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Sustainable Extraction, Functional Valorization, And Traditional Knowledge Governance of Plant-Derived Proteins and Bioactive Compounds: An Integrative Research Review

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Abstract: Background: The contemporary search for sustainable biomaterials, functional food ingredients, health-promoting phytochemicals, and circular bioeconomy feedstocks has intensified scholarly interest in plant-derived proteins, phenolics, alkaloids, flavonoids, and other bioactive constituents. At the same time, the scientific development of extraction and optimization technologies increasingly intersects with questions of traditional knowledge, biodiversity use, intellectual property, and equitable governance.

Objective: This article develops an integrative research review of plant-based protein and bioactive compound extraction with specific emphasis on eco-innovative processing, optimization strategies, functional applications, and the governance of knowledge systems that inform resource discovery and utilization.

Methodology: A qualitative integrative review design was used to synthesize the references provided, including studies on protein extraction, green extraction methods, ultrasound-assisted recovery, supercritical and pressure-based processing, antioxidant and antimicrobial bioactivity, capsaicinoid chemistry, flavonoid characterization, microalgal and residue valorization, and legal scholarship on traditional knowledge databases and intellectual property frameworks.

Results: The reviewed literature demonstrates four converging findings. First, plant proteins and phytochemicals can be effectively recovered from diverse agricultural materials, residues, and underutilized species through tailored extraction systems optimized by pH, solvent environment, enzyme assistance, cavitation, pressure, and response surface methodology. Second, green extraction approaches improve resource efficiency and support waste-to-value pathways, especially when linked to by-product recovery, microalgal processing, and biodegradable material production. Third, the biological and functional value of extracted compounds depends not only on yield but also on structural integrity, selectivity, purity, and downstream application context. Fourth, the translation of botanical knowledge into industrial innovation raises critical governance issues concerning traditional knowledge protection, digital documentation, and intellectual property asymmetries.

Conclusion: The future of sustainable plant bioresource innovation lies in combining extraction science, functional characterization, process optimization, and fair knowledge governance. A responsible pathway requires not only efficient recovery of compounds but also legal and ethical frameworks that acknowledge the cultural and epistemic origins of bioresource use.

Keywords: Green extraction, plant proteins, bioactive compounds, traditional knowledge, process optimization, circular bioeconomy, phytochemicals.

Introduction: The growing global emphasis on sustainable food systems, circular production models, plant-based innovation, and environmentally responsible industrial development has transformed the scientific study of plant-derived materials into one of the most dynamic areas of interdisciplinary research. Proteins, phenolics, flavonoids, alkaloids, capsaicinoids, oils, and structurally functional macromolecules derived from plants are no longer examined only as nutritional or botanical curiosities. They are increasingly understood as strategic raw materials for the development of functional foods, nutraceuticals, bioplastics, feed ingredients, fat replacers, antimicrobial agents, and bio-based chemicals (Lammens et al., 2012; Molina-Alcaide et al., 2008; Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater, 2021; Plant-derived proteins as a sustainable source of bioactive peptides: Recent research updates on emerging production methods, bioactivities, and potential application, 2023). This transformation has been driven by several converging pressures, including the environmental burden of conventional extraction systems, the underutilization of agricultural residues, the rising demand for plant-based formulations, and the need to align process design with ecological and socio-legal responsibility (Conventional versus green extraction techniques: A comparative perspective, 2021; A review on the extraction and processing of natural source-derived proteins through eco-innovative approaches, 2021).

A significant portion of this scientific momentum concerns extraction itself. Extraction is not a neutral preliminary step. It is the core process through which biochemical potential is converted into usable form. What is extracted, how it is extracted, under what conditions, at what scale, with which solvents, and for what final use all shape the commercial, nutritional, structural, and ecological meaning of the resulting product. Studies on protein isolation from Mucuna bean, lentil, and tea residues, for example, show that extraction conditions directly influence the recoverability and characteristics of proteins, including purity, structure, and functionality (Adebowale et al., 2007; Jarpa-Parra et al., 2014; Cui et al., 2017). Likewise, work on capsaicinoid extraction, phenolic recovery, and flavonoid characterization demonstrates that processing choices are inseparable from bioactive preservation and downstream application value (Sumate et al., 2008; Wang et al., 2018; Zhang et al., 2005).

The scientific literature increasingly reflects a shift from extraction as mere separation toward extraction as integrated resource valorization. This shift is visible in research on enzyme-assisted techniques, ultrasound-assisted processing, supercritical or high-pressure systems, negative-pressure cavitation, and other advanced strategies that aim to improve recovery efficiency while reducing environmental cost (Nadar et al., 2018; Wen et al., 2018; De Aguiar et al., 2019). The green chemistry perspective has contributed strongly to this transition by questioning solvent intensity, energy burden, poor selectivity, and waste generation associated with traditional methods (Conventional versus green extraction techniques: A comparative perspective, 2021; Castejón et al., 2018). Eco-innovative approaches are now valued not only for operational efficiency but also for their compatibility with sustainable production and circular bioeconomy objectives (A review on the extraction and processing of natural source-derived proteins through eco-innovative approaches, 2021).

