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The Commercialization of Plant-Based Bioactive Compounds: Challenges, Market Opportunities and Strategic Pathways for Biopharma Firms

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ABSTRACT: Plant-based bioactive compounds occupy an important position between natural-resource science and modern biopharmaceutical development, yet commercial translation remains constrained by raw-material variability, inconsistent standardisation, limited bioavailability, uneven clinical evidence, regulatory heterogeneity, manufacturing constraints and uncertain market positioning. This review systematically and critically examines these barriers, evaluates market opportunities, and identifies strategic pathways for biopharma firms. A PRISMA 2020-guided review framework was applied across multidisciplinary literature covering plant-derived bioactives, therapeutic development, formulation, regulation, scale-up, and commercial translation. Forty studies were retained for qualitative synthesis after screening. The findings show that commercialization depends on coordinated performance across scientific validity, technological reproducibility, clinical credibility, regulatory fit, manufacturing scalability, supply security, intellectual-property strategy, and market attractiveness. The evidence also identifies differentiated opportunities across phytopharmaceuticals, botanical drugs, nutraceuticals, advanced delivery systems, and sustainability-linked value chains. An evidence-to-market commercialization-readiness framework is proposed to support staged biopharma decision-making, with emphasis on product definition, early standardisation, formulation, evidence alignment, cross-sector partnerships and scalable manufacturing. Overall, plant-based bioactives are most commercially credible when scientific promise is converted into standardized, clinically anchored and economically scalable product propositions. The review emphasizes that market attractiveness should be assessed with evidence maturity, regulatory feasibility, supply resilience, and the cost of reducing development uncertainty

1. INTRODUCTION

Plant-based bioactive compounds are a highly diversified source of molecules and complex preparations, which still play a role in current research on human health. Polyphenols, flavonoids, alkaloids, terpenoids, carotenoids, peptides and related metabolites have been reported to have antioxidant, anti-inflammatory, antimicrobial, cardiometabolic, neuroprotective and anticancer properties, and the inherent diversity of their structure offers potential for their direct therapeutic use and for novel pharmacophores (Popovic and Rijkers, 2026; Thyagarajan et al., 2026; Talib et al., 2024; Barakat et al., 2025). Recent advances in the natural-product arena also demonstrate that natural products will continue to be important from the drug discovery perspective as they occupy biologically productive chemical space and have the potential to interact with multiple targets or pathways (Wang et al., 2024; Xie et al., 2025; Sawarkar et al., 2025).

The business value, however, is not the same as the biological potential. A compound can have good activity in the cell model but not systemic exposure, good reproducibility, acceptable toxicology, robust clinical benefit, and a viable manufacturing process. Poor bioavailability, structural instability, uncertainty about mechanisms, and limitations in preclinical models are

recurring problems that have been highlighted in recent studies of phytochemicals that are in the process of moving from the bench to the clinic (Kim et al., 2025). The same is true for plant-derived natural products since their preparation can be complicated and difficult; they are rare in plants, identification can be problematic, and authentication and obtaining reproducible material can be challenging (Ahmad et al., 2025; Nasim et al., 2022; Sohail et al., 2025).

When a bioactive is taken from its experimental status to being considered as a commercial product, a second challenge arises. Commercial development involves reproducible input materials, controlled extraction/isolation, analytical specifications, validated assays, appropriate formulation, scalable manufacture, regulatory classification, evidence appropriate to the claimed uses, secure supply, and a position in the market that would be able to withstand competition from synthetic drugs, established botanicals, and other health technologies. In contrast to a chemically defined drug, complex botanical products are regulated differently since the biological components and constituents that are responsible for the activity might be found in several parts. To ensure therapeutic consistency, the United States Food and Drug Administration thus places great emphasis on botanical raw-material controls, chemical and manufacturing quality controls, biological assays, and clinical data as a 'totality of the evidence' approach (Wu et al., 2020; Marouani et al., 2025). Similarly, Jadhav et al. (2025) point out the quality needs and legal differences between herbal medicines and phytopharmaceuticals.

There are a great number of books, but few of them are comprehensive. These reviews include different aspects of phytochemistry and mechanisms, extraction and delivery, clinical evidence, regulation, artificial intelligence, systems biology, or advanced manufacturing. This disintegration also mirrors the NRFHH publications from 2026, where each research area of phytochemical research and sustainable utilization, computational medicinal-plant discovery, bioactive peptides and polyphenols, network pharmacology, green nanotechnology, and therapeutic translation are discussed separately but related to each other (Christy et al., 2026; Benaziza et al., 2025; Shete et al., 2026; Suryavanshi et al., 2026; Wani et al., 2026; Raju et al., 2025). Although these contributions help build the scientific evidence base, they are not enough to answer the biopharma decision question, which is "When is a bioactive produced from a plant sufficiently advanced to go to commercialization, and what is the best development path to follow given the available evidence?"

The question of market growth is increasingly relevant, as scientific or regulatory uncertainty is not eliminated with market growth. When products are marketed prematurely before their standardization and/or clinical claims are sufficiently backed up, it can result in a market of insufficiently validated products. On the other hand, being too conservative in development can result in technically viable plant-derived products not becoming available to the market because the mechanism of action, formulation, process engineering, partnerships, and sequential evidence generation are undervalued. This is reflected in phytopharmaceutical research: there can be a great potential for therapeutic benefit, but quality definition, analytical reproducibility, alignment with pharmacopoeia, and clinically credible evidence are still key to success.

In this current review, however, commercialization is not viewed as the end step in the post-discovery process, but rather a systems issue. It covers literature throughout the whole process of identification of plant resources, chemical characterisation, standardisation, formulation, safe use, clinical translation, regulatory, manufacturing, security of supply, and market positioning. The review is specifically focused on identifying the most persistent challenges that are curtailing commercialization opportunities, potential opportunity spaces based on the available evidence, and the pathway for commercialization decision-making that aligns with the investment, partnership, and market entry strategy of the biopharma company. The difference lies in the science-to-commercialization logic, which is integrated into the scientific part of the study, taking science into the commercialization decision gates (as opposed to the market potential as a separate business discussion).

This review makes the point that there is no correlation between commercialisation readiness and scientific novelty or between market size and readiness. Instead, readiness is a condition that combines an evidence-generating system, a controllable product, and a viable business pathway in such a way that they are in harmony with the next development step. The approach to the review and the analysis of evidence in the evidence set are based on this premise.

Not being equal, the maturity of the global phytopharmaceutical ecosystem is also motivating the review. Other areas have a long history of traditional medical utilization and have abundant biological resources, but lack manufacturing or clinical-development abilities. Still others possess an established regulatory and pharmaceutical system, but are hampered by a lack of reproducible natural materials. So, scientific capability depends upon raw-material availability, which in turn depends on regulatory experience, which depends on the market needs. Standardization and regulatory capacities are still not evenly

distributed, with Kaundal and Kumar (2025) and Indrayanto (2024) showing some examples; Ahmad et al. (2025) properly state the sustainable management of resources for future discovery and development.

The idea of market opportunity should thus be considered as a dynamic dialogue between need, differentiation, and evidence. If there is a strong value proposition that can easily be substituted, it's not a good product opportunity even if there is a large consumer trend or disease burden. Differentiation for plant-based bioactives can be based on a new molecular structure, a standardized botanical fraction, improved bioavailability, a proprietary delivery system, a biomarker-based indication, sustainable sourcing, as well as a comprehensive evidence package. Recent NRFHH research on precision phytomedicine, computational discovery, and advanced delivery systems (Gharal et al., 2026; Saxena et al., 2026; Suryavanshi et al., 2026; Galal et al., 2024) exemplifies these technological capabilities that augment these options.

One of the other important distinctions is the biological activity and clinical actionability. Pathway modulation and antioxidant/growth inhibiting effects, which can sometimes be very strong with natural products, may be extensive, but they can differ in nature, size, and impact as a function of the conditions applied in the experiment. In oncology, there are many different mechanistic claims that can be advanced with compounds from plants, as Esmeeta et al. (2022) show, while the clinical interpretation can become more complicated if the formulation or dose differs or the quality of the clinical trials varies, as Khosravi and Seifert (2024) report. This void is a motivator for a commercialization-oriented review with the need to establish a hierarchy of the evidence to distinguish between biological signal and repeatable therapeutic value for commercial investors and developers.

Another difference between purified molecules and multi-component botanicals is their impact on the commercial environment. While complex botanicals need to focus more on composition, manufacturing consistency, and biological comparability, the use of medicinal-chemistry principles can help guide the development of purified plant-derived molecules. In the case of regulating botanicals, then, regulatory experience is about managing complexity, not removing it—for example, as noted by Wu et al. (2020). Complexity is a good thing for biopharma companies if it helps to have a more reproducible therapeutic profile, but once it can't be characterized and reproduced properly, it becomes a bad thing. The complexity, degree of standardisation and the chemical or technological limitations of the product commercial candidate the product is going to be should therefore be explicitly taken into consideration during the product development decision.

