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White pepper (*Piper nigrum* L.) production and processing: A review of conventional and emerging technologies

Phuc Nguyen Thien Le [1], Anh Ngoc Nguyen [1], Duyen Thi My Nguyen [1] and Phu Hong Le [2, *]

[1] *Department of Biotechnology, School of Biotechnology, International University – Vietnam National University of Ho Chi Minh City (VNU-HCM), Ho Chi Minh City, Vietnam.*
[2] *Department of Food Technology, School of Biotechnology, International University, Vietnam National University of Ho Chi Minh City (VNU-HCM), Ho Chi Minh City, Vietnam.*

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Abstract

White pepper is a high-value spice product obtained by removing the outer pericarp of ripe *Piper nigrum* berries, and its final quality is strongly influenced by the processing method applied. Conventional water retting remains the most widely used approach, particularly at smallholder level, but it is often associated with long processing time, inconsistent quality, labour intensity, microbial risks, and wastewater-related environmental concerns. This review aimed to examine recent advances in white pepper processing, with emphasis on the anatomical basis of pericarp removal, the main processing platforms currently available, and the comparative advantages and limitations of each method. Relevant studies on water-based retting and soaking, mechanical and thermos-mechanical processing, enzyme-assisted decortication, controlled microbial fermentation, chemical-assisted whitening, and other emerging routes were critically analyzed. The findings indicated that traditional soaking methods remain important because of their simplicity and low cost, whereas more controlled approaches can substantially improve process efficiency, product consistency, and hygienic quality. Enzyme-assisted and microbial methods show strong potential for accelerating pericarp degradation, while mechanical and thermos-mechanical systems can reduce labor demand and improve process control. Emerging technologies also suggest new opportunities for shortening processing time and reducing the limitations of conventional retting. However, no single method is universally optimal, since each involves trade-offs related to colour, aroma retention, microbiological safety, environmental impact, and economic feasibility. This review highlights the current progress, major limitations, and future prospects of white pepper processing technologies toward cleaner, faster, and more standardized production.

Keywords: Decortication; Enzyme-assisted processing; Mechanical peeling; Microbial fermentation; *Piper nigrum*; Quality evaluation; White pepper

1 Introduction

Piper nigrum L. is one of the most widely used spice crops in tropical and subtropical food systems, and its berries are processed into several commercial forms, most notably black pepper and white pepper. Although both products originate from the same fruit, they differ substantially in processing route and sensory characteristics. Black pepper is produced from immature berries dried with the pericarp intact, whereas white pepper is obtained from ripe berries after removal of the outer pericarp through retting, decortication, or related postharvest treatments [1]. As a result, white pepper generally exhibits a lighter appearance, a milder flavour, and fewer visible dark specks in finished foods, making it especially suitable for light-coloured soups, sauces, dressings, and processed products in which appearance is an important quality attribute [1, 2].

* Corresponding author: Phu Hong Le

Despite its culinary and commercial importance, white pepper production remains more challenging than black pepper processing because it requires additional steps, including soaking or fermentation, pericarp removal, washing, and drying. Conventional water retting is still widely practiced because of its simplicity and low capital requirement, particularly at smallholder level. However, it is also associated with several important limitations, including long processing time, labor intensity, variable product quality, off-odor formation, microbial contamination risks, and the generation of organic-rich wastewater [1, 3]. These constraints have stimulated growing interest in alternative processing approaches that can improve process control while maintaining or enhancing final product quality.

In recent years, white pepper research has expanded beyond traditional retting to include controlled soaking systems, mechanical and thermo-mechanical peeling, enzyme-assisted processing, guided microbial fermentation, and selected post-decortication whitening strategies. These developments suggest that white pepper processing is gradually shifting from empirically managed practices toward more targeted and technology-assisted systems designed to improve efficiency, hygiene, and consistency. This review therefore examines the major processing platforms currently used or explored for white pepper production, discusses the botanical basis of pericarp removal, and critically compares the methods in terms of quality preservation, processing efficiency, environmental sustainability, and economic feasibility. By synthesizing both established and emerging approaches, this review aims to clarify current technological progress and identify key research gaps for cleaner, faster, and more standardized white pepper processing.