Yet extraction science alone does not fully explain the contemporary relevance of plant-derived biomaterials. What gives urgency to this field is the possibility of turning underused biomass and plant knowledge into industrial, nutritional, medicinal, and environmental solutions. The literature on olive by-products, tea residues, microalgae-associated feedstocks, and structured emulsion gels from biological residues illustrates that materials once treated as waste or low-value side streams can be redesigned into meaningful components of advanced product systems (Molina-Alcaide et al., 2008; Cui et al., 2017; Construction of 3D printable Pickering emulsion gels using complexes of fiber polysaccharide-protein extracted from Haematococcus pluvialis residues and gelatin for fat replacer, 2023; Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater, 2021). This is a conceptual transformation as much as a technical one. It recasts biological leftovers as sources of recoverable structure, chemistry, and function.

A related development is the increasing attention paid to bioactivity. Bioactive compounds are studied not simply because they can be isolated, but because they may contribute antioxidant, antimicrobial, metabolic, or therapeutic properties relevant to food, pharmaceutical, and health applications. The phytochemical and antioxidant profiles of Adinandra tea varieties, the characterization of flavonoid extracts from Adinandra nitida, the molecular implications of apigenin, and the antimicrobial or biological activity associated with nicotine-related plant constituents all contribute to a growing recognition that plant molecules can carry highly differentiated biofunctional value (Chen et al., 2015; Liu et al., 2008; Mariappan et al., 2012; Zhong et al., 2010; Charles et al., 2000; Moldoveanu et al., 2016). However, the mere presence of a compound does not automatically translate into useful biological action. Extraction conditions, structural preservation, matrix effects, dosage context, and purity all influence functionality.

At the same time, the biological resource base that supports such innovation is deeply entangled with traditional knowledge. Many plants and natural materials enter scientific and commercial attention not solely through laboratory discovery, but through long-standing cultural, medicinal, agricultural, or community-based knowledge systems. India's Traditional Knowledge Digital Library and associated debates on knowledge governance, bibliometrics, legal plurality, and intellectual property illustrate that the extraction and commercialization of plant-based value cannot be separated from questions of epistemic justice and legal design (Gupta, 2011; Suwapan, 2016; Anand et al., 2015; Reddy & Chandrashekaran, 2017; Sattigeri, 2025; TKDL, 2026). Traditional knowledge is not a passive background to modern science. It often acts as an interpretive resource, a data source, a historical archive of use practices, and a contested terrain of ownership and benefit-sharing.

This is particularly important because plant-derived innovation can easily be narrated in purely technical terms, thereby obscuring the social and political histories behind resource identification and application. Mashelkar (2001) raised important concerns about intellectual property and the global inequalities embedded in innovation systems. Gupta (2011) similarly emphasized the need to protect India's traditional knowledge in the face of appropriation. Randeria (2003) further complicates the picture by showing how legal plurality and international institutional structures affect local communities and common property rights. When these works are read together, they suggest that sustainable extraction cannot be fully sustainable if it ignores knowledge provenance and governance.

The present article is motivated by a gap in the literature. Many studies address extraction optimization, specific compound characterization, green technology, or traditional knowledge governance separately. However, fewer integrative accounts examine how these domains relate to one another within a coherent framework of sustainable plant bioresource innovation. On one side, extraction science often focuses on yield, selectivity, process conditions, and functional quality. On the other side, traditional knowledge scholarship emphasizes documentation, protection, data intermediaries, and intellectual property dilemmas. The two conversations are rarely brought together, despite the fact that both concern the translation of biological and epistemic resources into socially valuable outputs.

Accordingly, this article develops a comprehensive integrative review based strictly on the provided references. Its purpose is to synthesize how the literature collectively explains the recovery, optimization, functional potential, sustainability dimensions, and governance implications of plant-derived proteins and bioactive compounds. Rather than treating these topics as disconnected, the article interprets them as mutually informing aspects of one larger transformation: the movement from raw botanical or residue-based matter toward value-added systems under conditions of ecological constraint and legal complexity.

The article is guided by four core questions. First, what extraction and optimization principles recur across the literature on proteins, phenolics, capsaicinoids, and related plant biomolecules? Second, how do green and advanced extraction methods reshape the efficiency and sustainability profile of plant-based resource recovery? Third, how does functional value emerge from the interaction of compound identity, extraction design, and end-use purpose? Fourth, what role does traditional knowledge governance play in shaping the legitimacy and ethics of plant-derived innovation?

The significance of the study is both theoretical and practical. Theoretically, it contributes to a more unified understanding of bioresource science by linking process engineering, functional chemistry, and knowledge governance. Practically, it offers a framework useful to food scientists, natural product researchers, sustainability scholars, and policymakers interested in responsible biovalue creation. Its central argument is that the future of plant-based extraction science lies not merely in higher efficiency or cleaner solvents, but in the coordinated integration of process optimization, residue valorization, functionality preservation, and equitable knowledge stewardship.

METHODOLOGY

This study uses a qualitative integrative review methodology. The chosen design is appropriate because the source material is heterogeneous in nature and includes experimental studies, optimization-oriented process research, review articles, legal and policy analyses, and governance-focused conceptual work. A strictly quantitative synthesis would not suit such a corpus because the references differ not only in subject matter but also in research aim, evidence form, and disciplinary orientation. The objective of the present study is not to statistically aggregate comparable outcomes, but to develop an analytically coherent interpretation of how the literature collectively describes sustainable extraction, functional utilization, and governance of plant-derived proteins and bioactive compounds.

The review corpus consisted exclusively of the references supplied by the user. No external references were introduced. This is methodologically significant because it ensures that the article remains grounded in the designated literature base and does not import outside assumptions or findings. The provided sources were treated as the complete interpretive universe for the analysis.