2. REVIEW METHODOLOGY

2.1 Review Design and Reporting Framework

This study adhered to the PRISMA 2020 reporting guideline for systematic reviews and employed a systematic and multidisciplinary literature search and qualitative synthesis. The reporting system provided for identification, screening, eligibility assessment, and inclusion. The research question involves a multidisciplinary design due to the multiple aspects of the research question, including phytochemistry, pharmacology, drug delivery, clinical translation, regulatory science, manufacturing, and commercialization. The aim was not to calculate a treatment effect, but to combine evidence from a variety of sources, to discover common factors in commercialization, and to understand them within the context of commercialization readiness. The synthesis therefore used a structured approach to selecting studies and a qualitative approach to thematically analyzing studies.

2.2 Information Sources and Search Strategy

The plant-based bioactive compounds, the human-health or biopharmaceutical applications, commercialization and market translation, and enabling dimensions (such as standardisation, bioavailability, formulation, regulation, manufacturing, scale-up, supply, and intellectual property) were the four concept blocks used to frame searches. Scopus, Web of Science, PubMed/MEDLINE, and ScienceDirect were searched on 8 September 2026. Scopus: TITLE-ABS-KEY(("plant-based bioactive*" OR phytochemical* OR "plant-derived natural product*" OR phytopharmaceutical* OR "bioactive peptide*") AND ("human health" OR therapeutic* OR pharmaceutical* OR biopharmaceutical*) AND (commerciali* OR transl* OR develop* OR formulation OR bioavailability OR standardi* OR regulation OR manufactur* OR "scale-up" OR sustainability OR supply OR "intellectual property")); Web of Science: TS=(("plant-based bioactive*" OR phytochemical* OR "plant-derived natural product*" OR phytopharmaceutical* OR "bioactive peptide*") AND ("human health" OR therapeutic* OR pharmaceutical* OR biopharmaceutical*) AND (commerciali* OR transl* OR develop* OR formulation OR bioavailability

OR standardi* OR regulation OR manufactur* OR "scale-up" OR sustainability OR supply OR "intellectual property")); PubMed: (("plant-based bioactive compounds"[Title/Abstract] OR phytochemicals[Title/Abstract] OR "plant-derived natural products"[Title/Abstract] OR phytopharmaceuticals[Title/Abstract] OR "bioactive peptides"[Title/Abstract]) AND ("human health"[Title/Abstract] OR therapeutic*[Title/Abstract] OR pharmaceutical*[Title/Abstract] OR biopharmaceutical*[Title/Abstract]) AND A commercialization database (ScienceDirect) was searched for compounds using the search terms plant-based bioactive, phytochemical, plant-derived natural product, phytopharmaceutical, human health, therapeutic, pharmaceutical, biopharmaceutical, and a supplementary research information source, Google Scholar, was used to complete the search for and track references. Search logic was modified to match the syntax of the database, while maintaining the same idea of intersection of bioactives (plant) and commercial translation. This multi-database approach is similar to what has been observed in recent NRFHH reviews, where a large number of biomedical and multidisciplinary databases were employed for posing more general natural-product questions (Wani et al., 2026).

2.3 Eligibility and Study Selection

Eligible sources discussed food-derived bioactives or natural products related to human health and involved at least one dimension of development (extraction and characterization, and/or formulation and delivery, including bioavailability; safety or pharmacology; clinical translation; regulation or quality control; manufacturing, scale-up or sustainable supply; commercialization and strategic development). Reviews were included when they provided analytical synthesis that directly addressed the research question, and primary studies were included when they provided evidence of translational performance, formulation, clinical use, or product development. Meaningful involvement in the development of plant-bioactive substances for human health was considered essential to include sources in the study.

2.4 PRISMA Flow and Final Evidence Set

There were five stages in the selection process. The records were searched in the databases and then consolidated. Second, before screening, other well-defined reasons for exclusion involved the duplication of records and records that were removed for other reasons. Thirdly, the titles and abstracts were screened for relevance to the review question. Fourth, the potentially eligible FTs were screened for the inclusion/exclusion criteria. Fifth, a qualitative synthesis of studies was conducted that met the above criteria. A total of 853 records were retrieved using the PRISMA flow; 173 were duplicates and put aside 20 records were put aside for other reasons, resulting in 660 records for screening. Of these, 540 were excluded at title/abstract screening, 120 reports were sought for retrieval, 5 of these were not retrieved, and 115 full texts were assessed, and 40 studies were included. The last flow and full-text exclusion categories are shown in Figure 1.

2.5 Data Extraction, Quality Appraisal and Evidence Synthesis

The data that were extracted include study year, source (plant, chemical, food), plant-bioactive domain, human-health application, scientific evidence stage, standardisation issues, formulation or bioavailability considerations, safety or clinical evidence, regulatory data, manufacturing considerations, supply-chain considerations, market opportunity and strategic implication. The structured evidence matrix was used to compare these areas. The methodological quality and relevance were assessed using design-appropriate appraisal criteria: AMSTAR 2 for systematic reviews, JBI critical appraisal criteria for narrative reviews and eligible primary studies, and a predefined transparency-and-relevance checklist for regulatory or market-oriented sources. Systematic and clinical evidence was interpreted as evidence with greater evidential weight to draw conclusions for translation to the human context, whereas regulatory documents and market-oriented evidence were contextual evidence to inform development needs, but not clinical efficacy evidence.

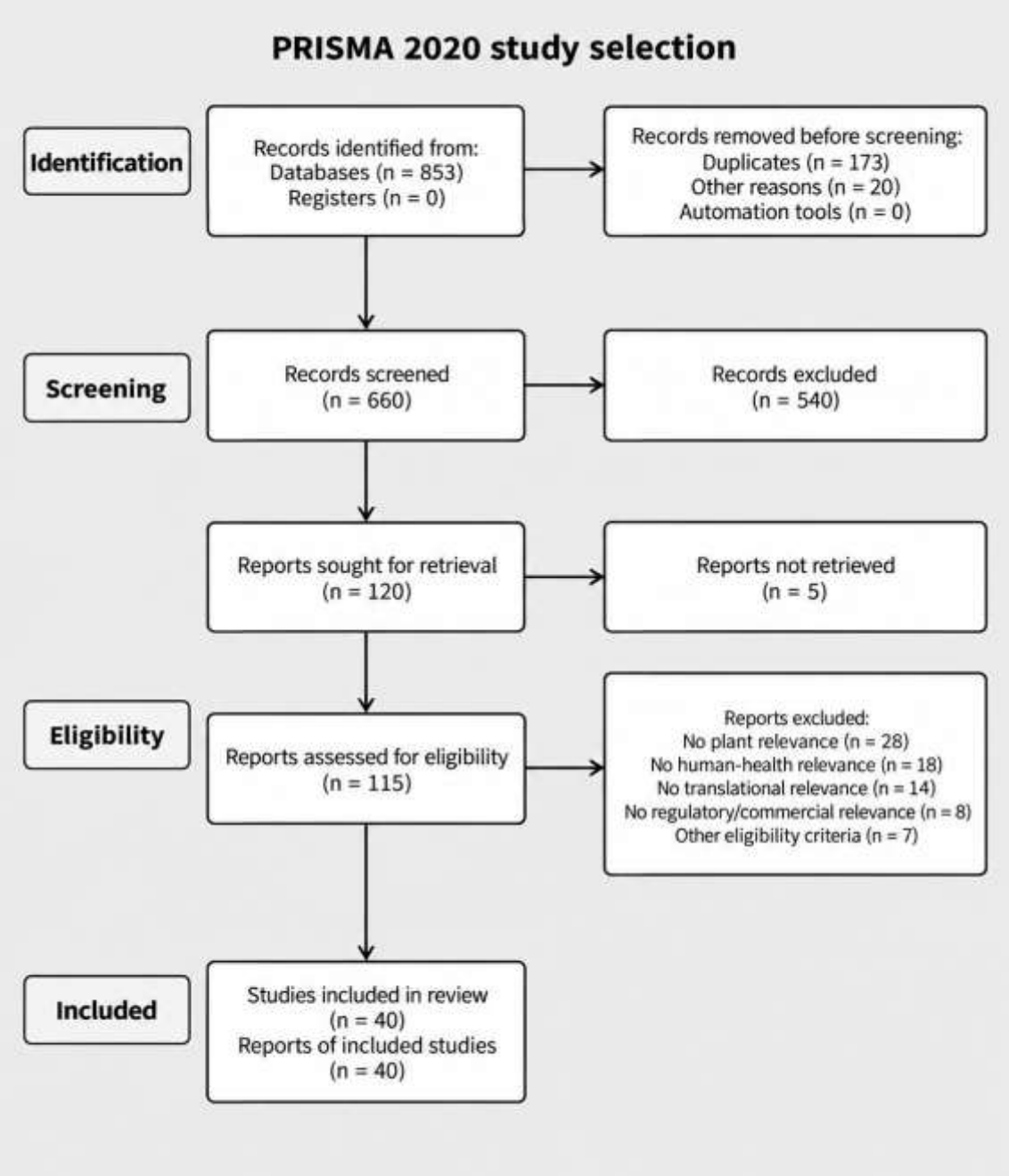

Figure 1: PRISMA study selection

The recency was also taken into account as an important aspect of selection for the review. The major evidence base was restricted to publications of the past five years (2021-2026) to align the synthesis to innovations in discovery using AI, delivery technologies, and regulation and commercial translation of phytopharmaceuticals. More basic sources had their retention limited to when they offered unique evidence of regulatory and/or conceptual development which was not covered by more recent publications. This approach includes the most up-to-date evidence while also providing needed content without resorting to unnecessary and outmoded assumptions about natural product development.