2 Botanical and anatomical basis of pericarp removal

The efficiency of white pepper processing is fundamentally determined by the structure and composition of the pepper berry pericarp. Botanically, the fruit is a single-seeded drupe with a fleshy outer rind and a hard inner core. The pericarp is classically divided into the exocarp, mesocarp, and endocarp; beneath the epidermis, the outer tissues become progressively thickened, and the next few cell layers develop lignified, pitted walls. A thick-walled sclereid layer beneath the epidermis provides mechanical protection and is one of the main reasons the skin remains firmly attached before processing. For white pepper production, this firm outer pericarp is the tissue that must be softened and detached from the seed [1].

At the biochemical level, pectin is the key “cementing” polymer in the middle lamella, maintaining adhesion among parenchyma cells in the mesocarp. During retting or enzyme-assisted peeling, pectinolytic activity increases, pectin content declines, galacturonic acid accumulates, and the peeling rate rises, indicating that pectin breakdown is the primary trigger for skin loosening. Hemicellulose and cellulose contribute additional structural support to the cell wall matrix, while lignified tissues and sclereids increase pericarp hardness and resistance to abrasion. As these non-cellulosic materials are progressively degraded, the cell wall ruptures, water uptake increases, cells swell, and the pericarp becomes soft enough to separate from the kernel by rubbing or mechanical peeling [4].

Ripening is also central to decortication success. As berries mature from green to yellow-red, the flesh becomes softer, which is why ripe berries are preferred for white pepper manufacture. Studies on soaking of mature berries show rapid hydration and swelling during the first few days of immersion, consistent with tissue loosening before peel removal. Cultivar and maturity stage likely influence processing efficiency as well, because pepper types differ in berry size and chemical composition, including volatile oil profiles and other constituents linked to tissue behavior; however, direct comparative processing studies across cultivars remain limited [5, 6].

3 Processing technologies for white pepper production

White pepper production has evolved from a predominantly traditional soaking-based practice into a broader set of processing platforms designed to improve efficiency, product quality, and process control. These platforms can be classified according to their dominant mode of action, including water-based retting, mechanical and thermo-mechanical treatments, biochemical and microbial approaches, and selected chemical-assisted or emerging technologies. Understanding these processing routes in a structured way is essential for evaluating how different technologies influence pericarp removal, final product quality, and industrial applicability.

3.1 Water-based retting and soaking methods

Water-based retting remains the most established platform for white pepper production because it is simple, inexpensive, and readily adopted by smallholders. In traditional soaking, fresh mature berries are immersed in water until the pericarp softens sufficiently for rubbing and removal; however, this process is inherently slow and often requires about 8-15 days, depending on berry maturity, water conditions, and local practice [1]. Its major advantage is low technological demand, but prolonged soaking also increases the risk of off-odor formation, inconsistent product quality, and deterioration of soaking-water quality through the accumulation of organic matter and leached bioactive compounds [7]. Flowing-water retting has therefore been explored as a practical refinement of the conventional method. By continuously renewing the soaking medium, flowing water can reduce sedimentation and help maintain better water quality during retting, thereby improving process hygiene and potentially supporting more consistent peeling performance [8]. A further intensification strategy is the combination of soaking and short boiling. This approach shortens the effective retting period to 4-6 days while still producing white pepper that meets Indonesian quality standards under selected conditions, although excessive heating may reduce piperine and alter aroma quality [3]. Overall, water-based methods remain highly relevant, but current trends clearly favor more controlled soaking systems that reduce processing time while improving consistency and hygiene.

