REVIEW ARTICLE

Preserving Nutritional and Health-Promoting Compounds in Spices through Improved Processing Technologies

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Abstract

Spices are valued for their nutritional and health-promoting compounds, yet conventional processing often causes significant degradation. This review examines innovative technologies to minimize losses and enhance preservation, including electrically assisted thermal methods (ohmic heating, microwaves), non-thermal techniques (high-pressure processing, pulsed electric fields, ultrasonics, cryogenic milling), and advanced packaging systems. These approaches effectively retain bioactive phytochemicals, antioxidants, and volatiles while ensuring microbial safety and sensory quality. By integrating energy-efficient, sustainable strategies, they address industrial challenges, extend shelf life, and boost product functionality. The evidence supports a shift to next-generation processing, providing a roadmap for superior spice quality and global market competitiveness.

Key words: Bioactive compounds, electrically assisted thermal technologies, flavor and color retention, microbial safety, non-thermal processing, spice processing

INTRODUCTION

"In every corpuscle of spice lies a world of flavor waiting to unfold." Ancient medical regimes like Sushruta and Charaka documented their therapeutic properties, embedding them in traditional systems like Ayurveda.[1,2] Beyond culinary applications, spices align with holistic dietary philosophies.[3,4] Despite their potent taste, they are used sparingly, thus adding minimal calories, even many spice seeds contain essential nutrients, and their impermeable structure limits their accessibility, containing substantial fats, proteins, and carbohydrates by weight.[5] In India, Rajasthan and Gujarat are responsible for producing over 80% of the country's seed spices, largely due to the fertile land and expertise of their skilled farmers, significantly influencing India's gastronomic and agricultural legacy.[6] Spices not only enhance flavor but also support digestion by encouraging the secretion of saliva and gastric fluids. Medicinal plants commonly used to alleviate gastrointestinal problems frequently feature spices as their main constituents. Volatile oils impart distinctive aromas, whereas oleoresins offer pungent, sweet, and bitter nuances.[7] Spice manufacturers must meet strict standards for microbial count, color consistency, granulation, and essential oil content to guarantee product uniformity. The cultivation and refinement of spices have profoundly shaped agricultural practices and international commerce, weaving diverse culinary traditions into the cultural fabric of civilizations.[7] Technological advancements [Table 1] are

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constantly redefining processing methods, thereby enhancing both the quality and productivity of the spice industry.[8,9]

SPICE KINETICS

The release and perception of spice flavors are regulated by intricate interactions between the active ingredients in food and their molecular frameworks, with binding sites influencing the rate of release and the intensity of the sensory experience.[10] Compounds derived from spices, which include both volatile and non-volatile aromatics, display species-specific distribution patterns, with their bioavailability being influenced by matrix encapsulation effects and chemical bonding states Naknean *et al*.[11]

SENSORY ALCHEMY: FLAVOUR PATHWAYS AND PERCEPTION

Flavor release in spices is driven by phase equilibrium disruption and mass transfer kinetics, shaped by solid-liquid-air interactions. Intrinsic traits such as botanical genotype and maturity stage define volatile profiles, with genotype influencing compound composition and ripening, reducing fruity esters and altering limonene levels.[12,13] "External influences" temperature, soil quality, hydrology, and post-harvest methods further modify flavor. Temperature follows the Arrhenius principle, soil and water affect biochemical stability, drying governs volatile retention, particle size impacts mass transfer, and sterilization alters microbial and biochemical integrity. Overall, flavor reflects both intrinsic and external factors, while its sensory strength is expressed as organoleptic potency.[14]

CUTTING-EDGE METHODS AND NOVEL APPROACHES FOR PRESERVING FLAVOURS

Table 1: Core aims of diametric pre-treatment strategies

Pre-treatment method	Key features	References
High-pressure processing	High-pressure processing sustain the peak antioxidant and other bioactive compounds present in agricultural produce	[15]
Enzyme-assisted processing	Enzymatic pre-treatments furnish product with softness and even-textured quality	[16]
Pulse electric field processing	Pulsed electric field performs superior pathogenic diminution like aflatoxins more or less 80–85%	[17]
Ultra-sonication processing	Ultrasound pretreatment on the physicochemical parametric quantity and structuralism changes of various commodities.	[18]