For analytic purposes, the references were grouped into five broad clusters. The first cluster comprised studies on plant protein extraction and characterization, including work on Mucuna bean, lentil, tea residues, and general eco-innovative protein processing (Adebowale et al., 2007; Jarpa-Parra et al., 2014; Cui et al., 2017; Plant-derived proteins as a sustainable source of bioactive peptides: Recent research updates on emerging production methods, bioactivities, and potential application, 2023; A review on the extraction and processing of natural source-derived proteins through eco-innovative approaches, 2021). The second cluster included research on green, ultrasound-assisted, enzyme-assisted, supercritical, and cavitation-based extraction technologies and optimization models (Bezerra et al., 2008; Nadar et al., 2018; Sumate et al., 2008; Wen et al., 2018; Castejón et al., 2018; De Aguiar et al., 2019; Wang et al., 2018). The third cluster involved phytochemical, flavonoid, alkaloid, and capsaicinoid characterization studies relevant to bioactivity and functionality (Chen et al., 2015; Wang et al., 2003; Zhang et al., 2005; Liu et al., 2008; Garcés-Claver & Barbero, 2019; Tripodi et al., 2018; Mariappan et al., 2012; Zhong et al., 2010; Charles et al., 2000; Moldoveanu et al., 2016; Koppad & Shivanna, 2010). The fourth cluster focused on residue valorization, circular applications, and alternative end uses such as feed, fat replacers, and bioplastics (Lammens et al., 2012; Molina-Alcaide et al., 2008; Construction of 3D printable Pickering emulsion gels using complexes of fiber polysaccharide-protein extracted from Haematococcus pluvialis residues and gelatin for fat replacer, 2023; Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater, 2021). The fifth cluster contained legal, bibliometric, and policy-oriented scholarship on traditional knowledge, digital documentation, and intellectual property governance (Mashelkar, 2001; Randeria, 2003; Gupta, 2011; Anand et al., 2015; Suwapan, 2016; Reddy & Chandrashekaran, 2017; Sattigeri, 2025; TKDL, 2026).

The analytic process unfolded in four stages. In the first stage, all references were read closely and coded according to their primary thematic emphasis. Codes included extraction mechanism, optimization variable, green processing, structural functionality, antioxidant activity, antimicrobial or biological effect, residue valorization, bio-based application, traditional knowledge protection, intellectual property, and governance infrastructure. In the second stage, cross-text comparisons were conducted to identify recurring relationships. For example, studies emphasizing pH, solvent selection, or pressure conditions were compared with works on green extraction to determine whether sustainability and efficiency were being pursued as complementary or competing aims. Similarly, references on traditional knowledge governance were compared with plant resource valorization studies to assess how scientific innovation intersects with legal and epistemic concerns.

In the third stage, thematic synthesis was developed through the construction of higher-order interpretive propositions. Rather than reviewing each study in isolation, the article sought to explain what the literature collectively reveals about major structural dynamics in the field. This process produced four central themes: the conditional nature of extraction efficiency; the transition from conventional recovery to eco-innovative valorization; the dependence of functional performance on extraction logic and structural preservation; and the necessity of governance frameworks for ethically legitimate plant-based innovation.

In the fourth stage, these themes were translated into a narrative structure aligned with the requested article format: introduction, methodology, results, discussion, conclusion, and references. Throughout the writing process, every major interpretive claim was grounded in one or more of the supplied sources using author-year citation style.

The method is interpretive and explanatory rather than experimental. It does not generate new primary data, nor does it attempt to rank studies by a fixed quality scale, because the literature includes both empirical process studies and normative legal analyses. Instead, the contribution lies in synthesizing how different types of knowledge together illuminate the contemporary field of sustainable plant extraction and valorization. This is particularly important because scientific innovation in natural products and plant biomaterials does not occur solely at the laboratory bench. It also unfolds through legal institutions, knowledge systems, market logics, and sustainability discourses.

The methodology has several strengths. It accommodates disciplinary diversity, preserves contextual nuance, and allows the development of a multi-layered conceptual account. It also supports a form of scholarship that is especially useful where technical and governance questions intersect. At the same time, it has limits. Because the review is restricted to the supplied references, it does not represent the totality of global literature on plant bioactives, green extraction, or traditional knowledge policy. Some sources are review-based or broad in scope, while others focus narrowly on a single compound or process. As a result, the conclusions should be read as integrative interpretations rather than universal empirical generalizations.

Despite these limitations, the methodology is well suited to the present objective. The literature provided is sufficiently rich to support a detailed and conceptually coherent account of how extraction science, functional biomolecule recovery, circular bioeconomy strategies, and traditional knowledge governance are becoming increasingly interconnected.

RESULTS

The integrative analysis yielded four major findings. These findings emerged from repeated thematic comparison across the literature and reflect the most consistent patterns in the supplied references.

Extraction efficiency is conditional, multi-variable, and inseparable from material context

The first major finding is that extraction efficiency cannot be understood as a single, universal property of a technique. It is highly conditional upon the biological material, the target compound, the physical and chemical environment, and the desired downstream functionality. The literature repeatedly shows that successful recovery depends on tuning process conditions to the structural characteristics of the raw material and the sensitivity of the compounds being extracted.

Work on plant proteins provides a clear illustration. Adebowale et al. (2007), in examining proteins from Mucuna bean, show that isolation and fractionation are not generic operations but depend on understanding the compositional and functional profile of the source matrix. Likewise, Jarpa-Parra et al. (2014) demonstrate that optimization of lentil protein extraction is strongly influenced by process pH, and that pH does not affect yield alone. It also shapes protein structure and functionality. This is a crucial point because extraction is often judged narrowly through recovery percentage, yet a protein extracted under aggressive or poorly calibrated conditions may lose valuable structural qualities relevant to emulsification, gelation, digestibility, or ingredient performance.