3.2 Mechanical and thermo-mechanical methods

Mechanical and thermo-mechanical approaches are designed to reduce dependence on prolonged retting by accelerating pericarp removal through abrasion, friction, pressure, or heat-assisted softening. In the simplest form, rubbing or de-branning is performed manually after soaking, when the pericarp has already been weakened and can be detached by gentle abrasion. More advanced systems use abrasive decorticators or dehulling-type machines in which compressive and shearing forces remove the softened outer layers under controlled speed and pressure. These methods are attractive because they can improve throughput, reduce labor intensity, and offer better process hygiene than traditional hand- or foot-rubbing. However, their efficiency depends strongly on machine settings, because pepper berries are small, spherical, and mechanically fragile; excessive force may increase kernel breakage and reduce product uniformity [1]. Thermo-mechanical assistance, especially steaming prior to peeling, has been explored to further weaken the pericarp and facilitate faster decortication. Earlier work indicated that short steaming or blanching can promote skin loosening, although excessive thermal exposure may impair color and aromatic quality through volatile loss [1]. The Pepper Peel-O-Matic significantly shortens the retting/soaking phase from 14-20 days to only 6-9 days, while providing a more hygienic alternative to manual hand-rubbing or foot-shearing. Featuring a hopper with sprinklers, dual rubbing discs, and a vibration sifter, the machine can increase white-pepper production by over 50% without compromising product quality compared to commercial standards [9]. More recently, scientists showed that immersion time, steaming duration, and peeling speed significantly influence the volatile profile of white pepper, confirming that thermo-mechanical peeling can be efficient, but only when process intensity is carefully optimized to balance peeling performance with aroma retention [10].

3.3 Enzyme-assisted processing

Enzyme-assisted processing is one of the most targeted and controllable alternatives to conventional water retting because it employs defined cell-wall-degrading enzymes, particularly pectinases, to hydrolyze the pectin-rich middle lamella and selectively weaken the adhesion between the pepper pericarp and the seed [1, 11]. This selectivity is important because it facilitates pericarp removal without relying on prolonged soaking or uncontrolled spontaneous microbial activity. Compared with traditional retting, enzyme-assisted systems can be adjusted through specific operating parameters, including enzyme type, concentration, pH, temperature, and treatment duration, thereby improving process reproducibility, hygienic control, and batch-to-batch consistency in the final product [1, 11].

In Vietnam, studies using Rohapect and commercial pectinase preparations have demonstrated strong technical feasibility for white pepper production. Pericarp-removal efficiency of 99.8% was achieved using Rohapect at 1000 ppm for 108 h, and a subsequent whitening step with 300 ppm enzyme for 12 h produced more than 97% white and yellow-white kernels with a bright and attractive appearance [12]. Similarly, white pepper was successfully produced from dried black pepper berries under conditions of 1000 ppm pectinase, pH 4, 45 °C, and 108 h, followed by bleaching at 300 ppm for 20 h. After drying, the product met TCVN 7037:2002, with 12.52% moisture, 6.8% piperine, 2.15% volatile oil, only 0.24% black seeds, and no detectable coliforms, *Salmonella*, or *E. coli* [11]. These findings indicate that enzyme-assisted processing can support not only efficient pericarp separation but also acceptable physicochemical and microbiological quality in the finished product.

The integration of enzyme technology into mechanized decortication systems has further highlighted its potential for improving operational efficiency. Total processing time was reduced to five days in an enzymatic retting machine while still producing white pepper that complied with International Pepper Community quality requirements [13]. However, enzyme-assisted processing is not entirely free of trade-offs. A treatment with 500 ppm PeelZyme enabled white pepper production within five days and improved surface morphology without blanching, but piperine content decreased by 3.04% under these conditions. In contrast, hot-water blanching increased piperine content by up to 40%, although the resulting surface appearance was less desirable [14]. Overall, the available literature suggests that enzyme-assisted processing is among the more promising and controllable alternatives to conventional retting because it can improve consistency, hygiene, and product uniformity while reducing dependence on poorly controlled fermentation.

Nevertheless, its broader industrial adoption will still depend on enzyme cost, food-grade regulatory compliance, and robust process standardization across different raw materials and production scales.

3.4 Controlled microbial fermentation

Controlled microbial fermentation has emerged as a promising alternative to conventional spontaneous retting because it improves process control, shortens peeling time, and can enhance both product quality and microbial safety. Unlike traditional soaking, which depends on uncontrolled natural microbiota, this approach introduces selected functional microorganisms with strong pectinolytic and cellulolytic activities to accelerate pericarp degradation. Several studies have demonstrated the effectiveness of this strategy. Fermentation for 5 days supplemented with 25% *Acetobacter* sp. produced white pepper that satisfied Indonesian National Standard (SNI) requirements, with 3.82% piperine, 2.4% essential oil, and a total plate count of 1.25×10^2 $CFU.g^{-1}$, indicating improved chemical quality and microbiological safety [15]. Similarly, *Bacillus pumilus* was identified as an effective isolate capable of reducing retting time to 4.25 days while maintaining essential oil and oleoresin quality and reducing off-odor formation [16]. Mixed-culture systems appear even more efficient. A combination of *Aspergillus oryzae* and *Bacillus subtilis* achieved 99.34 ± 0.48% peeling within only 60 h under optimized solid-state fermentation conditions, highlighting the strong potential of microbial co-cultures for rapid white pepper processing [17]. Microbiome analysis further supports this approach, showing that mixed microbial communities are closely associated with pectin- and hemicellulose-degrading activities during fermentation [18]. Earlier large-scale work using Bacillus strains also confirmed that fermentative processing can produce white pepper with acceptable volatile oil, piperine content, low microbial contamination, and good storage stability [19]. Overall, controlled fermentation represents a biologically efficient and scalable strategy, although strain selection, inoculum balance, and process reproducibility remain critical for industrial application.