CRYOGENIC GRINDING

Colorimetric alterations in spices: Assessing the role of cryogenic grinding

Recent studies have found that grinding spices at extremely low temperatures (−97–−50°C) results in exceptional preservation of quality, leading to a 30–40% higher retention of volatile compounds such as monoterpenes in peppers compared to traditional methods [Figure 2].[19,20] An advanced method produces particle distributions that are 20–30% finer, and it achieves an energy savings of 15–25% during the processing of cinnamon and turmeric,[21] showing that cassia bark retains its color well (ΔE<2.0) at −97°C.[22] The technology is especially beneficial for color-sensitive applications, retaining 40% more chromatic integrity in *Byadagi chili* despite increased operational costs.[23] Optimizing processes shows that keeping temperatures below −80°C is necessary to prevent particle clumping in cloves,[24] and controlling moisture levels at <8% boosts fenugreek's functional properties by increasing its surface area.[25] Quality benchmarks encompass a volatile oil recovery of 2.15 mL/100 g in black pepper, specifically with optimized color indices of L: 65.2 and b: 28.4.[26]

Modulation of bio-active compounds in cryogenic grinding spices

Cryogenic grinding minimizes heat generation during size reduction, which prevents the thermal degradation of heat-sensitive bioactive compounds in king chilli, such as capsaicinoids, phenolics, and carotenoids.[23] The technology consistently enhances volatile oil yields, as evidenced in coriander (0.14–0.39%), black pepper (1.7 vs. 0.9 mL/100 g), cumin (33.9% increase with cumin aldehyde rising to 56.1%), and clove (29.5% improvement).[20,24,27,28] Optimal cryogenic conditions (−50–−90°C) preserve key quality markers like linalool in coriander and allicin in garlic,[29,30] while fenugreek shows 37.36% higher oil content.[31] The method also boosts phenolic compounds, flavonoids, and antioxidant activity across all tested spices,[25] confirming its industrial potential for flavor and nutrient preservation.

OHMIC HEATING

Ohmic heating [Figure 3], a groundbreaking and efficient food processing method, employs an electric current passed through liquid-particulate foods to produce heat quickly.[32]

Chromatic transformations in spices: Ohmic thermal effects

Ohmic heating shows greater effectiveness in dehydration processes by losing the most water while minimizing color deterioration compared to conventional methods.[33] This electrothermal technique also boosts the extraction of bioactive compounds from plant matrices. Extraction using ohmic heating in saffron petals resulted in extracts containing high levels of kaempferol derivatives and anthocyanin, which showed maximum antimicrobial activity and significant lipase inhibition.[34] The resulting extracts provide an economically viable source of natural flavorings, pigments, and high-purity antioxidants, which are suitable for use in food, beverage, and pharmaceutical industries. Research comparing ginger extracts revealed that ohmic heating before processing resulted in the most consistent color, with a color difference (ΔE) of 1.17.[35]

Optimizing spice bioactive through ohmic-assisted extraction

Significant ohmic heating boosts black pepper's oleoresin yield and piperine content by causing cellular fractures that make it easier for solvents to penetrate, as seen in microstructural analysis of the treated samples.[36] Traditional hydro distillation is outperformed by ohmic heating-assisted hydro distillation in clove bud essential oil extraction, achieving higher yields while reducing energy consumption and preserving the bioactive integrity of the oil.[37] Research on cinnamon and bay leaf essential oils has found that applying ohmic heating in hydro distillation not only boosts extraction efficiency but also increases the concentration of key volatile compounds, resulting in concurrent enhancements to their antioxidant and antimicrobial properties.[38] In addition to extraction, innovative thermal processing techniques enhance functional characteristics. Induction heating successfully decreases microbial contamination in cumin seeds without impairing quality, providing a practical non-thermal method of decontamination.[39,40] Treating ginger slices with ohmic methods disrupts the cell matrix, releasing bound flavonoids and substantially increasing their extractable content.[41]