The evidence matrix cross-referenced each of the studies included to pertinent stages of the product development process. Bioactive class and evidence stage coding were captured by scientific coding, and exposure and delivery constraints were captured by formulation coding; quality requirements, product classification, and jurisdictional implications by regulatory

coding; and manufacturing, supply, market, and strategic considerations by commercialization-oriented coding. This framework enabled a convergence of heterogeneous studies to be found, but this did not necessarily imply that all the evidence types have the same causal weight. It is a qualitative synthesis, however, of recurrent determinants and not a statistical score against incompatible study designs.

The identification pool was not the same as the resulting evidence bank, because the database search was applied, and it was found that the resulting identification pool for the search was different. These records beyond initial screening were further screened for content relevance to the review question, methodological transparency, and the potential to add to a decision to commercialize. The number of citations and prestige of the journal were not the main criteria for weighting. This was required because the quality of regulatory guidance, formulation reviews, and clinical evidence and mechanistic studies cannot be measured with a single metric.

The selection criteria were developed to ensure that evidence with a strong translational relevance was kept. If a plant compound was reported to have a biological effect, but the report didn't contain the word "report," it was not included. To be entered in the final synthesis, the source must have provided input for at least one decision downstream from its use, such as defining the product, source control, source extraction, chemical characterisation, source standardisation, formulation, exposure, safety, clinical translation, regulatory positioning, manufacturing, sustainability or market strategy. This criterion imposed on the review prevented the review from being a catalogue of the pharmacological effects, and kept the review focused around product development.

The sources were evaluated for their relevance to the subject matter and were only English-language scholarly and regulatory sources. Search terms were created to reflect both science related to natural products and product development. The core concepts included were plant-based bioactive compounds, phytochemicals, plant-derived natural products, phytopharmaceuticals, bioactive peptides, sustainability, market strategy, and biopharmaceutical development, along with commercialization, development, translation to humans, formulation, bioavailability, standardization, regulation, manufacturing, and scale-up. To find highly relevant records indexed under alternative terms, which were found to be conceptually relevant in recent reviews of the literature that also incorporate manual screening to complement database searching due to the conceptually dispersed literature (Kim et al., 2025), citation chaining was performed.

3. RESULTS

A total of 40 studies were included in the final evidence set, most of which were published between 2021 and 2026, and some of the earlier foundational, but relevant, studies were retained because of their distinctive regulatory and/or development evidence. As much as possible, the evidence base was diversified and comprised NRFHH reviews that were closely related to journal scope, multidisciplinary NRFHH reviews, delivery/formulation reviews, clinical and translational reviews, regulatory and standardization reviews, as well as recent perspectives on commercialization and development. Table 1 provides a summary of the evidence base.

Table 1 shows that there are five broad themes within the literature that are interrelated, such as scientific discovery/therapeutic evidence, standardisation and quality, formulation and bioavailability, clinical and regulatory translation, and commercialisation, manufacturing and strategic development. NRFHH papers have had a huge impact on the scientific and translational communities. NRFHH's wide scope of connecting natural resources and human-health evidence is reflected in recent NRFHH reviews, such as bioactive peptides and polyphenols, medicinal-plant research, systems biology, and phytochemical integration and sustainable utilization (Christy et al., 2026; Saxena et al., 2026; Thyagarajan et al., 2026; Wani et al., 2026).

In the literature provided, an array of human health applications of plant bioactives was found. The literature reviewed included polyphenols, flavonoids, alkaloids, terpenoids, and metabolites of these various families, which have been reported for their antioxidant, anti-inflammatory, antimicrobial, cardiometabolic, anticancer, and neuroprotective properties (El-Saadony et al., 2025; Esmeeta et al., 2022; Popovic and Rijkers, 2026). In addition to the wide range of phytochemicals being identified, reviewed, and prioritized, several computational approaches are being used to identify, prioritise, and characterise candidate molecules, as highlighted by NRFHH reviews. The evidence thus suggests a significant opportunity landscape; however, not every compound class is development-ready.

Table 1: Characteristics of included studies

Evidence domain	Studies	Main emphasis	Development relevance
Scientific discovery and therapy	12	Phytochemistry, mechanisms, targets	Candidate selection
Standardisation and quality	6	Authentication, analytical control	Reproducible material
Formulation and bioavailability	7	Delivery, stability, exposure	Product performance
Clinical and regulatory translation	6	Safety, trials, regulation	Evidence readiness
Commercialisation and scale-up	5	Manufacturing, market, strategy	Investment readiness
Strategic and enabling technologies	4	AI, partnerships, platforms	Capability development

The most compelling scientific evidence is the growing consideration of therapeutic activity using multi-target and systems approaches (Rasheed et al., 2026). The network pharmacology and systems biology reviews by NRFHH discuss the mechanisms involving multiple targets at a molecular network level, multi-omics, docking and associated approaches, and how these can explain complex mechanisms that are hard to understand in the context of a single-target paradigm (Saxena et al., 2026; Shete et al., 2026). More general natural product reviews also list computational chemistry, high-throughput screening, and target-based approaches as methods to enhance lead prioritisation and alleviate the early burden in discovery (Saldívar-González et al., 2021; Wang et al., 2024). These advances are of commercial interest as quicker prioritisation can lead to less waste in the experimental setup; however, this does not provide proof of clinical and/or manufacturing feasibility. Evidence on extraction and characterization indicates that early development decisions are often process decisions. Natural products may occur at low concentrations, within complex chemical matrices, and vary across species, locations, cultivation conditions, and harvest stages. Ahmad et al. (2025) point to low availability and challenging isolation, and El-Saadony et al. (2025) postulate the trade-offs between yield, solvent utilization, degradation, and sustainability. Nasim et al. (2022) also highlight the need for the development of authentication and fingerprinting. These factors affect the choice of source and result in a commercial as well as scientific choice of source. Standardization was thus continually found as a requirement, with Kaundal and Kumar (2025) and Indrayanto (2024) highlighting the requirement of validated pharmacognostic, analytical, and pharmacopoeial approaches, and the recent NRFHH reviews also endorsing the need for standardization for safe and evidence-based phytopharmaceutical development (Thyagarajan et al., 2026; Wani et al., 2026). The main obstacles that have been revealed throughout the evidence are presented in Table 2. Small molecule phytochemicals were especially prevalent in their limitations in bioavailability. Poor absorption, instability, and pharmacokinetic uncertainty are highlighted as translation barriers by Kim et al. (2025), and formulation strategies to overcome various challenges such as low solubility, fast metabolism, and inadequate exposure are described by Hegde et al. (2023). Khosravi and Seifert (2024) review the abundant interest in curcumin critically and its potential clinical benefits and demonstrate that, despite the interest, the clinical evidence to date is not persuasive, due to a lack of appropriate clinical endpoints, formulation, and pharmacokinetics.

Table 2: Commercialization barriers across development

Barrier	Evidence signal	Commercial effect	Priority response
Raw-material variability	High	Batch inconsistency	Authenticated sourcing
Extraction and yield	High	Cost and reproducibility	Process optimisation
Standardisation	Very high	Weak specifications	Validated methods
Bioavailability	Very high	Low exposure	Formulation strategy
Safety evidence	Moderate-high	Development uncertainty	Product-specific testing
Clinical evidence	High	Weak claims	Defined endpoints
Regulatory heterogeneity	High	Market delay	Early classification

Scale-up/GMP	High	Manufacturing risk	Pilot-to-GMP planning
Supply security	Moderate-high	Continuity risk	Traceable cultivation
IP/appropriability	Moderate	Differentiation risk	Process/formulation IP