Cui et al. (2017), studying protein extraction and decoloration from tea residues, further reinforce the argument that extraction is a balance among recovery, purity, and usability. Tea residues may contain valuable proteins, but the practical usefulness of those proteins depends on dealing with associated pigments and matrix components that affect appearance, consumer acceptability, and downstream formulation. Thus, the extraction problem is rarely just about removing a target molecule. It is about producing a functional ingredient from a complex biological system.

Optimization literature supports this conditional view. Bezerra et al. (2008) discuss response surface methodology as a tool for optimization in analytical chemistry, and the conceptual relevance of this work extends well beyond laboratory analytics. It formalizes the idea that multiple variables interact nonlinearly and must be evaluated together rather than one at a time. In the context of plant extraction, this is especially important because solvent concentration, temperature, time, pressure, pH, solid-to-liquid ratio, and energy input can reinforce or counteract each other. The literature suggests that efficient extraction is best achieved not by adopting fashionable technologies in the abstract, but by methodically matching process design to material properties and intended uses.

Studies on capsaicinoids and phenolics confirm the same principle. Sumate et al. (2008) show that ultrasound-assisted extraction of capsaicinoids from Capsicum frutescens can be performed across laboratory and pilot scales, implying that process intensity and scale-up considerations are central to practical recovery. De Aguiar et al. (2019) use sequential high-pressure extraction to obtain capsinoids and phenolic compounds from biquinho pepper, demonstrating that multiple target compounds may require staged or selective processing rather than a one-step approach. Wang et al. (2018) employ ultrasound-negative pressure cavitation for phenolic extraction from blueberry leaves, again highlighting that specific compound classes respond differently to extraction environments.

The broader lesson is that extraction science is fundamentally relational. There is no universally superior technique detached from context. Ultrasound may be advantageous in one matrix, but less suitable in another. Pressure-based systems may improve selectivity for some compounds while complicating costs or stability for others. Enzyme-assisted extraction may enhance release from cell walls, but its success depends on substrate compatibility and process conditions (Nadar et al., 2018). This makes the field intellectually demanding, because it requires detailed knowledge of plant matrix architecture, compound chemistry, and application goals.

A related observation concerns variability within botanical materials themselves. Tripodi et al. (2018) show that genetic and environmental factors influence yield performance and bioactive compound content of hot pepper varieties. Garcés-Claver and Barbero (2019) similarly report progression in total and individual capsaicinoids across Capsicum chinense cultivars. These findings mean that extraction efficiency is not shaped only by technology. It is also shaped by biological variability in the feedstock. The same processing method may yield different outcomes depending on cultivar, maturity stage, growth conditions, or post-harvest treatment. In practical terms, sustainable valorization requires not just better extraction tools but better integration between agricultural variation and process design.

The literature therefore rejects simplistic process determinism. Extraction is not merely a matter of choosing the newest or greenest technology. It is a matter of aligning technique, material, chemical target, and product purpose. This finding has broad implications for scale-up, industrial design, and sustainability assessment because it shows that efficiency is inherently contextual rather than absolute.

The field is shifting from conventional extraction toward eco-innovative and circular valorization models

The second major finding is that extraction research is increasingly embedded in a larger sustainability transition. The literature reflects a move away from purely conventional solvent-intensive approaches toward green, low-waste, residue-aware, and circular valorization strategies.

This transition is explicit in comparative and review-oriented literature. Conventional versus green extraction techniques: A comparative perspective (2021) frames the distinction not as a superficial technical preference but as a major reorientation in process philosophy. Green extraction is valued for reducing hazardous solvent use, improving environmental compatibility, and supporting safer and more sustainable product systems. A review on the extraction and processing of natural source-derived proteins through eco-innovative approaches (2021) extends this logic specifically to proteins, suggesting that the future of protein recovery lies in methods that reconcile efficiency with ecological responsibility.

Nadar et al. (2018) describe enzyme-assisted extraction as a novel extraction technology, and this is significant because enzyme-based systems represent a broader shift from brute-force separation toward biologically informed processing. Rather than relying only on harsh solvents or energy-intensive conditions, enzyme-assisted systems may use catalytic specificity to open structural barriers and release target compounds more selectively. Wen et al. (2018) document advances in ultrasound-assisted extraction of bioactive compounds from cash crops, illustrating how acoustic energy can enhance mass transfer and reduce time or solvent demand. Castejón et al. (2018) similarly discuss alternative oil extraction methods using advanced techniques and green solvents. Together these sources indicate that green extraction is not a single method but an evolving family of approaches oriented toward reduced environmental cost and improved process intelligence.

Importantly, the sustainability transition is not limited to cleaner extraction chemistry. It also includes a revaluation of feedstock choice. Materials historically treated as waste or by-products are increasingly positioned as valuable resource streams. Cui et al. (2017) study tea residues, Construction of 3D printable Pickering emulsion gels using complexes of fiber polysaccharide-protein extracted from Haematococcus pluvialis residues and gelatin for fat replacer (2023) investigates residue-derived structuring systems, and Molina-Alcaide et al. (2008) review potential use of olive by-products in ruminant feeding. These works collectively suggest that the sustainable future of extraction is linked to waste minimization not only at the process level but also at the resource level. Recovery from residues reduces disposal burdens, increases total biomass utilization, and opens new pathways for circularity.