ULTRA-SONICATION

Accustomed hydro distillation techniques for extracting aromatic and flavor compounds from herbs and spices are being progressively supplanted by ultrasonication, a more expeditious and eco-conscious alternative. Unlike traditional methods, ultra-sonication [Figure 4], significantly reduces solvent consumption, shortens extraction time, and intensifies both yield and extract quality.[42] The underlying mechanism of ultrasound is mechanical in nature, reducing deeper solvent penetration into the plant matrix, enhancing contact between solid and liquid phases, and accelerating solute diffusion.[43] This phenomenon is driven by acoustic cavitation, the fabrication, growth, and collapse of micro bubbles generated by ultrasonic waves, which disrupts cell walls and promotes the rapid release of bioactive constituents.[44]

Influence of acoustic cavitation on thermally labile nutrients

Sonication has emerged as a highly efficient extraction method, surpassing traditional techniques by substantially increasing yields and drastically cutting processing times, as seen in the extraction of coriander volatile oil (yielding 0.284% with high-purity fragrance)[45] and saffron stigma (yielding crocin: 498.7 vs. 423.9; picrocrocin: 49.71 vs. 49.6; safranal: 151.7 vs. 151.2 compared to the conventional method).[46] The effectiveness of these technologies is due to acoustic cavitation, which damages cellular structures, enhances the penetration of solvents, and increases the surface area for solute release.[43,44] This is visually evident from scanning electron microscopy analysis of ultrasonically-treated samples showing the breakdown of cell walls, which facilitates the release of bioactive compounds such as curcumin from *Curcuma amada*[47] and piperine from black pepper,[48] resulting in extraction rates 1.75 times quicker than traditional Soxhlet methods.[49] Ultrasonication extraction stands out for its ability to preserve thermolabile compounds, retaining high levels of terpinyl acetate and 1,8-cineole in cardamom essential oils, achieving faster extraction times,[50] and delivering outstanding results for fenugreek saponins[51] and Himalayan ginger, which shows exceptionally high polyphenol extraction efficiency of 15.27%.[52] The method's environmental benefits are highlighted by its 37% decrease in energy usage and 50% shorter drying time for cumin seeds,[53] as well as its versatility across different solvents and minimal thermal degradation.[54] The UAE backs the development of methods like the prolonged release of star anise volatile oil in stable Nano emulsions,[55] enhanced clove essential oil encapsulation efficiency,[56] increased polysaccharide extraction from *Zingiber mioga* leaves,[57] and optimized oleoresin Nano emulsions in red ginger.[58]

Ultrasonic modulation of pigment and flavor constituents in spice matrices

Studies by SicZlabur *et al*.[59] showed that ultrasonic treatment of turmeric and ginger extracts led to increased yellow pigmentation because of higher levels of curcuminoids, resulting in extracts with up to 67% more vitamin C, 69.4% more total carotenoids in turmeric, and 40% more total phenols in ginger compared to conventional methods at matched temperatures. Furthermore, garlic extracts treated with ultrasound showed inhibitory effects against *Listeria monocytogenes*, highlighting their antimicrobial potential. Recent extraction methods, such as ultra-sonication, allow for eco-friendly, resource-optimized production of natural colorants without compromising industrial feasibility.[60]