The use of delivery technologies is an important opportunity, as they can change the pharmacokinetics of compounds with poor intrinsic pharmacokinetics and can make compounds more commercially viable. Kothapalli and Vasanthan (2024) summarize the lipid-derived nanocarriers for plant-derived molecules, Zhang et al. (2024a) summarize the hyaluronic acid delivery systems designed to enhance stability, targeting, and therapeutic efficacy, and McClements (2022) describes plant-derived proteins, polysaccharides, and lipids as components of colloidal delivery systems. Together, these studies imply that it is the combination of the commercial product and the bioactive, and not the unformulated bioactive, that is more competitive in terms of formulation, reproducibility, and control. Another important gate that was identified as critical was safety and clinical validation. Even the well-studied phytochemical withaferin A also has a lack of pharmacokinetic and toxicity data, as shown by Devabattula et al. (2024). Similarly, Shoaib et al. (2023) differentiate between extensive mechanistic and preclinical evidence and the more limited evidence needed for definitive clinical translation. Some of the challenges identified by Liu et al (2022) include poor yield, unknown absorption, bioavailability, and lack of in vivo evidence of plant-derived bioactive peptides. These results have shown that commercial strategy should be based on product-specific, dose-specific, and clinically interpretable evidence and not only on mechanistic plausibility. Product definition is a critical development issue mentioned in the product literature. The U.S. botanical-drug framework is based on a totality-of-the-evidence approach as outlined by Wu et al. (2020), which involves the use of botanical raw materials, chemistry and manufacturing controls, and biological/clinical evidence. There are significant disparities between jurisdictions, as highlighted by Indrayanto (2024), and regulatory and quality requirements for various products of phytopharmaceuticals, as described by Jadhav et al. (2025). Aware et al. (2022) and Nasim et al. (2022) also highlight the differences among crude herbal products, standardized herbal fractions, and more defined phytopharmaceutical products. Therefore, regulatory classification should be considered as a first step and not as a last step in the administration. From natural-product drug development examples, supply and process strategy is a critical aspect of commercial viability. The authors of Butler et al. (2026) illustrate the ongoing impact of natural products on current drug pipelines by mapping natural products-derived drugs and clinical candidates over the last ten years (2014-2024). Additionally, industrial practice reveals that scaling discovery workflow into development involves process development as well as a continuous supply of compounds. Industrial experience also indicates that process development, as well as a continuous flow of compounds, is necessary to scale discovery workflows into development (Helf et al., 2024; Singh et al., 2025). The challenge is, therefore, to turn part industrial synthesis of a molecule of pharmaceutical interest into a reproducible, scalable product.

Market evidence suggests that there are multiple opportunity spaces instead of one market. Indrayanto (2024) explains the existence of a huge expanding global market for herbal drugs, and El-Saadony et al. (2025) elucidate applications ranging from food and functional health to pharmaceutical products. Wani et al (2026) and Thyagarajan et al (2026) state that there are other related opportunities such as bioactive peptides, polyphenols, phytochemicals, functional foods, and nutraceuticals. It helps to build a "product portfolio" where a single scientific platform can provide a variety of products with varying clinical, regulatory, and commercial needs.

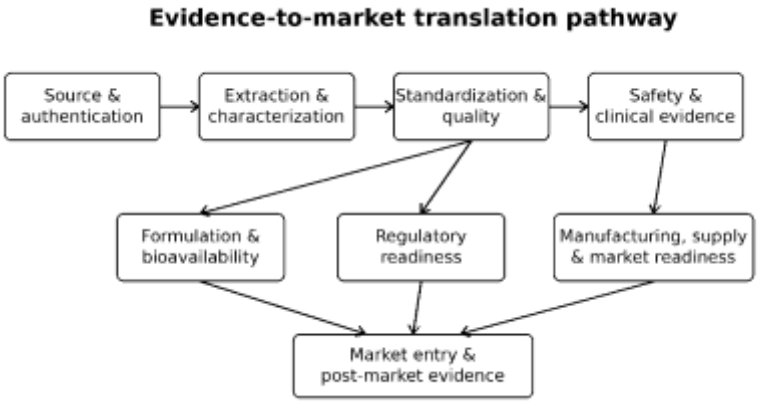

Figure 2: Plant bioactive commercialization pathway

One of the most obvious opportunity areas that can be leveraged through technology is in delivery and formulation systems. Examples of formulation and delivery strategies suitable for plants are provided by Hegde et al. (2023), McClements (2022), and Kothapalli and Vasanthan (2024), and some of these are aimed at increasing the clinical viability of poorly bioavailable compounds. Further, green nanotechnology is emerging and connecting the performance of the delivery with applications in the field of food and health, with a focus on sustainability (Suryavanshi et al., 2026). Technologies that are a validated formulation or delivery platform, and not a commodity extract, can form a more robust commercial position for a firm.

Commercial variables were sustainability and supply security, rather than just environmental variables. Ahmad et al. (2025) talk about plant and marine natural products and sustainable extraction and discovery, while Thyagarajan et al. (2026) emphasise protection of biodiversity, sustainable utilization and quality assurance. The sourcing can have an impact on sourcing reliability, sourcing continuity, brand legitimacy, regulatory confidence, cultivation strategy, and geographic diversification. The incorporation of sustainability should, therefore, be considered as part of the overall enterprise plan for commercialization as part of the long-term product reproducibility and supply resiliency.

The last output domain was related to strategic pathways of companies. There is no commercialisation model identified in the literature that is applicable to all the candidates. The most likely explanation for an internal build strategy is if the candidate has a good support package and the firm has the formulation, manufacture, and regulatory expertise to develop the candidate. Partnership is more suitable between companies that have market or manufacturing strengths but fail to have botanical authentication, phytochemical analytics, or early discovery. When the extraction processes, delivery systems, biomarkers, and/or candidate assets are managed by academic or biotechnology partners, licensing or co-development is more relevant. Multiple technologies and disciplines are suggested as a viable solution to tackle natural-product complexity (Wang et al., 2024; Basnet et al., 2025). The pathways are summarised in Table 4.

Table 3: Market opportunities and risks

Opportunity	Commercial rationale	Evidence burden	Main risk
Phytopharmaceuticals	Therapeutic differentiation	High	Clinical/regulatory
Botanical drugs	Defined therapeutic claims	Very high	Quality consistency
Nutraceuticals	Faster product access	Moderate	Claim substantiation
Advanced delivery	Bioavailability advantage	High	Scale-up/safety
Functional health	Broad consumer demand	Moderate	Market competition
Sustainable value chains	Supply and brand resilience	Moderate	Feedstock continuity

Table 3 brings together these opportunity spaces, development requirements, and the key risks. High-value therapeutic differentiation can be achieved on pharmaceutical and phytopharmaceutical pathways, yet it is the most evidence- and regulatory-intensive. Nutraceutical and functional-health pathways can provide for rapid market access, but can be limited by claim substantiation and the variability of products. The emergence of advanced delivery systems results in technological differences and adds scale-up and safety issues. Value chains for sustainable and circular products provide supply and brand opportunities and require a certain level of feedstock security and proper value chain benefits. The evidence thus lends support to a strategy for opportunity selection that takes into account the interaction of readiness and risk/market position and not the perceived popularity of a compound.

Across the 40 included studies, commercialization readiness emerged as multidimensional. Strong performance in one domain cannot compensate for a critical weakness in another: scientific evidence requires reproducible material; reproducible material must be supported by adequate formulation and pharmacokinetics; clinical credibility must align with a scalable process and regulatory pathway. Figure 2 presents this evidence-to-market pathway as interconnected development gates rather than a simple linear sequence.

The cross-study comparison led to the development of the proposed commercialization-readiness framework shown in Figure 3. The framework recognises the interdependent aspects of scientific, technological, clinical, regulatory, manufacturing, supply-chain, IP, and market readiness dimensions. The results show that in attaining the goal of advancing candidates based on a strong performance on one dimension, companies should not rely on that dimension alone. Rather, the minimum of the critical readiness dimensions could be the limiting factor for investment. This is particularly relevant with regard to plant-based

products because variability can have an impact on analytical specifications and clinical reproducibility and regulatory acceptability.

Table 4: Strategic pathways for biopharma

Pathway	When suitable	Core capability	Key risk
Build	Strong internal capability	R&D and GMP	Capital intensity
Partner	Capability gaps	Collaboration network	Coordination
License	Validated external asset	IP evaluation	Dependence
Co-develop	Shared development risk	Complementary expertise	Governance
Platform	Reusable technology base	Process/formulation platform	Portfolio complexity

Computational tools were also identified as enabling technologies. Patil et al. (2026) and Saldívar-González et al. (2021) discuss the application of AI, machine learning, and cheminformatics in the areas of metabolite identification, dereplication, target prediction, metabolite discovery, and lead optimization. Gupta et al. (2026) provide an illustration of the prioritization of natural-product leads using docking, supervised learning, and ADMET prediction. However, these methods may help to streamline commercial operations by minimizing the amount of low-value experimentation in the early stage of development, but the fact that a chemical can be predicted on a computer does not prove that it will be useful in medicine. However, data quality, interpretability, standardization, and experimental validation are still significant constraints (Christy et al., 2026; Saxena et al., 2026).

The results show, in general, that commercialization is a coordinated process with regard to the generation of evidence and risk reduction. The most viable candidates are the ones for which the product can be defined and reproduced, clinically relevant exposure can be shown, there is sufficient regulatory documentation, the manufacturing can be scaled up, supply can be controlled, and the market proposition is defensible. The synthesis is the basis for the interpretation developed in the Discussion.