Lammens et al. (2012) extend this idea by discussing protein-derived amino acids as feedstock for bio-based chemicals. This is conceptually important because it locates plant and protein resources within a broader industrial metabolism. Proteins are not only nutrients. They can also be precursors in bio-based chemical systems. The circular economy implication is substantial: biomass can be fractionated into multiple value streams, each with distinct functional or industrial relevance.

The microalgal literature contributes another angle. Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater (2021) presents a model in which renewable biological systems, waste streams, and material innovation are linked. Although this source is not restricted to plant extraction in the narrow sense, it aligns closely with the wider logic of eco-valorization. It shows that sustainable production increasingly depends on integrating feedstock recovery, waste reuse, and functional material creation rather than treating each as a separate domain.

A crucial implication of this transition is that extraction is becoming part of systems thinking. The target is no longer simply higher yield per batch. It is value maximization across resource chains with lower ecological burden. This includes considering energy input, solvent recovery, co-product generation, residue reintegration, and product end use. The shift also changes how scientific success should be evaluated. A method that produces slightly lower yield but significantly better environmental compatibility, lower toxicity, or better residue utilization may be more valuable in real-world terms than a method optimized only for immediate recovery percentage.

The literature also indicates that green extraction is not ideologically opposed to performance. Rather, many advanced methods promise improvements in both sustainability and selectivity. However, this should not lead to an uncritical assumption that all green methods are automatically superior. The reviewed sources suggest a more nuanced conclusion: eco-innovation is most meaningful when its environmental advantages are matched by realistic technical performance and application relevance (Castejón et al., 2018; Wen et al., 2018; Nadar et al., 2018). The field is therefore moving toward a model of justified sustainability, where environmental claims must be supported by process functionality.

Functional and biological value depend on preservation, selectivity, and application-oriented design

The third major finding is that the value of extracted plant compounds lies not merely in their successful isolation but in how well their functional, structural, or biological properties are preserved and directed toward specific uses. Yield without functional integrity can be scientifically impressive yet commercially or nutritionally limited.

This principle is especially visible in protein studies. Jarpa-Parra et al. (2014) explicitly show that process pH influences protein structure and functionality during lentil protein extraction. This is a critical result because it demonstrates that extraction is always a form of transformation. The resulting ingredient is not identical to the original matrix-bound protein; it has been modified by the extraction environment. Therefore, process selection must be guided by the intended role of the protein. A protein for beverage stabilization, gel formation, emulsification, peptide release, or textural engineering may require different preservation priorities.

The literature on plant-derived proteins as sources of bioactive peptides broadens this insight by indicating that proteins can be valued not only as intact macromolecules but as precursors to bioactive sequences released through subsequent processing or digestion (Plant-derived proteins as a sustainable source of bioactive peptides: Recent research updates on emerging production methods, bioactivities, and potential application, 2023). This complicates the meaning of functionality. A protein ingredient may be evaluated for techno-functional properties, nutritional quality, and latent bioactive potential all at once. Eco-innovative extraction therefore has to consider multiple value dimensions simultaneously.

Studies on phytochemicals and flavonoids reinforce the same theme. Chen et al. (2015) demonstrate differences in phytochemical profiles and antioxidant activity among Adinandra tea varieties, suggesting that compositional richness and functional activity are tightly linked. Liu et al. (2008) characterize flavonoid extracts from Adinandra nitida and examine antioxidant activity, showing that extraction is closely related to biologically relevant capacity. Wang et al. (2003) and Zhang et al. (2005) deepen the chemical understanding of Adinandra nitida through compositional and analytical work, illustrating that meaningful functionality depends on precise identification and quantification.

The case of apigenin is also revealing. Mariappan et al. (2012) investigate the spectroscopic properties of apigenin, while Zhong et al. (2010) examine its molecular targets in colorectal cancer cells. Together, these sources show that compound characterization and bioactivity research are inseparable. A molecule becomes application-relevant when its structure, stability, and biological pathways are sufficiently understood. This is an important reminder that extraction alone does not produce therapeutic or nutraceutical value. It produces a candidate material whose relevance depends on rigorous downstream characterization.

Nicotine-related studies complicate the picture further. Charles et al. (2000) report antimicrobial activity of nicotine against bacterial and fungal pathogens. Moldoveanu et al. (2016) examine nicotine in non-tobacco plant materials, and Koppad and Shivanna (2010) report biological effects of nicotine on Drosophila melanogaster. Giovino et al. (2012), through tobacco control context, remind us that compound functionality is not equivalent to desirability. A bioactive molecule may exhibit interesting laboratory properties while remaining problematic or hazardous in public health terms. This means that functional value must always be interpreted in context. Not every extractable and active compound is suitable for beneficial application, and scientific enthusiasm must be balanced by toxicological and societal considerations.

The literature on capsaicinoids offers another nuanced example. Capsaicinoids are desirable in food, sensory science, and possibly specialty bioactive applications, but their value depends on controlled concentration, cultivar choice, extraction selectivity, and intended end use (Sumate et al., 2008; Tripodi et al., 2018; Garcés-Claver & Barbero, 2019; De Aguiar et al., 2019). In some cases, preserving pungency-related compounds is desirable; in others, selective recovery or controlled fractionation may be necessary.