Ultrasonic sterilization kinetics: Modeling microbial inactivation in spices

Sonication parameters must be thoroughly documented to conduct a reliable microbial load assessment in medical science,[61] and in food applications, this technology allows for low-temperature inactivation of pathogens without compromising nutritional quality.[62] Cogent evidence of sonication parameters is essential for high-fidelity microbial load assessment in medical device processing,[61] while in food applications, it offers a low-temperature disjunctive for pathogen inactivation that preserves nutritional quality.[62] Cocci like *Staphylococcus aureus* exhibit greater resistance than rod-shaped bacteria, primarily due to their reduced surface area, with susceptibility patterns emerging post this distinction.[63] The technology showcases dual capabilities in spice processing: It achieves rapid microbial inactivation via a 5-min high-intensity ultrasound treatment compared to traditional 24-h methods for suppressing Salmonella in Thai spices[64] while also improving bioactive extraction efficiency. Traditional methods are surpassed by ultrasonic-assisted extraction, which results in a 1.75-fold increase in recovery rates. This is demonstrated in studies of ginger polyphenol isolation[65] and the fabrication of garlic oil nanoemulsions, with optimal results achieved after 5 min of sonication, yielding particles of 52.27 nm in size and exhibiting enhanced antifungal activity against *Penicillium italicum*.[66] The technique also optimizes flavonoid recovery when used in combination with lactic acid extraction[67] and serves as a basis for novel applications of materials, such as transparent antimicrobial cellulose films produced from ginger nanofibers, which contain 88% cellulose and are 5 μm in thickness after undergoing 60 min of sonication.[68]

HIGH PRESSURE PROCESSING

High-pressure processing has become a transformative non-thermal technology for noble food preservation, operating across a broad pressure spectrum from tens to hundreds of (MPa) in applications spanning from homogenization to pasteurization.[69] This groundbreaking method successfully neutralizes microorganisms while satisfying increasing consumer demand for minimally processed, additive-free foods with extended shelf life.[70] High-pressure processing improves processing efficiency beyond microbial control by making cells more permeable, as seen in red paprika, where pre-treatment with pressure greatly increased dehydration rates by altering tissue structure.[71]

Principal of high pressure-processing

Le Chatelier's principle states that pressure preferentially increases the intensity of reactions and phase transitions that decrease system volume while inhibiting volume-increasing phenomena.[72] The isostatic principle leads to a uniform pressure distribution across the food matrix [Figure 5], according to Rikimaru *et al*.[73,74]

Pressure-induced microbial reduction: Kinetic analysis in spice matrices

High-pressure processing has been shown to be effective in reducing microorganisms in spices, with a 300–800 MPa[75] pressure range achieving the desired antimicrobial effect, but sublethal pressures of 100 MPa[76] can confer thermal resistance on certain bacteria, such as *Lactobacillus rhamnosus*. Both aerobic and anaerobic spores are effectively removed without altering volatile profiles using multi-stage treatments (e.g., 30 min at 80 MPa + 30 min at 350 MPa, 70°C, with a value of at least 0.91).[77] Coriander and parsley that had been pressure-treated showing lower counts of viable bacteria; however, pseudomonas was resistant to the biocide,[78] whereas the use of helium in high-pressure processing improved the microbial quality of caraway and coriander, a factor which depends on the moisture content.[79] High-pressure processing boosts the potency of spice phytochemicals, as shown by the improved preservation of phenolic and carotenoids in red pepper paste[80] and extended shelf life in low-salt sausages when combined with clove/cinnamon extracts, despite potential oxidation challenges.[81] The marinating process enhances seafood quality by further delaying spoilage in prawns.[82] The technologies efficacy is dependent on the strain and matrix, necessitating customized pressure-time combinations,[83] with essential oils enhancing microbial inactivation via structural synergism.[78]

High-pressure impact on spice pigmentation profiles

High-pressure processing causes measurable yet minimal color changes in spices, with ΔE* values ranging from 0.2 to 2.8, spanning the thresholds between imperceptible and noticeable changes.[80] The narrow range, as defined against standard visual perception benchmarks (0.0: Imperceptible; 0.5: Slightly noticeable; 1.5: Noticeable; 3.0: Well visible; 6.0: Great), shows that HPP has a superior color preservation compared to thermal methods. The positive link between pressure intensity and holding time with the magnitude of ΔE* suggests that although chromatic shifts are slight, they are nonetheless affected by the processing conditions.