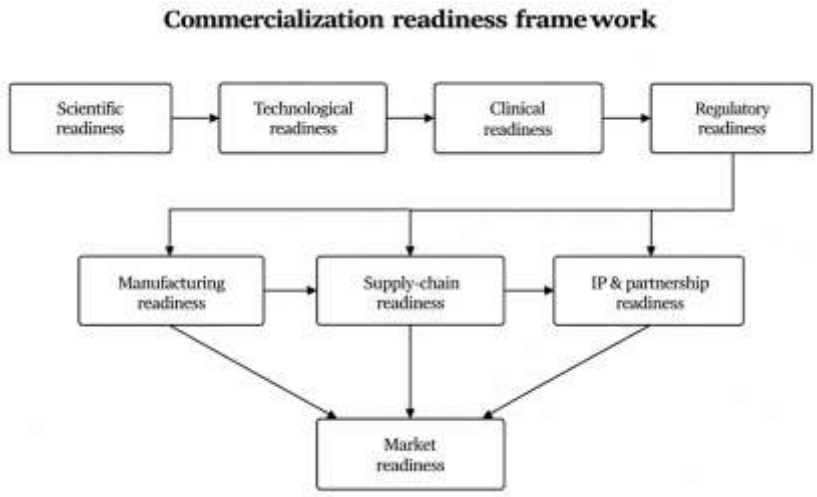

Figure 3: Commercialization readiness framework

The synthesis shows that there are overlapping barriers to commercialization and they build on each other. There is a risk of variability of the plant source, which may compromise the ability to ensure standardisation; insufficient standardisation can result in variation of the clinical material, which can decrease regulatory confidence and market entry. Similar dependency chains apply to bioavailability, formulation, manufacturing, and supply. Table 2 therefore presents barriers in terms of their downstream commercial consequences rather than as isolated scientific problems.

There were fewer formal elements of IP evidence than there were of scientific and regulatory evidence, though it was still of great strategic importance. Natural products may offer a lower level of compositional exclusivity in open applications but may offer defensible positions based on standardized preparations, extraction processes, formulation, delivery technology, manufacturing control, analytical methods, and defined therapeutic applications. However, in a commercial program, IP must be considered in conjunction with scientific differentiation and not once technical development is finished.

Sustainability was not a single isolated endpoint but a cross-cutting readiness dimension. Stability of access to plant material can influence manufacturing continuity, cost forecasting, quality assurance, and regulatory confidence. Ahmad et al. (2025) and Thyagarajan et al. (2026) link sustainable sourcing to the long-term viability of natural-product discovery, while Suryavanshi et al. (2026) show how green technologies can connect resource efficiency with delivery innovation (Maind et al., 2025). Sustainability indicators can therefore be incorporated into business readiness rather than treated solely as external reporting metrics.

Market evidence indicated that market paths need to be split by use and evidence. For high-value therapeutic products, the level of clinical and regulatory support is the highest; for nutraceutical and functional-health products, there may be several avenues of access, but they still have a need for quality control and credible claims. Wani et al. (2026) warn against taking a step from general biological statements to specific product statements lacking clinical support, and Indrayanto (2024) demonstrates that regulation and quality assurance continue to be key to the credibility of herbal products. This market map, which reveals a set of differentiated product propositions, rather than an undifferentiated natural products market, is likely to lead to a market map that benefits these product propositions.

It is helpful to consider plants as sources for biologics and as a production platform. While the small molecule phytochemicals vary, the same factors – cost, scalability, product quality, regulatory compliance, and investment sustainability – are all key in commercializing plant expression systems. Washida et al. (2025) discuss the requirements for the commercialization of recombinant pharmaceuticals in plants, both from an economic and technical point of view. This evidence extends the commercialization approach, considering plants as a platform for the production of complex health products besides the bioactive molecules they provide.

When technology is used for a well-defined development constraint, it can be used to enhance translation. Prioritizing candidates can be quicker with AI assistance; network pharmacology can be used to generate a multi-target hypothesis, and delivery systems can be optimized for better exposure. They are still dependent on validation and integration, however. Machine learning and computational screening have potential for prioritization (Gupta et al., 2026; Patil et al., 2026), and AI-driven natural-product discovery is covered by Basnet et al. (2025). It is therefore advisable to regard technology as a facilitator of readiness, not as evidence, and to use it in this way.

There was a wealth of mechanistic and translational information in the evidence base, with a comparatively low number of product-specific, well-controlled clinical data. Sahoo et al. (2026), Devabattula et al. (2024), and Shoaib et al. (2023) all cite challenges with solid clinical evidence in various therapeutic domains. That is, the volume of evidence should not be synonymous with the level of evidence maturity because there may be considerable uncertainty about dose, exposure, formulation, patient selection, and clinically meaningful outcomes for a compound, even when there is evidence in the literature.

Scientific evidence was more robust for the recurrent classes of phytochemicals (polyphenols, flavonoids, alkaloids, and terpenoids), and activity profiles were different, depending on compound, preparation, disease model, and exposure. Popovic and Rijkers (2026) highlight the wide physiological and therapeutic significance of phytochemicals, and Madan et al. (2026) demonstrate the ongoing pharmaceutical significance of classes of phytochemicals with anticancer properties. The evidence does suggest, though, that the commercial unit is not a "bioactive compound", but may be a purified molecule, a standardized fraction, a complex botanical product, or a formulated delivery system.

40 studies were included in the evidence base, and there was significant overlap between the themes represented, some of which were stronger than others. Most papers were of a discovery type with general information about chemical diversity and technological developments, while papers related to commercialization included more standardisation, product definition, scale-up and/or regulatory readiness. The evidence map reveals a wealth of evidence in the field, but few integrated studies of a particular candidate over the development pathway. This discovery indicates a need for an approach that transcends from one domain to another rather than one based on one domain only.

The proposed framework also links the publication-oriented research with the product-oriented development. Mechanistic insight, novelty, and volume of published work can be good indicators of academic progress, whereas reproducibility, evidence quality, time, costs, regulatory acceptability, and market adoption can be useful indicators of commercial progress. In order to create translationally mature plant-bioactive ecosystems, it is necessary to intentionally establish interfaces between these ecosystems, such as shared standards, data structures, partnership models and development milestones. The framework aims to be a tool to explicitly make these interfaces visible to biopharma decision makers.

The other interface is evidence communication. Commercial stakeholders need value propositions and scientific/regulatory stakeholders need statements of evidence. Therefore, there should be consistency between marketing statements, investment statements, and evidence. It's important to maintain mechanistic plausibility, preclinical efficacy, exposure, and clinical benefit that are distinct. The trend of broad health-promoting claims to chemically standardized preparations and mechanisms of the product has also been seen in recent NRFHH literature (Wani et al., 2026).

The market findings also indicate that biopharma companies can add more value to their options with investments in reusable platforms. Several bioactives can be supported by a validated extraction process, an analytical fingerprinting method, formulation technology, or a clinical biomarker. This can spread out the risk of development and minimize reliance on an asset that is risky. An important aspect of using platform logic is that it shouldn't weaken the product-specific evidence for each product in the pipeline, however. A reusable capability brings strategic value only if each product in the pipeline maintains its own quality, safety, and efficacy requirements.

A "staged decision vocabulary" of action options (go, refine, partner, license, defer or stop) is supported due to the cross-study comparison. These options are suitable if the critical readiness domains are good, the critical bottleneck is identified and does not need to be solved, an external capability is needed, or a technology or asset can shorten the development time or lower the risk. This approach does not make an assumption that one number threshold will apply to all plant-based candidates.

The evidence also backs up the concept of "concurrent planning" of sustainability and commercial strategy. Source risk can be mitigated by long-term sourcing contracts, environmental and social safeguards, geographic diversification, and traceability. When traditional knowledge (TK) or genetic resources (GR) are used for development, there may be a connection between benefit-sharing and the legitimacy of the partnership as well as the intellectual-property strategy. Even with a solid scientific underpinning, the failure to consider these dimensions can be a reputational, legal, and supply continuity risk.

It is helpful to make a parallel with production platforms based on plants. While plant expression systems are not synonymous with phytochemical products, they share many of the same essential components of technical productivity and stable product quality, cost control, regulatory acceptance, and a sustainable business case associated with the commercialization of pharmaceutical products. Plant expression systems and phytochemical products are not the same, but many of the same key principles of technical productivity and stable product quality, cost control, regulatory acceptance, and a sustainable business case exist when commercializing a pharmaceutical product. Similarly, this principle can be utilized in the design of extraction platforms, biosynthetic pathways, delivery technologies, and analytical workflows for small-molecule plant bioactives.

