commercial pathways from innovation

With the emergence of a strong licensing regime and the focus on commercialization of technologies including varietal technology, varietal licensing has been increasingly used in making seed material of improved varieties widely available in the country. However, the growing demand for planting materials of these popular varieties often exceeds supply. To address this, the institute has adopted a strategy of granting non-exclusive licenses for the commercial production of varieties developed through public-funded research. Through the ITM-BPD Unit, ICAR-IISR has facilitated non-exclusive license agreements for the commercialization of released spice varieties, micronutrients, bioagents, and biocapsule technologies, and has filed seven patents. Additionally, the Spice Processing Unit (SPU) has incubated six companies, successfully launched products into the market, and supported entrepreneurs. The institute also actively promotes value chain development for spices such as turmeric and black pepper, working in partnership with government agencies, farmer producer organizations (FPOs), and NGOs at both state and national levels.

Incubation support and facilities at ICAR-IISR

- *iFAME:* Incubation facility for microbial encapsulation
- Pilot plant for crop specific micronutrient production
- *Krishidhan nursery:* Quality planting material production and marketing
- *Spiisry:* Sales outlet for spices and value-added products
- *www.spiisry.in:* E commerce platform for marketing spices, value-added products and agri-inputs
- *Kisan Seva Kendra:* Sales outlet for marketing quality agri input
- *Impower:* Incubation facility for women entrepreneurship development
- *Product development lab:* For development of cosmetic products and spice processing facility.



Online portal and Sales point "Spiisry"

Kisan Seva Kendra

CONCLUSION

Technological innovations in the spice sector are primarily driven by the need to address critical challenges in crop production. Key issues include the impacts of climate change–such as drought, excess moisture, and temperature extremes during sensitive growth stages–along with the emergence of pests and disease outbreaks, widespread adulteration in the value chain, and contamination from pesticide residues and mycotoxins, absence of defined MRL (Maximum Residue Limits) and acceptable daily intake standards. Effectively addressing these challenges depends on the development of simple, affordable, and farmer-friendly technologies. There is significant potential to enhance the productivity of major spices by adopting practices that help bridge the yield gap between research stations and on-farm realities. Strengthening the adoption of proven techniques and innovations across the spice value chain is essential to overcoming global competition, meeting international market demands, and ensuring a sustainable, inclusive, and resilient production system.

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