Molecular responses of spice compounds to high pressure

High-pressure processing has been shown to be highly effective in preserving the structural integrity of proteins (including quaternary and secondary conformations) and volatile flavor compounds while also retaining bioactive compounds in spices.[84] The isostatic principle guarantees uniform pressure distribution resulting in superior preservation of phenolic and carotenoid compounds relative to thermal methods.[15] Research revealed that modifying fennel essential oil through pressure-dependent phytochemical alteration preserved an oil yield of 93.4%, with post-processing concentrations

Table 2: Patented bioprocessing techniques for flavor and chroma extraction

S.No.	Crop	Description	References
Flavours			
1.	Ginger	Proprietary bioconversion method for producing premium liquefy flavor core from recalcitrant tropical fruits and tuberous substrates.	[115]
2.	Vanilla	bio catalytic method is patented for prevail natural vanilla flavor through enzymatic liberation of glucovanillin and recuperation of ethanol extract aromatic fractions	[116]
3.	Garlic	Enzymatic digestion (celluloses) of crushed garlic and ensuant steam distillation yields volatile garlic oil, which is applied in anti- wilting agro formulations	[117]
Colors			
1.	Paprika oleoresin	Lipase-mediated bioprocessing of paprika oleoresin, conjugated with solvent extraction, yields a high-purity colorant devoid of capsaicin odor, ideal for erogenous formulations across industries.	[115]
2.	Chilli	Enzymatic (cellulolytic) pre-treatment optimizes pigment and capsaicin retrieval during binary solvent extraction, yielding a clustered oleoresin with superior chromatic and pungency profiles.	[115]

Figure 1: International spice flux major supplier and consumer markets

of 8.21 versus 8.79 mL/100 g.[85] Furthermore, cashew-apple juice had higher levels of soluble polyphenols when subjected to 250 MPa for 3 min, and this process also boosted its 2-diphenyl-1-picrylhydrazyl antioxidant activity without altering the levels of ascorbic acid or pH stability, as stated in reference.[86] Unlike thermal/vacuum drying, it led to safranal breakdown in saffron but boosted levels of 4-β-hydroxysafranal,[87] and ginger showed the greatest retention of phenolic and flavonoid compounds.[88] High-pressure processing enhances dehydration kinetics in ginger, combining with osmotic treatment to speed up water loss while saving energy and preserving quality.[89]

PULSE ELECTRIFIED

Recent advancements are revealing enhanced drying rates for produce that is high in antioxidants[94] and broadened applications in wastewater treatment and agriculture.[95] Pulsed electric field (PEF) causes cellular membrane electroporation (electro plasmolysis) through high-voltage pulses (1–5 kV/cm) at temperatures below 40°C, significantly enhancing moisture diffusivity and bioactive extraction without compromising product quality.[90,91] Typically used in fruit processing, PEF treatment involves thermal/chemical methods to preserve the natural properties and phytochemical content.[92] Its applications encompass microbial inactivation, reduction of aflatoxins,[17] and improved extraction of phenolic/flavonoids.[93] Recent developments show improved drying kinetics for antioxidant-rich produce[94] and dilated uses in wastewater treatment and agriculture.[95]

Phytochemical dynamics under pulsed electrification

PEF technology greatly improves spice extraction through electroporation-induced cellular disruption, illustrating dual mechanisms of surface cleaning (via turgor-driven juice