3.5 Chemical-assisted whitening, steam explosion and other emerging routes

Chemical-assisted treatment in white pepper processing is more appropriately discussed as a whitening or bleaching strategy than as a primary decortication method. In practice, chemical agents are used mainly to improve the visual appearance of white pepper after pericarp removal by increasing brightness, reducing residual dark tissues, and enhancing market acceptability. Earlier reviews noted that, after decortication, white pepper could be treated with 4% sodium hydroxide followed by boiling to obtain a whiter product, indicating that alkali-assisted whitening has long been recognized as a practical post-processing option [1]. However, such treatments also require careful washing and process control because they introduce additional chemical inputs into a food product.

Besides alkali-based whitening, more recent studies have explored oxidative or sanitation-linked whitening approaches. For example, ozonated water has been investigated as a quality-improvement step after soaking; the best reported treatment, 6 days of soaking followed by 20 min in 0.25 ppm ozonated water, produced white pepper meeting SNI standards, with improved lightness, low microbial load, and no detectable butanoic acid off-flavor [15]. In parallel, chemical washing treatments involving acidic, alkaline, and salt-based agents have also been reported to reduce aflatoxin levels in black and white pepper during processing, suggesting that chemical post-treatment may serve not only to improve color but also to support product safety when carefully controlled [20]. Nevertheless, the long-term direction of the field appears to favor milder and more consumer-acceptable whitening strategies, especially those that combine improved appearance with lower residue concerns and better environmental compatibility.

The thermomechanical action of steam explosion has proven remarkably effective in disrupting surface structures. According to researchers, applying a pressure of 0.45 MPa for a mere 120 second yields peeling results comparable to those of a conventional 7-day soaking period. This suggests that the rapid pressure release and thermal energy of the steam explosion process can bypass the lengthy diffusion times required by traditional hydration methods [21].

Table 1 Concise comparison of major white pepper processing platforms

Processing platform	**Typical time**	**Major strengths**	**Major limitations**	**References**
Conventional water retting	Long (typically several days to weeks)	Simple, low-cost, widely practiced	Slow, inconsistent, high water use, odor and wastewater issues	[1, 7]
Soaking with thermal assistance	Shorter than conventional retting	Faster peeling, improved colour development	Heat may affect aroma and pungency if not controlled	[3]

Mechanical / thermo-mechanical processing	Short to moderate	Higher throughput, better hygiene, reduced labour	Requires equipment and process optimization to avoid kernel damage or volatile loss	[9, 10]
Enzyme-assisted processing	Moderate, but more controllable	Selective pericarp removal, better reproducibility, improved hygiene and product consistency	Enzyme cost, food-grade compliance, and scale-up standardization	[11, 12, 14]
Controlled microbial fermentation	Shorter than spontaneous retting	Faster peeling, better biological control, potential quality improvement	Requires strain control, inoculum management, and reproducibility	[16, 17]
Chemical-assisted whitening	Usually a post-treatment step	Improves visual appearance and may support safety control	Residue, acceptability, and regulatory concerns	[15, 20]
Steam explosion / emerging physical methods	Very short	Rapid peeling and strong process intensification potential	Still emerging and equipment-dependent	[21]