The scale-up of manufacturing to commercial scale increases the challenge of development. Laboratory extraction can be more tolerant of low levels, process parameters that depend on the operator, and a small window of feedstocks, while commercial production must be validated, supply continuous, process capable, impurity controlled, stable, and change managed. The standardisation literature reflects that these controls are not only operational standards but actually an extension of the product definition of the scientific product (Indrayanto, 2024; Kaundal and Kumar, 2025). Early recognition of manufacturability, therefore, can help to avoid late-stage discovery that a laboratory process cannot be successfully scaled up to commercial production.

These can be complemented by development with the support of AI. Artificial Intelligence, Network Pharmacology, Molecular Docking, and Multi-omics have been demonstrated to speed up the discovery, selection of targets, and candidate prioritization through recent computational reviews by NRFHHs (Patil et al., 2026; Saxena et al., 2026; Shete et al., 2026). The commercial application should, however, ensure there is a clear relationship between the prediction, experimental validation, and product decision. This minimises the threat of the evidence being lagged behind the increasing complexity of computation in the decision-making process for the regulatory body or the patient.

The results are congruent with the idea of an "evidence minimum package". A candidate has reached a commercial decision gate; before that can happen, the sponsor must be able to answer 5 questions: What is the product? Is it possible to be made regularly? Are the intended levels of exposure achieved with the intended formulation? Do the target population(s) benefit from the claimed benefit? Are there scalable solutions for providing and managing the product? If one or more of these questions is not answered, risk might be dominated in the downstream direction. Thus, a minimum evidence package is more useful for making decisions than just several publications.

The results of the market research also question the notion that all plant-based products can be developed on a pharmaceutical route. Some products could be used in a therapeutic program with a strong evidence burden, and others might be more appropriate for nutraceutical, functional-health or enabling-technology programs. This will vary based on the evidence base, claim, risk profile, manufacturing burden, regulatory category, and the market need. These dimensions bring in commercial value without trying to fit all bioactives into the traditional pharmaceutical model.

The same goes for the selection of the partners. Partnerships are best suited to an area of capability that is a constraint for development, not just for making it more visible. The universities can offer the mechanistic know-how; biotechnology companies can offer extraction, fermentation, delivery, and screening platforms, or GMP manufacturing or clinical execution services can be provided by contract organizations. Wang et al. (2024) exemplify the multidisciplinary integration advocated, which is around natural product development.

The goal of investment for biopharma companies should be to eliminate uncertainties that will affect the efforts, not to run a wide range of low-priority experiments. If the variability of the sources is the predominant risk, the emphasis needs to be on authentication, cultivation, and analytical control. If a risk of exposure is the main risk, then formulation and pharmacokinetic studies should be given priority. If there is still no clinical evidence, then, instead of further mechanistic screening, a well-designed trial should be done. This resource allocation based on the values of the portfolio can increase the efficiency of the portfolio.

The readiness framework should not be applied in a blanket manner and should not be used as a single, numerical score since the score should vary for each product class. Conventional chemical characterization might be adequate for a purified small molecule, but more extensive fingerprint, process controls, and an overall "totality-of-the-evidence" rationale may be needed for a multi-component botanical. Adopting a context-specific quality approach, as shown by Wu et al. (2020) and Jadhav et al. (2025), is crucial. The framework, therefore, is more useful as a tool to help make decisions on the intended product, the evidence needed for that product, the weakest critical domain, and the intervention most likely to improve the weakest domain efficiently.

These results also extend the definition of 'novelty' in the context of commercialization of natural products. Novelty can either lie within the molecule itself, but can also come from the controlled product architecture or from a controlled formulation of an existing bioactive molecule into the precisely formulated therapeutic product. For instance, a compound that has an established indication, a well-established biomarker, clinically relevant exposure, and a known scalable source might find itself to be more commercially viable than a novel compound that has no scalable source, no biomarker, and a less well-established indication. The curcumin literature is a good example of ways in which formulation and clinical-study design can have a significant impact on the interpretation of a well-known compound (Hegde et al., 2023; Khosravi and Seifert, 2024).

4. DISCUSSION

Integration between specialist areas is also needed for effective commercialization. Ethnobotanists can identify resources, chemists can characterize molecules, pharmacologists can study mechanisms, formulation scientists can work on ways to increase the exposure to the molecule, clinicians can test how effective the molecule is, quality scientists can help set specifications, and regulatory scientists can help develop pathways for approval. These activities can frequently be isolated. The reviewed evidence indicates that integration should be initiated at an earlier stage in clinical development (before the late stage) in order to have measurements used later in the process as critical quality attributes, biomarkers, or regulatory evidence.

Based on this review, it is fair to say that a lack of scientific ability is a single cause for commercialization failure. Instead, more frequently it is the misalignment of domains of development that creates risk. Biologically active compounds can be commercially underdeveloped due to source variability that risks preventing standardisation (Indrayanto, 2024; Kim et al., 2025);

limited exposure trials that compromise the clinical interpretability limits; uncertainty over mechanism of action that can make it hard to position for regulation; and inability to reproduce the material used for research during manufacturing (Indrayanto, 2024; Kim et al., 2025). A systems perspective thus changes the management question from "Does the compound work?" to "Is the desired product well controlled, well documented, and able to be scaled up to a new investment gate?"

This systems interpretation builds upon and expands upon recent NRFHH reviews. Wani et al. (2026) review the production, mechanism, pharmacokinetics, formulation, clinical applications, safety, and regulatory aspects of bioactive peptides and polyphenols. The authors of Thyagarajan et al. (2026) correlate phytochemical discovery with quality assurance, extraction, characterization, pharmaceutical and nutraceutical uses, regulation, and sustainability. Christy et al. (2026), Saxena et al. (2026), and Patil et al. (2026) highlight the importance of computational speedup and innovation in the field. In the present review, these scientific and translational capabilities are brought together in a commercialization decision system for biopharma companies, taking one step further down the stream. It's the decision-focused integration, and not the identification of any new element, that makes its contribution.

The first strategic implication is to be sure of the desired product at an early stage. The extract of a plant is not a standardized botanical fraction, purified active molecule, combination product, nutraceutical ingredient, or a botanical drug. There is unique evidence, quality systems, regulatory pathways, and market claims for each product class. The importance of regulatory consistency and quality with product type and evidence has been illustrated in Wu et al. (2020) and Jadhav et al. (2025), and the recognition of phytopharmaceutical pathways from conventional herbal products in Nasim et al. (2022) has been outlined. The analytical, clinical, and manufacturing evidence needs are dependent on this product class definition and should be planned for significant investment downstream, as appropriate to the product class, to be made before the product class is defined.

The second is that standardization can add value; it can offer more than just compliance. The evidence reviewed indicates that biological variability is more manageable for industrial development through the process of standardization. The validated quality parameters and pharmacopoeial standards are highlighted by Kaundal and Kumar (2025) and by Indrayanto (2024), who points to the requirement of product-specific validated methods in case of complex mixtures. The firm that proves itself to be able to obtain raw material authenticated with certainty, reproducible chemical fingerprints, reference markers, validated analytical methods, and process controls can benefit in clinical reproducibility, regulatory assurance, transfer of contract manufacturing, and/or process-related intellectual property.

The third implication is in terms of formulation. Low bioavailability is not only an inconvenience in the formulation of a compound, but can affect the commercial model of the compound. Although good preclinical data indicate that a conventional extract or tablet may have some promise, the dose and exposure may not be adequate. Other formulations may be necessary if the active is not very soluble or is very metabolized. Examples of how delivery technologies can enhance the stability, solubility, targeting and/or exposure of a product are provided by Hegde et al. (2023), Kothapalli and Vasanthan (2024), McClements (2022), and Zhang et al. (2024a). But there are other risks with formulation innovation, such as excipients, process reproducibility, scale-up, stability, and safety. The strategic goal is not to adopt nanotechnology per se, but rather to choose an appropriate method for delivering the technology that addresses a specific translational need and is commercially viable.

The fourth implication is product-specific clinical development. As is the case in many instances, positive preclinical evidence (Haif et al., 2024) may coexist with conflicting and/or limited clinical evidence. As illustrated by Devabattula et al. (2024), this disconnection can be seen with withaferin A, and Khosravi and Seifert (2024) outline similar situations with curcumin, where there is a host of studies, but few consistent treatments for any given indication. Wani et al. (2026) also highlight that there is only biological plausibility, not necessarily human benefit. Because of this, commercial programs ought to specify exactly what formulation, dosage, biomarker of exposure, target population, and clinically relevant endpoint they are looking to apply to their intended product, and not assume that all previously published data on a molecule or plant are relevant to that product.

Regulatory approach should be integrated from the start of the product development process as well. The formulation and evidence package can be accepted in one market but not in another, because of the presence of some jurisdictional differences (Indrayanto, 2024). U.S. FDA botanical guidance focuses on a totality-of-the-evidence approach, which consists of raw-material controls, chemistry and manufacturing controls, and biological or clinical data (Wu et al., 2020). The authors of the Jadhav et al. (2025) paper also demonstrate that dedicated quality and regulatory approaches are needed for each product type of herbal and phytopharmaceutical products. Companies focused on the design of analytical methods, clinical packages, and

manufacturing controls, considering the classifications of the target markets, can minimise later redesign in development, which can be costly.