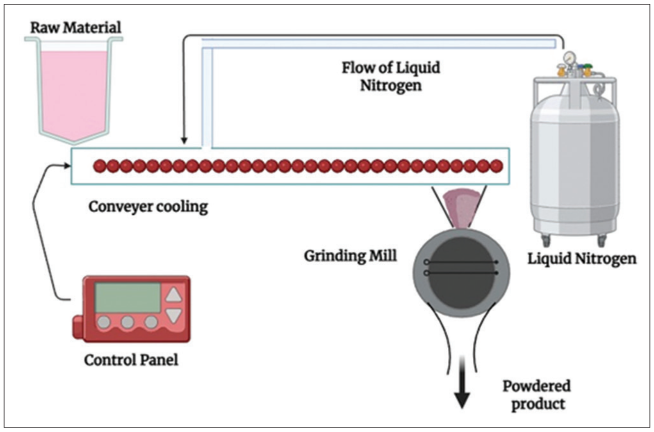

Figure 2: Systematic representation of cryogenic grinding

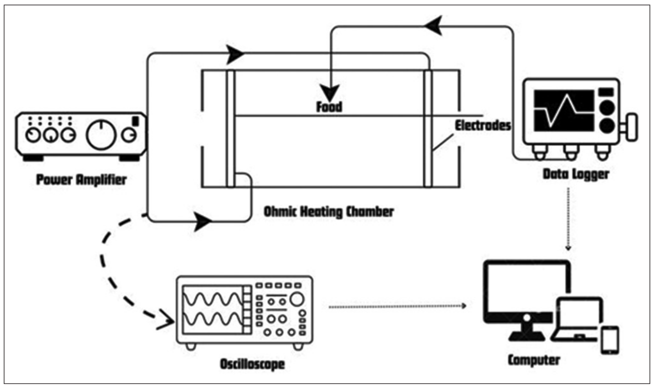

Figure 3: Operational framework of direct resistance heating

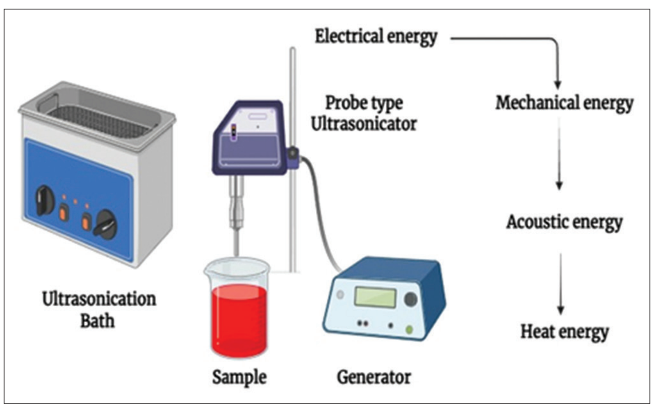

Figure 4: Schematic overview of ultrasonic processing methods

release) and intracellular solute movement.[96] Adjusting optimal PEF parameters to 1–5 kV/cm with 40–55 pulses results in a 13–73% increase in essential oil yield for red ginger and galangal, as well as a shorter distillation time,[97] and a 24–41% increase in phenolic extraction for green tea and cinnamon by enhancing cell membrane permeability.[98,99] The voltage-dependent efficacy of these technologies is evident in coriander, where 1 kV/cm (≤55 pulses) achieved the maximum recovery of essential oil and phenolic compounds before irreversible electroporation took place.[100] PEF also serves as a powerful detoxification agent, removing

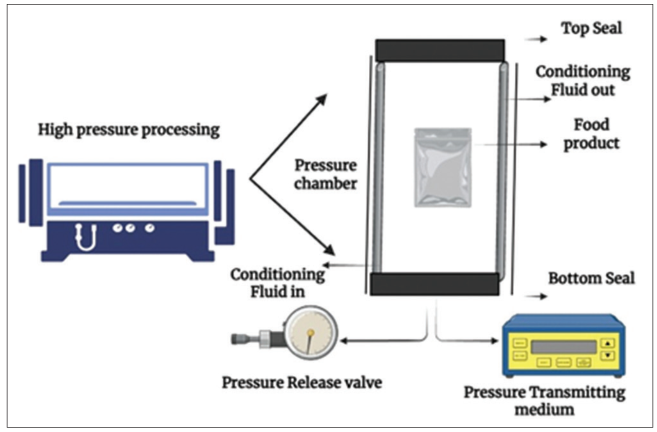

Figure 5: A graphical exploration of hydrostatic processing

ochratoxin A and fungal impurities in paprika without compromising its quality.[101] Optimization of the cognitive process shows significant performance at 1.18 kV/cm through 48 pulses, resulting in exceptional oil yield at a press speed of 11.01 rpm, while maintaining oxidative stability and phenolic content.[102]