4 Evaluation of processing methods

4.1 Quality parameters

The quality of white pepper should be assessed through an integrated set of physicochemical, microbiological, and sensory indicators rather than by appearance alone. Among the most informative parameters are lightness (L*), piperine content, essential oil retention, volatile profile, microbial load, moisture content, and the physical integrity of the pepper kernels. Recent studies confirm that processing conditions strongly influence these attributes. In a soaking-boiling system, extending soaking from 4 to 6 days improved color development and enabled the product to meet a higher quality grade; the highest reported L* value was 45.28 under 6 days of soaking combined with 15 min boiling, whereas the best overall treatment was 6 days soaking plus 5 min boiling because it provided a better balance between product grade, microbial reduction, and sensory acceptability. However, prolonged heating tended to reduce piperine and may also accelerate volatile losses [3]. Enzyme-assisted processing has shown particular promise in improving both product uniformity and safety: under optimized pectinase conditions, white pepper produced from black pepper berries reached 12.52% moisture, 6.8% piperine, 2.15% volatile oil, only 0.24% black seeds, and no detectable *Coliforms*, *Escherichia coli*, or *Salmonella*. Volatile quality is likewise method-dependent [11]. A recent study showed that mechanical peeling without steaming retained higher total volatile content than manual peeling or steaming followed by mechanical peeling, while a 15 min steaming pretreatment generated a volatile profile most comparable to manually peeled white pepper after 7-10 days of immersion. The same study identified 3-carene, D-limonene, and β-caryophyllene among the major contributors to white pepper aroma [10]. By contrast, insufficiently controlled soaking can promote off-flavor formation, including propanoic acid, butanoic acid, hexanoic acid, 4-methyl indole, and p-cresol. Overall, the best method is therefore not necessarily the whitest one, but the one that simultaneously preserves pungency and aroma, minimizes microbial contamination, and limits kernel damage and off-odor development.

4.2 Processing time and efficiency

Processing time remains one of the clearest differentiators among white pepper production methods. Conventional water retting is simple and low-tech, but it is inherently slow; in some producing regions, fresh pepper berries are still soaked under running water for approximately 12–14 days, and even in recent comparative experiments, manual peeling was evaluated after 5, 7, or 10 days of immersion before rubbing [7, 10]. Process intensification strategies have therefore focused on shortening the softening and peeling stages without sacrificing final quality. For example, combining soaking with short boiling reduced the effective retting period to 4-6 days while still delivering acceptable or superior quality depending on the treatment combination [3]. Enzyme-assisted systems also reduce process duration: a commercial pectinase protocol required 108 h for pericarp loosening plus a further 20 h bleaching step [11], whereas an integrated mechanical-enzymatic system reportedly produced acceptable white pepper in only 5 days [14]. Even more strikingly, steam explosion has recently been shown to achieve a peeling effect comparable to a 7-day soaking process in only 120 s at 0.45 MPa [21]. Collectively, these studies indicate that the major efficiency gains in modern systems arise from replacing passive microbial softening with targeted physical, enzymatic, or thermo-mechanical disruption of the pericarp. From a resource perspective, conventional retting is water-intensive because it depends on prolonged soaking, often in flowing water, whereas modern approaches reduce water residence time but may require more equipment, heat, or mechanical energy [7, 21]. Manual retting and rubbing also remain labor-intensive and difficult to standardize, while mechanical and automated systems are better suited to continuous operation and scale-up, provided that operating parameters are optimized to limit kernel breakage and preserve product quality [10, 13].

4.3 Environmental and sustainability considerations

Environmental performance is increasingly important in evaluating white pepper processing technologies. Traditional retting generates wastewater with a high organic load because compounds from the pericarp leach into the soaking medium over time. In a kinetic study, it was reported to increase sharply during soaking, reaching 2133.33-3243.33 $mg.L^{-1}$ by day 7 depending on the berry loading, while turbidity increased and both pH and dissolved oxygen declined, indicating progressive deterioration of water quality [7]. Another study further emphasized that prolonged retting can blacken the soaking water, create anaerobic conditions, and generate foul odors, and it warned that direct discharge of this wastewater into natural watercourses may contribute to environmental pollution. It also explored NaOH-modified durian husk as a low-cost adsorbent to improve soaking-water quality, illustrating that wastewater treatment and by-product valorization can be incorporated into more sustainable process design [22]. From a broader sustainability perspective, emerging physical technologies such as mechanical peeling and steam explosion are attractive because they are intended to reduce soaking time, water residence, and odor generation. Mechanical peeling has already been described as more environmentally friendly than manual peeling, while steam explosion has been proposed as an efficient and eco-friendly alternative to conventional soaking. Nevertheless, a trade-off remains: lowering water use and retting-related pollution may come at the cost of higher thermal or mechanical energy inputs. At present, pepper-specific life-cycle assessment and carbon-footprint comparisons are still limited, so the environmental superiority of one method over another is best interpreted cautiously and in relation to local water availability, effluent treatment capacity, and energy sources.