Similarly, Construction of 3D printable Pickering emulsion gels using complexes of fiber polysaccharide-protein extracted from Haematococcus pluvialis residues and gelatin for fat replacer (2023) illustrates that functionality can be structural rather than biochemical in a narrow sense. Here, extracted biological materials contribute to texture engineering and fat replacement. This broadens the concept of plant or residue valorization. Extracted compounds are not only nutritionally active or chemically interesting; they can be architecturally useful in designing next-generation food systems.

The cumulative implication is that extraction science must be application-aware from the beginning. The same raw material may yield different valuable outputs depending on whether the target is antioxidant formulation, protein fortification, peptide generation, emulsification, feed use, bioplastic feedstock, or legal-commercial documentation of a traditionally known material. Functional value is therefore not an inherent essence waiting to be uncovered. It is a relational property emerging from the interaction of source, method, purity, structure, and purpose.

Scientific valorization of plant resources is inseparable from traditional knowledge governance and intellectual property debates

The fourth major finding is that plant-based extraction and innovation cannot be responsibly discussed only in biochemical or engineering terms. The literature on traditional knowledge, intellectual property, and legal governance shows that the identification, documentation, and commercialization of biological resources often involve knowledge systems with historical, cultural, and political significance.

Gupta (2011) emphasizes the importance of protecting India's traditional knowledge, highlighting the vulnerability of community-rooted knowledge to misappropriation. Mashelkar (2001) similarly situates intellectual property within third world concerns, implying that innovation systems are shaped by global inequalities in legal capacity and recognition. These works are highly relevant to plant extraction science because many natural materials become subjects of commercial and scientific value precisely because of long-term human experience with them.

Anand et al. (2015), through bibliometric and thematic analysis of traditional knowledge research in India, demonstrate that traditional knowledge has itself become a structured field of inquiry. This indicates that the governance of such knowledge is not merely reactive; it is now part of formal academic and policy discourse. Suwapan (2016) discusses the Traditional Knowledge Digital Library as a model from which broader lessons may be learned. TKDL (2026) provides institutional context. Together these sources suggest that digital documentation can function as a defensive and strategic tool, helping establish prior art, prevent illegitimate patenting, and create more visible records of culturally embedded knowledge.

Sattigeri (2025) adds a contemporary layer by describing traditional knowledge databases as data intermediaries in relation to emerging data governance principles. This is a significant conceptual development. It means traditional knowledge protection is no longer only a matter of archiving the past. It is also about how knowledge is structured, mediated, and governed in digital environments shaped by new data logics. In the context of plant bioresource innovation, this has profound implications. Databases can influence which knowledge becomes visible, how it is interpreted, who can claim novelty, and how evidence is mobilized in intellectual property disputes.

Reddy and Chandrashekaran (2017) frame India's intellectual property dilemmas in terms of creation, copying, and disruption, which is highly relevant to plant-derived innovation. The dilemma is not simply whether to patent or not patent. It concerns how to reconcile innovation incentives with historical knowledge circulation, collective epistemic rights, and equitable access. Randeria (2003) complicates this further by highlighting legal plurality, rights of local communities, and the role of international institutions. This suggests that plant extraction cannot be understood as a purely technical or national issue. It unfolds across layered legal orders involving local use, national regulation, international law, and commercial regimes.

The significance of these governance sources for extraction science is sometimes underestimated. Yet they address a foundational question: from where does scientific value originate? Laboratory optimization may transform a material into a high-value ingredient, but the initial recognition of that material's relevance may derive from long-standing traditional use, agrarian familiarity, or community practice. If this epistemic genealogy is erased, then sustainability becomes incomplete. A process may be green in solvent terms while remaining extractive in legal and cultural terms.

This finding supports a broader understanding of responsible innovation. Responsible plant valorization should involve not only environmentally sound extraction and efficient recovery, but also transparent acknowledgment of knowledge origins, careful treatment of traditional data, and governance frameworks that resist biopiracy or one-sided appropriation. The literature does not provide a single universal solution, but it clearly indicates that digital libraries, legal protection mechanisms, and intellectual property reform are central to the future of plant-based science in culturally diverse contexts (Gupta, 2011; Suwapan, 2016; Sattigeri, 2025).

Taken together, the results show that sustainable extraction is not only a technical challenge. It is an integrated scientific, industrial, environmental, and governance problem. Extraction efficiency depends on material context. Green methods are reshaping process logic. Functional value is determined by application-aware preservation and characterization. Traditional knowledge governance shapes the legitimacy of scientific and commercial use. These findings provide the basis for a deeper discussion of what responsible plant bioresource innovation should look like in theory and practice.

DISCUSSION

The findings of this review reveal that the contemporary science of plant-derived proteins and bioactive compounds has entered a new phase in which extraction can no longer be treated as a narrow laboratory technique. It has become a strategic point of convergence among process engineering, food science, bioactive compound research, sustainability transitions, circular economy design, and knowledge governance. This broader view is necessary because the value generated through plant extraction is never produced by chemistry alone. It is co-produced by material selection, optimization logic, environmental priorities, downstream application, and legal-ethical context.

The first major interpretive implication concerns the meaning of efficiency. Traditionally, extraction efficiency has often been evaluated in terms of yield and purity. While those remain important, the literature reviewed here strongly suggests that a modern understanding of efficiency must be more layered. A process may recover a large fraction of target molecules, yet still be suboptimal if it damages protein structure, degrades bioactive compounds, requires environmentally harmful solvents, generates excessive waste, or fails to preserve application-relevant functionality (Jarpa-Parra et al., 2014; Conventional versus green extraction techniques: A comparative perspective, 2021). Thus, efficiency should be reconceptualized as a composite criterion that includes recovery, selectivity, structural preservation, environmental performance, and suitability for downstream use.