Voltage-dependent color profile evolution

Treatment with a PEF at a range of 1.0–2.5 kV/cm with pulses of 30 μs at 100 Hz frequency significantly enhances color quality during spice processing, as shown in *Capsicum annuum* L. (red pepper), where it reduced drying time while improving color attributes by increasing b* values and methodology for measure of pigments ASTA units by more than 10% without affecting structural integrity. The scope of PEF technologies also encompasses oil extraction, where a higher electric field intensity and a greater number of pulses (optimally set at 1.18 kV/cm, 48 pulses) lead to a proportionate increase in the color index of black cumin seed oil.[102]

Pulse-driven micro biomes

Non-thermal processing innovations are transforming the field of spice extraction and preservation, with electroporation-based methods providing a promising alternative to traditional thermal processes. PEF technology has shown notable potential as a pre-treatment for essential oil extraction, combining intensified processing with enhanced microbial safety. Coriander seeds, when processed by PEF, have shown strong inhibitory effects against *Candida albicans* as well as Gram-positive and Gram-negative bacteria, mainly due to mechanisms causing membrane disruption.[100] Furthermore, PEF has been shown to be beneficial for extracting plant protein from legumes, nuts, and seeds, resulting in improved yields and nutrient retention by reducing thermal degradation. The combination of improved bioactive recovery, microbial decontamination, shorter processing times, and longer shelf-life makes PEF a ground-breaking approach to spice processing, addressing both quality and safety through precise, electroporation-driven cellular permeabilization.[103]

Enzyme-assisted – paradigm shift in spice bioactive recovery

The traditional spice processing industry has undergone significant changes due to the targeted use of hydrolytic enzymes, which facilitates the precise breaking down of cells, leading to a 25–70% rise in yields of essential oils from black pepper and cardamom via the targeted degradation of the cell wall.[104,105] Methods assisted by microorganisms also show remarkable effectiveness, as evidenced by *Bacillus subtilis*-mediated retting, which yields high-quality white pepper within 48–96 h and eliminates unpleasant smells.[106] Turmeric rhizomes see curcumin recovery boosted by 5.73% through enzymatic pre-treatment through starch matrix hydrolysis,[107] and cellulase-assisted distillation enhances oil yields by 27%.[108] The adaptability of these technologies encompasses delicate flavor compounds, with freeze-enzyme synergy converting 4.62% of glucovanillin to vanillin in vanilla pods,[109] and pressurized enzymatic extraction enhancing gingerol recovery by 40–50%.[110] Structural studies confirm that these methods maintain molecular integrity while speeding up the extraction process, with fennel seeds showing a 22.5% increase in oil yield without altering their composition,[111] and coriander experiencing improved linalool recovery.[112] Three-phase partitioning systems significantly enhance process intensification by reducing the extraction time of turmeric oleoresin from 12 to 4 h.[113] In addition, binary enzyme treatments have a notable effect, increasing saffron polyphenols.[114]

NEXT GENERATION PACKING

Advanced spice packaging [Table 2] addresses challenges such as caking, rancidity, discoloration, and pest infestation by employing nanocomposite barriers, gas scavengers, and moisture-regulating sorbents to safeguard volatile compounds. Active systems with oxygen absorbers, desiccant polymers, antimicrobial emitters, ultraviolet-protective laminates, and thermal buffers further extend shelf life by maintaining oxidative stability and critical water activity.[118,119]

CONCLUSION

The integration of advanced technologies such as cryogenic grinding, PEFs, ultra-sonication, and enzyme-assisted extraction has transformed spice processing, offering precision in flavor retention and bioactive preservation. However, challenges remain regarding scalability, cost-effectiveness, long-term impacts on quality and safety, and the preservation of traditional expertise. Future progress requires research into hybrid synergies, standardized guidelines, and consumer-oriented approaches that balance innovation with cultural heritage. By critically addressing these gaps, the spice industry can advance toward sustainable, high-quality, and commercially viable processing systems.

AUTHOR CONTRIBUTIONS

Mirudhula S writing original draft, visualization, resources data curation, conceptualization. V Rajasree: Writing review and editing, visualization, validation, supervision. M Mohonalakshmi: Visualization, validation, supervision, formal analysis. N Senthil: Formal analysis, conceptualization. N Saranya and S Vellaikumar: Conceptualization.

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