4.4 Economic feasibility

Economic feasibility depends not only on direct processing cost, but also on cycle time, labor demand, equipment investment, product quality, and compliance with export standards. Conventional retting remains attractive for smallholders because of its low capital requirement and operational simplicity; however, its long processing time, heavy dependence on water, variable product quality, and high labor input for rubbing, washing, sorting, and drying reduce overall efficiency. In contrast, enzyme-assisted methods offer a more controlled process and can produce white pepper with strong physicochemical and microbiological quality, but they introduce the recurring cost of food-grade enzymes and require tighter control of pH, temperature, and process duration. Mechanical and automated systems reduce manual labor and shorten throughput time, which improves scalability and makes them more suitable for industrial production, but they require higher upfront investment and careful control to avoid excessive kernel damage. The integrated mechanical-enzymatic machine is a useful example of this trade-off: it shortened production to 5 days and improved product quality relative to conventional retting, suggesting that capital-intensive systems may become economically attractive when labor cost, processing speed, and quality consistency are prioritized [13]. Chemical peeling methods can be rapid and technically effective, but their commercial acceptability is constrained by concerns over chemical residues and food-safety perception. Overall, the literature suggests that traditional retting is still economically viable at the household or village scale, whereas enzyme-assisted, mechanical, and hybrid systems are more promising for standardized, medium- to large-scale processing. Importantly, however, the currently available literature still provides far more quality data than rigorous techno-economic analysis; direct head-to-head cost models comparing traditional, enzyme, mechanical, and chemical routes remain scarce and should be prioritized in future studies.

5 Development of white pepper bioprocessing in Vietnam: from microbial discovery to green circular technologies

The transition from traditional white pepper production to advanced biotechnological processing represents a significant leap in spice manufacturing. Over the past decade, continuous research has systematically addressed the limitations of conventional water retting through targeted biological interventions. This section traces the evolutionary trajectory of white pepper bioprocessing, highlighting key milestones from the initial discovery of indigenous microbiota to the development of fungal bioproducts and enzymatic intensification. Ultimately, it outlines the modern paradigm shift toward green technologies and sustainable, zero-waste circular bioeconomy.

5.1 Discovery and characterization of indigenous pepper microbiota for targeted bioprocessing

The transition from empirical water retting to controlled bioprocessing necessitated a foundational understanding of the microbial resources naturally associated with the pepper plant (*Piper nigrum* L.). In Vietnam, the early research trajectory was defined by a function-oriented screening approach, aiming to identify indigenous microorganisms capable of synthesizing the specific enzymes required to breach the pepper pericarp's structural integrity. Since the outer skin of the pepper berry is a complex matrix primarily composed of cellulose and pectin, the discovery of isolates with high cellulolytic and pectinolytic activities was paramount [23, 24].

Comprehensive surveys of pepper plant materials, including roots, stems, leaves, and berries, led to the isolation of diverse microbial communities, comprising bacteria, fungi, and yeasts. Specifically, a specialized group of five fungal strains, two bacteria (notably *Bacillus amyloliquefaciens* and *Bacillus polyfermenticus*), and one yeast (*Sporobolomyces carnicolor*) was successfully identified for exhibiting potent hydrolytic potential (Pham and Le, 2010). This work was significant because it linked taxonomic identification directly to biochemical functionality, specifically the production of galacturonic acid from pectin and the clearing of cellulose in agar plate assays [23].