This broader view is especially important for proteins. Protein extraction is not analogous to the isolation of inert matter. Proteins are conformationally sensitive, functionally diverse macromolecules whose technological and nutritional value can shift dramatically under different processing conditions. The literature on lentil, Mucuna bean, and residue-derived proteins indicates that the extraction step often determines whether a recovered protein becomes practically valuable as a food ingredient, peptide source, or structuring agent (Adebowale et al., 2007; Jarpa-Parra et al., 2014; Cui et al., 2017). Consequently, future research should resist crude comparisons based solely on extraction percentage and instead evaluate the integrity and performance of recovered proteins in their intended applications.

A second major implication concerns the relationship between green extraction and industrial realism. The literature supports a strong movement toward eco-innovative technologies such as ultrasound, enzyme assistance, pressure-based systems, and green solvents (Nadar et al., 2018; Wen et al., 2018; Castejón et al., 2018; De Aguiar et al., 2019). However, the enthusiasm surrounding green extraction should not obscure a practical tension. A method is not necessarily valuable simply because it is environmentally attractive in principle. It must also be scalable, reproducible, economically viable, and appropriate for the target matrix. The ideal scientific contribution therefore lies not in rhetorical celebration of green techniques, but in demonstrating where and why they outperform conventional systems under realistic operating conditions.

This point has particular importance in fields where sustainability language is widely invoked. Green extraction risks becoming a branding concept if not anchored in specific material and process evidence. The reviewed literature, fortunately, tends to avoid this simplification. It shows that eco-innovation must be justified through performance in context. Ultrasound, cavitation, or enzyme-assisted systems matter because they may improve mass transfer, reduce solvent dependence, or enhance release from plant matrices. Their value is empirical, not merely aspirational (Sumate et al., 2008; Wang et al., 2018; Nadar et al., 2018). This suggests a mature pathway for the field: move beyond binary opposition between conventional and green, and instead develop nuanced assessments of process sustainability under actual use conditions.

The third major issue is valorization. The literature repeatedly points toward the transformation of residues and underutilized biomass into high-value outputs. This includes tea residues, olive by-products, microalgal residues, and protein-derived intermediates for chemical production (Molina-Alcaide et al., 2008; Cui et al., 2017; Lammens et al., 2012; Construction of 3D printable Pickering emulsion gels using complexes of fiber polysaccharide-protein extracted from Haematococcus pluvialis residues and gelatin for fat replacer, 2023). The importance of this trend cannot be overstated. It reframes sustainability from damage reduction toward positive redesign. Instead of merely making extraction less harmful, researchers are asking how extraction can help redesign biological waste streams into ingredient systems, functional materials, and industrial feedstocks.

This circular perspective is among the most promising developments in the field. It aligns resource efficiency with innovation rather than treating sustainability as a regulatory burden. At the same time, it raises new scientific questions. Residues often have variable composition, complex impurity profiles, and challenging processing characteristics. Therefore, valorization science must address heterogeneity, safety, consistency, and market acceptability. A residue may be chemically rich yet technologically difficult. The future success of circular bioresource systems will depend on how effectively research can move from proof-of-concept extraction toward stable value chains.

The discussion of bioactivity introduces an additional layer of complexity. There is a tendency in plant science and functional ingredient research to move quickly from detection to desirability. Once antioxidant, antimicrobial, or biologically active properties are observed, a compound may be framed as inherently beneficial. The reviewed literature invites a more careful stance. Flavonoids, phenolics, capsaicinoids, and related compounds indeed show promising properties, but their functional meaning is context-dependent and frequently mediated by concentration, bioavailability, formulation, and broader health considerations (Chen et al., 2015; Liu et al., 2008; Zhong et al., 2010). In the case of nicotine, the complexity is even clearer. A compound may show antimicrobial or other biologically interesting effects, yet remain embedded in public health concerns that limit positive application narratives (Charles et al., 2000; Giovino et al., 2012; Moldoveanu et al., 2016). Therefore, future work in this field must distinguish between measurable bioactivity and socially desirable functionality.

Another important interpretive issue is the role of analytical precision. Studies on Adinandra nitida, capsaicinoids, and spectral characterization demonstrate that meaningful valorization depends on detailed chemical knowledge (Wang et al., 2003; Zhang et al., 2005; Mariappan et al., 2012; Garcés-Claver & Barbero, 2019). This suggests that extraction research should not become overly process-centric. Process design and compound identification must develop together. A high-performing extraction system is of limited value if the resulting extract is not adequately characterized, standardized, and linked to specific functional claims. In practical terms, the field needs stronger bridges between separation science, analytical chemistry, formulation science, and biological validation.

The most distinctive contribution of this review lies in its integration of technical and governance dimensions. Traditional knowledge scholarship is often treated as peripheral to laboratory-based extraction science, but the literature provided here makes clear that this separation is analytically inadequate. The scientific discovery and industrial use of plant resources frequently rely, directly or indirectly, on historical bodies of knowledge concerning medicinal, nutritional, agricultural, or ritual use. The Traditional Knowledge Digital Library and related scholarship demonstrate that knowledge protection has become a formal institutional response to this reality (Gupta, 2011; Suwapan, 2016; TKDL, 2026). Sattigeri (2025) advances the conversation by framing traditional knowledge databases as data intermediaries, suggesting that governance questions now extend into digital infrastructures and data politics.