Based on market analysis, the commercialisation is most likely to be achieved if scientific differentiation is coupled with market differentiation. Generally, commodities are less protected and compete on a cost basis, in terms of brand or distribution. A standardized product with a standardized biomarker, bioavailability, process, and a defensible clinical position, in contrast, will help to differentiate better. Natural product-derived products are moving further along in the process of clinical development and drug approval (Butler et al., 2026), and plant knowledge is also being translated into products that are based on evidence (Aware et al., 2022; Nasim et al., 2022). The competition should, therefore, be based on a differentiated product proposition, and not on the general natural product competition.

When plant material is utilized as an industrial input, then sustainability is also strategic. The authors of the papers by Ahmad et al. (2025) and Thyagarajan et al. (2026) demonstrate that sustainable harvesting, conserving biodiversity, and resource management are fundamental to the development of products in the long term. A change in variability, depletion, or disruption of a source can be a regulatory, quality, and cost risk. These measures can help enhance supply continuity through controlled cultivation, geographic diversification, traceability, and alternative production platforms. Eventually, it would be possible to synthesize and/or engineer some rare metabolites without harvesting the natural sources, which are vulnerable. (Ahmad et al., 2025; Basnet et al., 2025).

The same holds for developing an IP strategy. Discovery may be based on TK and GR, but commercial protection is unlikely to rely solely on the knowledge of traditional use of these plants. Rather, firms could be required to secure standardized compositions, extraction processes, formulations, delivery systems, analytical methods and/or specific therapeutic applications, as well as ensure provenance and benefit-sharing obligations. Therefore, a candidate's legal, access, and partnership status should not only be considered at the time of imminent market entry but early on as well.

The strategic pathways identified in the review could be viewed as a portfolio of capabilities, rather than a specific set of choices. An internal 'build' strategy works when a company has the analytical, formulation and clinical development expertise to bring the product to market and the company believes that it has a sufficiently differentiated asset which is designed to support a differentiated market. Where these important capabilities are spread over academia, botanical suppliers, developers of biotechnology, and clinical organisations, a partnership strategy is more appropriate than a stand-alone approach. Licensing may be used to speed up access to proven technologies or potential assets, while co-development can provide a way to share clinical development and manufacturing risk. Wang et al. (2024) make a clear statement of the importance of integrating multiple technologies and multiple disciplines, especially for natural product complexity, and that this integration should be provided for in partnership models, which are based on complementary expertise.

AI and computational tools can play a role in this partnership and logic of capabilities. Saldívar-González et al. (2021), Basnet et al. (2025), and Patil et al. (2026) demonstrate the capability of computational systems to speed up the prioritization of candidates, the prediction of their structure, the dereplication, and the assessment of their biological activity. They are of commercial value depending on whether they help with downstream decision-making. Inaccurate models can be resource-consuming, not resource-saving. Therefore, the capability of AI should be measured in terms of the quality of the decisions, how fast this can be achieved, how experiments can be prioritized, evidence traceability and validation, rather than just novelty of the algorithm (Christy et al., 2026; Saxena et al., 2026).

Commercialization readiness is thus best considered a "gate system. A scientific rationale that the evidence is credible and that the material is controllable, formulation addresses the relevant exposure problem, safety and clinical evidence supports the intended claim, the regulatory pathway is sufficiently clear, and manufacturing and supply risks are manageable. If one domain is weak, the best course of action might be to improve the product, join forces to acquire the missing capability, license the technology, or not make any further progress. The dimensions of readiness shown in Figure 3 are not merely a checklist, but rather are intertwined aspects of a business choice.

It also provides a clear guideline to the opportunity offered by the market from the inception of development. The type of dosage form, type of evidence, regulatory classification, batch size, packaging, and claims allowed may be influenced by intended positioning. The evidence packages and partnership models to be shared may therefore be different for a therapeutic botanical

versus a functional-health product that is derived from the same botanical. The design of a product, evidence planning, and regulatory design contribute to market opportunity as well, not just at the end of the technical development.

Another contribution is the Identification of binding constraints. Typical reviews include multiple barriers, but they are not explicitly prioritized. According to the present synthesis, the following steps for the firms to take should be: Identifying the least-ready critical dimension that could stop the firms on the intended business path. Even if a candidate possesses good clinical data, it may not be sufficient because of scale-up and/or sustainable supply concerns; and even if a widely used bioactive has robust clinical evidence, it may be hampered mainly by the lack of good clinical evidence. By making the binding constraint a priority, the barrier list becomes a prioritized staged decision/funding tool.

The strength of the claim must also be balanced with the strength of the evidence to be commercially successful. The broad antioxidant or health claims may be of interest to the market, but they don't necessarily result in a clinically differentiated product. Wani et al. (2026) and Kaundal and Kumar (2025) argue that there is a trend towards moving towards chemically defined preparations and evidence-backed claims. The most compelling market propositions are a combination of formulation, validated specification/bio-markers, clinically relevant endpoints, and a value statement. This minimises the likelihood of an over-ambitious marketing objective that is not supported by scientific and/or regulatory evidence.

Overall, the findings helped to broaden the focus from a compound-centric to product-system perspective. The commercial unit is not just the molecule they're also the authenticated source and process, the formulation and composition, the clinical evidence, the regulatory pathway, the manufacturing system, the supply network, and the IP position and market claim. Existing NRFHH reviews provide scientific support for many of these components, while the present review organizes them through a business-oriented readiness logic. This structure can be used to compare opportunities, identify missing evidence, and decide whether to build, partner, license, co-develop, defer, or stop without assuming that every plant-based bioactive should become a conventional pharmaceutical.

Overall, plant-based bioactive commercialization requires scientific depth, product engineering, and strategic coordination. Commercial potential is most likely to be realized when the intended pathway is considered from the beginning of development. Commercialization should therefore be treated as an ongoing process of reducing uncertainty while preserving the distinctive value of natural-resource-based products.

Commercialization readiness should also be reassessed dynamically. Readiness is not a single evaluation performed at the end of preclinical development. New evidence may reveal that a previously low-risk domain has become the dominant constraint, for example after a formulation change, loss of a source region, or failure to meet a clinical endpoint. The framework can therefore be used as an ongoing portfolio-review tool in which the sponsor updates the evidence profile at each development gate, identifies the current binding constraint, and adjusts strategy accordingly.

The review is also supportive of co-design of regulatory and market strategy. Unlike a nutraceutical, a prescription botanical drug will need to have an evidence pathway that meets the requirements of therapeutic claims, as well as a quality regime. Indrayanto (2024) and Jadhav et al. (2025) illustrate how the lack of distinction between product classes and jurisdictions can have development implications for practice. Discussions with regulators in the early stages can thus minimize the investment in an inappropriate product architecture for the targeted market (Tanveer et al., 2025).

Local manufacturing and supply might be especially significant in emerging markets. Traditional knowledge and raw materials can be found in certain areas of the world that are rich in medicinal plants, but may not have advanced analytics, clinical development, and manufacturing infrastructure for GMP. Partnerships may bring together local sourcing and knowledge and special quality, formulation, clinical and/or regulatory expertise. The arrangements should be based on clear agreements for the sharing of benefits and intellectual property, particularly if the selection of candidates is based on TK.

Product complexity is also a factor in the commercial pathway. It is more challenging to integrate a multi-component extract into existing CMC and analytical workflows than a highly purified compound, but complex botanicals can have reproducible combinations that are responsible for clinically-relevant activity. Both Aware et al. (2022) and Nasim et al. (2022) discuss the importance of deliberately selecting one of these concepts of development over the other, as often as not, purification is not better development. Complexity should be kept to the extent that it adds to the value proposition that can be repeated in therapy, and stripped away when it adds mostly to the extraneous variability of the process (Singla et al., 2025).

The review also suggests that Evidence Infrastructure can be a competitive advantage. Research efficiency and regulatory communication can be enhanced by well-structured metadata, curated clinical data, well-structured fingerprints, and quality phytochemical databases and reference materials. Data quality and standardization are cited as key factors restricting the applicability of AI for discovery (Patil et al., 2026; Saxena et al., 2026; Rehman et al., 2025). Investment in evidence infrastructure can then help mitigate any duplications and speed up learning on several candidates' portfolios.

Plant-derived products compete not only with other natural (pharmaceutical, biologic, and conventional dietary supplement) products, but also with medical foods, procedural health interventions, digital health interventions, and other plant-based products. They rely on the differentiation that they provide in terms of efficacy, safety, tolerability, convenience, cost, and sustainability. The literature on approved natural-product-derived drugs indicates that there is no single formula for success and that viable products may occupy clinically meaningful niche markets (Butler et al., 2026; Madan et al., 2026; Aoudia et al., 2025).