Building upon this, a more targeted screening of fourteen isolates cultured on rice bran was conducted to evaluate their exopectinase and exocellulase productivities [24]. This initial screening narrowed the field to four high-performing molds, *Aspergillus oryzae, Aspergillus niger, Penicillium citrinum*, and *Rhizopus oryzae*, which demonstrated clearance zones ranging from 19.2 mm to 26.5 mm. These findings were crucial as they moved the research beyond a simple microbiological survey into the realm of applied biotechnology. By identifying strains that could thrive on inexpensive agricultural substrates while producing the necessary enzymes for husk removal, these foundational studies established the biological "toolkit" for subsequent bioproduct development. Moreover, the rigorous screening for safety, ensuring the absence of mycotoxin production, confirmed that these indigenous isolates were suitable for food-grade processing, setting a standard for all later interventions in the Vietnamese pepper industry.

5.2 Development and application of fungal bioproducts for the acceleration of decortication process

With a robust library of functional microorganisms established, the research shifted toward the formulation of practical bioproducts, designated as the "Biopep" series, to address the inefficiencies of traditional 15-day water retting. This phase marked the transition from laboratory screening to process intervention, focusing on whether controlled fungal fermentation could normalize production and enhance product quality. Initial efforts concentrated on the genus *Trichoderma*, leading to the development of Biopep-2, Biopep-4, Biopep-6, and Biopep-8, derived from *Trichoderma harzianum, Trichoderma longibrachiatum, Trichoderma piluliferum*, and *Trichoderma reesei*, respectively [25].

The application of these bioproducts yielded remarkable results, reducing the decortication period to only 3 days. Biopep-2 and Biopep-6 emerged as the most effective formulations, achieving 100% skin removal with only a 25% inoculum ratio [25]. A parallel line of research explored the *Aspergillus* genus, developing bioproducts such as Biopep-21 (*A. niger*) and Biopep-22 (*A. oryzae*), which achieved similar rapid decortication while significantly improving the soluble solid content [26]. These studies consistently demonstrated that biological assistance not only accelerated the process but also improved the sensory attributes of the white pepper. Fermented products were characterized by a light ivory appearance, a more pronounced aroma, and a total absence of harmful aflatoxins, which are frequent contaminants in poorly managed traditional retting [27].

Furthermore, critical operating parameters, such as a 35% bioproduct ratio and a 54% moisture content, were identified to optimize the fermentation of black pepper into high-quality white peppercorns [27]. By replacing the uncontrolled natural microbiota of traditional ponds with targeted, high-activity fungal preparations, this stage of the research provided a scalable alternative for the industry. The Biopep series proved that biotechnological intervention could overcome the bottleneck of long processing times while simultaneously elevating the standards for hygiene and consistency in Vietnamese white pepper production.

5.3 Enzymatic treatment as a solution for piperine yield enhancement

The third stage of the research trajectory focused on intensifying the enzymatic process and elucidating the biochemical mechanisms that govern the quality of the final product, particularly regarding its pungency. While early work focused on raw bioproducts, later studies explored the synthesis of cellulase through solid-state fermentation (SSF) and the comparative efficacy of commercial enzyme preparations. Subsequent studies demonstrated that *A. oryzae* and *Pichia citrinum* could be grown on cheap, renewable agricultural wastes like rice bran and husk to produce cellulase with high activity via SSF. The application of a 2% crude enzyme extract from *A. oryzae* enabled complete peeling within 72 hours and, crucially, increased the piperine content by 26% compared to untreated controls [28].

To provide solutions for larger industrial scales, the efficacy of commercial enzymes such as Viscozyme® L and Pectinex® Ultra SP_L was also evaluated. Evaluations of these commercial preparations revealed that Viscozyme® L could achieve 100% husk removal in as little as 8.5 hours at a 2.67% concentration, outperforming Pectinex Ultra SP_L in both speed and resulting piperine concentration (5.3–5.5%). This accelerated process confirmed that targeted enzymatic hydrolysis of the pectin and cellulose links was not only faster but also more energy-efficient than traditional methods [29].

A pivotal discovery during this phase was the scientific explanation for why biological processing increases the pungency of white pepper. Mechanistic investigations explained that in traditional retting, a significant portion of the pepper's soluble solids, including piperine, remains trapped within the rigid cell wall matrix [30]. By using specific bioproducts from *Aspergillus* and *Trichoderma*, especially *T. piluliferum*, the enzymes specifically degrade the cellulose and pectin within these walls, effectively releasing the trapped piperine. This mechanism allowed for an increase in piperine extraction yield of up to 21%. This finding was transformative, as it redefined white pepper processing not just as a method of skin removal, but as a means of bio-activation that enhances the functional value and market price of the spice.