This has major implications for how the field defines sustainability. Environmental sustainability alone is insufficient if the system remains unjust in epistemic or legal terms. A plant-derived product may be extracted through a green process and marketed as eco-friendly, yet still rest on unacknowledged or inequitably appropriated traditional knowledge. Therefore, sustainability should be broadened to include procedural fairness, recognition of knowledge provenance, and mechanisms for protective documentation or benefit-sharing. The literature does not resolve all tensions in this area, but it strongly suggests that plant innovation cannot be responsibly detached from intellectual property debates and community rights (Mashelkar, 2001; Reddy & Chandrashekaran, 2017; Randeria, 2003).

There is also a methodological implication for future interdisciplinary research. Scientists working on plant extraction and valorization often operate within frameworks dominated by chemistry, process engineering, and food functionality. Legal scholars of traditional knowledge, by contrast, often focus on institutions, patents, databases, and governance mechanisms. The present review indicates that these domains should be brought into closer conversation. Technical innovation changes the stakes of governance, while governance structures influence the legitimacy and accessibility of innovation. Interdisciplinary collaboration would therefore strengthen the field by enabling more complete assessments of value creation.

The review also exposes several limitations in the current literature base. First, many extraction studies focus on a single raw material or compound class, which is necessary for rigor but can limit the comparability of broader conclusions. Second, some references emphasize promising extraction technologies without fully engaging with long-term industrial adoption barriers such as cost, maintenance, regulatory acceptance, or supply chain variability. Third, the literature on traditional knowledge protection is conceptually rich but does not always map clearly onto specific extraction case studies. This means that the governance connection, while analytically persuasive, still requires more directly integrated empirical research.

Future studies would benefit from multi-criteria designs that evaluate extraction systems simultaneously for yield, structural integrity, environmental burden, scale-up viability, and end-use performance. Research on plant proteins should more consistently connect extraction conditions with functional and nutritional outcomes in real formulations. Bioactivity studies should pay greater attention to translation pathways, distinguishing in vitro promise from realistic application. Circular valorization work should examine residue consistency, safety, and market feasibility over time. Finally, governance research should develop more case-linked models showing how traditional knowledge documentation interacts with commercial development of plant-derived products.

Despite these limitations, the overall message of the literature is clear. The field is moving toward a model of plant bioresource science that is more selective, more sustainable, more circular, and more attentive to the socio-legal conditions of innovation. This is a positive development, but it also imposes a higher standard on researchers and institutions. It is no longer enough to extract a compound effectively. One must also ask whether the method is responsible, whether the compound remains functional, whether the biomass is being fully valorized, and whether the knowledge ecology surrounding the resource has been treated fairly.

CONCLUSION

The integrative review presented in this article demonstrates that the science of plant-derived proteins and bioactive compounds is undergoing an important conceptual and practical transformation. Extraction is no longer best understood as a preliminary technical step aimed only at maximizing recovery. Instead, it has become a central site where sustainability, selectivity, structural preservation, product functionality, waste valorization, and knowledge governance intersect. Across the reviewed literature, the same broad insight repeatedly emerges: plant resources are valuable not merely because they contain useful molecules, but because carefully designed extraction and processing systems can convert those molecules into socially relevant, industrially meaningful, and biologically functional forms (Adebowale et al., 2007; Jarpa-Parra et al., 2014; Nadar et al., 2018; Plant-derived proteins as a sustainable source of bioactive peptides: Recent research updates on emerging production methods, bioactivities, and potential application, 2023).

The first core conclusion is that extraction efficiency is conditional rather than universal. The success of a method depends on source material, target compound, optimization variables, and intended application. Proteins, capsaicinoids, phenolics, flavonoids, and structurally functional residues each demand context-specific process design (Bezerra et al., 2008; Sumate et al., 2008; Wang et al., 2018; De Aguiar et al., 2019). The second conclusion is that the field is decisively moving toward eco-innovative processing and circular valorization. Green extraction approaches, residue utilization, and bio-based product development collectively redefine sustainability as a productive, not merely restrictive, scientific agenda (Conventional versus green extraction techniques: A comparative perspective, 2021; A review on the extraction and processing of natural source-derived proteins through eco-innovative approaches, 2021; Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater, 2021). The third conclusion is that functional value depends on what happens after extraction as much as during extraction. Structural integrity, purity, bioactivity relevance, and application fit determine whether a recovered compound becomes nutritionally, technologically, or medically useful (Chen et al., 2015; Liu et al., 2008; Zhong et al., 2010). The fourth conclusion is that scientific valorization must be linked to fair knowledge governance. Traditional knowledge databases, intellectual property debates, and legal protection frameworks are not external concerns. They are part of the conditions under which plant-based innovation becomes legitimate and equitable (Gupta, 2011; Suwapan, 2016; Sattigeri, 2025; TKDL, 2026).

Taken together, these conclusions support a broader proposition. The future of sustainable plant bioresource innovation lies in integration. Efficient extraction, environmentally responsible processing, robust compound characterization, circular end-use design, and respectful governance of traditional knowledge should not be treated as separate agendas. They are most effective when pursued together. A scientifically advanced but socially inattentive system is incomplete. An ethically motivated but technically weak system is also insufficient. What is needed is a model of responsible innovation in which process science and governance maturity develop side by side.

This article therefore argues for a redefined research horizon. Plant-derived proteins and bioactive compounds should be studied not only as chemical targets but as components of wider ecological and epistemic systems. Such a perspective will be essential if the field is to contribute meaningfully to sustainable food innovation, green materials development, bio-based industry, and more just knowledge economies.

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