5.4 Potential integration of green biotechnology and circular bioeconomy into pepper processing in Vietnam

The modern research landscape is undergoing a critical transition toward a holistic "waste-to-value" philosophy rooted in the circular bioeconomy. For white pepper production, this paradigm shift necessitates re-evaluating the by-products of decortication, primarily the pectin- and cellulose-rich husks, not as environmental liabilities, but as renewable reservoirs of secondary metabolites. The established principles of utilizing targeted microbial bioproducts for husk removal [25, 27] provided the conceptual foundation for integrated biorefinery approaches where pericarp degradation and bioactive recovery are pursued simultaneously.

This sustainable trajectory is further supported by recent advancements in green extraction methodologies for botanical resources. The optimization of ethanol extraction parameters has been shown to significantly enhance the recovery of polyphenols and antioxidant activity in medicinal roots [31]. Similarly, the determination of ideal conditions for high-yield recovery of saponins from *Codonopsis pilosula* underscores the efficiency of targeted, eco-friendly extraction protocols [32]. These strategies, along with the methodologies used for maximizing the value of *Eurycoma longifolia*, demonstrate the robust feasibility of using non-toxic solvent systems on tough lignocellulosic biomass.

By integrating these innovations into a circular processing model, white pepper production can move toward a zero-waste framework. The combination of rapid enzymatic decortication [29] with green downstream processing offers a promising route to both produce premium white peppercorns and valorize the discarded husks. This transformation aligns with the broader vision of a circular bioeconomy, where intrinsic value and valorization coexist within the same biotechnological framework, ensuring that agricultural practices are both economically viable and environmentally harmonious.

6 Innovations and future research directions

Recent advances in white pepper processing show a clear transition from conventional soaking-based practices to more controlled and innovation-driven processing systems. Technologies such as enzyme-assisted retting, selected microbial fermentation, mechanical and thermo-mechanical peeling, and steam-based intensification have opened new possibilities for reducing processing time, improving product uniformity, and minimizing microbial and environmental problems associated with traditional retting. Despite these promising developments, many studies remain limited to laboratory-scale optimization, and direct comparisons across methods are still scarce. Future research should therefore prioritize pilot-scale validation, cultivar-specific process optimization, standardized quality metrics, sensory and volatile profiling, wastewater and energy assessment, and techno-economic analysis to support wider industrial adoption.

7 Conclusion

In conclusion, white pepper processing has progressed from traditional water retting toward a broader range of controlled processing platforms, including mechanical, thermo-mechanical, biochemical, microbial, and selected chemical-assisted approaches. Across these methods, the main technological objective remains the same: to facilitate efficient pericarp removal while preserving the physicochemical, microbiological, and sensory quality of the final product. Traditional soaking-based systems remain relevant because of their simplicity and low cost, particularly for small-scale production, but they are limited by long processing times, inconsistent quality, labor intensity, and environmental concerns associated with wastewater generation. In contrast, emerging technologies such as enzyme-assisted retting, controlled microbial fermentation, and thermo-mechanical processing offer promising routes toward faster, cleaner, and more standardized white pepper production. Nevertheless, no single method can yet be considered universally optimal, as each involves trade-offs in quality retention, operational complexity, and economic feasibility. Future progress in the field will depend on pilot-scale validation, standardized comparative assessment, and greater attention to sustainability, resource efficiency, and industry adoption. As evidenced by the research trajectory from foundational microbial discovery to advanced enzymatic intensification, the next major paradigm shift will be rooted in the circular bioeconomy. Integrating green biotechnologies to recover high-value bioactives from discarded husks will drive a "waste-to-value" approach, moving the industry beyond simple decortication. Overall, the transition toward cleaner and more efficient white pepper processing is both necessary and increasingly achievable, but further research is still needed to bridge the gap between laboratory innovation and commercial implementation.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest.

Author contributions

- Phu Hong Le: conceptualization, administrative support, critical revision
- Phuc Nguyen Thien Le: manuscript structuring, manuscript writing (original draft), revision
- Anh Ngoc Nguyen: manuscript structuring, manuscript writing (review and editing)
- Duyen Thi My Nguyen: literature collection, proofreading
- All authors read and approved the final manuscript

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