There is also clinical evidence that there is a need to differentiate proof of concept from product validation. A positive clinical signal in a small exploratory study alone is not sufficient to create a commercially defensible indication if the formulation, dose, patient population, and/or endpoint is not reproducible. Khosravi and Seifert (2024) demonstrate the need to consider the design and formulation of trials and the exposure when interpreting clinical claims related to curcumin. The same challenges exist in the field of phytochemistry, and large amounts of preclinical data and information can be accompanied by few, if any, large-scale clinical trials (Kim et al., 2025; Shoaib et al., 2023). In addition, a related systematic review of the bioactives from plants in central nervous system disorders also argues for indication-specific translational evidence (Zhang et al., 2024b). Firms should, therefore, develop programs for predetermined evidence levels, not around the number of publications.

Formulation strategy should also be aligned with the intended route of administration and therapeutic goal. Improved solubility creates value only when it produces a meaningful improvement in exposure or clinical performance. Uptake enhancers or advanced delivery systems, on the other hand, can cause manufacturing, toxicology, or regulatory challenges that do not justify their use in specific applications. Specific formulation limitations can be overcome using plant-compatible delivery systems (Kothapalli and Vasanthan, 2024; McClements, 2022; Zhang et al., 2024a), but these need to be considered in combination with the other aspects of formulation, such as stability, manufacturability, safety, and evidence of translatability. Therefore, the overall benefit-risk profile, and not physicochemical improvement, should be considered in commercial decisions.

Another discovery is with regard to the timing of the standardization. Additional quality attributes should be specified prior to the generation of pivotal efficacy claims, to ensure that the clinical or commercial product is similar to the product which yielded the original signal. There are several factors that can influence the active fraction in complex botanical products, including harvest time, source geography, plant species, and processing. This will help to use an analytical method, process parameter, and biological assay in a "quality by design" relationship from the beginning. Conservation of standards literature and NRFHH reviews also suggest that quality assurance should not be performed only after therapeutic changes. Similarly, the standardisation literature and NRFHH reviews say that it should be integrated into the extraction and characterisation process and not only after therapeutic changes (Kaundal and Kumar, 2025; Thyagarajan et al., 2026).

5. CONCLUSION

The phytopharmaceutical, botanical-drug, nutraceutical, and advanced-delivery products are hugely promising for using bioactive compounds from plants as therapeutic agents, but to take advantage of this potential, scientific and technological readiness, clinical validation, regulatory approval, and industrialization of the compounds are needed. The variability of raw materials, bioavailability, evidence quality, standardization, scale-up, supply, and market positioning are not independent issues, but are all interconnected. A commercialization-readiness approach can then help drive staged decision gates, capability building focused on the product, and evidence generation. Depending on the binding constraint, biopharma companies could need to develop in-house, partner, license, or leverage platform technologies. Standardization, clinical support, manufacturability, defensible value proposition, sustainability, and commercial success are most likely if plant-derived products meet these requirements.

6. STRENGTHS AND LIMITATIONS

In this review, the evidence from both a scientific and a commercial and regulatory point of view is combined, and a selection process was conducted through a transparent PRISMA process, which included 40 studies. It is a multidisciplinary approach

that allows for comparison of various fields such as phytochemistry, formulation, clinical translation, regulatory, manufacturing, and strategy. Key caveats include that the evidence included is of variable study design, outcomes for commercialization are not routinely reported, the regulatory context varies by jurisdiction, and evidence from the market is not directly comparable across product classes. Therefore, the review is not able to estimate pooled effects, and thresholds of universal commercialization are not defined. The proposed framework should be viewed as a model for decision support purposes that needs to be validated in the future with the help of case studies of firms, longitudinal development data, costs and time, regulatory milestones, and commercialization outcomes.

7. FUTURE RESEARCH AND RECOMMENDATIONS

The proposed commercialization-readiness framework should be evaluated in prospective plant-bioactive development programs, and the different dimensions of readiness should be correlated with subsequent development success. Key focus areas are validated standardization techniques, meaningful biomarkers, product comparability, scaled-up formulation, regulatory harmonization, sustainable feedstock systems, and post-market evidence. Time to market and development cost must also be considered in future biopharma research with regard to partnerships, licensing, prioritization to be supported by AI and platform manufacturing. Comparative case studies may show the strongest predictor of success in therapeutic versus nutraceutical pathways, and interventions that most effectively minimize commercial risk, regarding the dimensions of readiness.

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AUTHOR CONTRIBUTIONS

Author1: Conceptualization, methodology, investigation, data curation, formal analysis, writing—original draft, writing—review and editing. Author2: Conceptualization, methodology, validation, supervision, writing—review and editing. All authors approved the final manuscript.

CONFLICT OF INTEREST

The authors declare that they have no known conflict of interest.

ETHICS STATEMENT

Ethical approval was not required because this review used previously published literature and publicly available scientific or regulatory information and did not involve human participants, animals, or identifiable personal data.

DATA AVAILABILITY STATEMENT

The search strategy, study-selection logic and extracted evidence matrix supporting this review are available from the corresponding author upon reasonable request.

REFERENCES

[1] Ahmad, M., Tahir, M., Hong, Z., Zia, M.A., Rafeeq, H., Ahmad, M.S., Rehman, S., Sun, J., 2025. Plant and marine-derived natural products: sustainable pathways for future drug discovery and therapeutic development. Frontiers in Pharmacology 15, 1497668. doi:10.3389/fphar.2024.1497668.

[2] Aware, C.B., Patil, D.N., Suryawanshi, S.S., Mali, P.R., Rane, M.R., Gurav, R.G., Jadhav, J.P., 2022. Natural bioactive products as promising therapeutics: A review of natural product-based drug development. South African Journal of Botany 151, 512–528. doi:10.1016/j.sajb.2022.09.002.

[3] Barakat, M., Thiab, S., Alzaghari, L.F., Abdulrazzaq, S.B., Hasen, E., Abuarab, S.F., Nasereddin, L., Omar, A., Barakat, Y., Chellappan, D.K., Al-Najjar, M.A.A., 2025. Cannabis and the immune response: A comprehensive review of therapeutic potential and concerns. Phytomedicine Plus 5(4), 100876. doi:10.1016/j.phyplu.2025.100876.

[4] Basnet, B.B., Zhou, Z.-Y., Wei, B., Wang, H., 2025. Advances in AI-based strategies and tools to facilitate natural product and drug development. Critical Reviews in Biotechnology 45(7), 1527–1558. doi:10.1080/07388551.2025.2478094.

[5] Butler, M.S., Capon, R.J., Blaskovich, M.A.T., Henderson, I.R., 2026. Natural product-derived compounds in clinical trials and drug approvals. Natural Product Reports 43(1), 20–88. doi:10.1039/d5np00031a.

[6] Christy, J.H., Bansal, P., Singh, J., Ravishankar, P., Yeasmin, L., Desai, M.M., Xasanova, N., Kumar, A.A., 2026. Medicinal Plant Research: Current Advances, Challenges, and Future Directions. Natural Resources for Human Health 6(3).

[7] Devabattula, G., Panda, B., Yadav, R., Godugu, C., 2024. The Potential Pharmacological Effects of Natural Product Withaferin A in Cancer: Opportunities and Challenges for Clinical Translation. Planta Medica 90(6), 440–453. doi:10.1055/a-2289-9600.

[8] El-Saadony, M.T., Saad, A.M., Mohammed, D.M., et al., 2025. Plant bioactive compounds: extraction, biological activities, immunological, nutritional aspects, food application, and human health benefits—A comprehensive review. Frontiers in Nutrition 12, 1659743. doi:10.3389/fnut.2025.1659743.

[9] Esmeeta, A., Adhikary, S., Dharshnaa, V., Swarnamughi, P., Maqsummiya, Z.U., Banerjee, A., Pathak, S., Duttaroy, A.K., 2022. Plant-derived bioactive compounds in colon cancer treatment: An updated review. Biomedicine & Pharmacotherapy 153, 113384. doi:10.1016/j.biopha.2022.113384.

[10] Gharal, R.R., Paswan, D., Karavadi, B., Singh, A., Kalra, S., Raja, K.V.N., Makhmudov, A., Chamundeeswari, D., 2026. Medicinal Plants as Sources of Multi-Target Therapeutics: Advances in Phytochemistry and Computational Biology. Natural Resources for Human Health 6(3).

[11] Gupta, S., Kumar, B.S., Sahoo, A., Sapaev, I., Tiwari, Y., Sonavale, R., Bhati, H., Sundarasamy, K., 2026. An Integrated Molecular Docking and Machine-Learning Framework for Prioritising Natural Anticancer Leads from South Indian Medicinal Plants against Multiple Validated Cancer Targets. Natural Resources for Human Health 6(3).

[12] Haif, S.K., Al Kury, L.T., Talib, W.H., 2024. Combination of Thymoquinone and Intermittent Fasting as a Treatment for Breast Cancer Implanted in Mice. Plants 13(1), 35. doi:10.3390/plants13010035.

[13] Hegde, M., Girisa, S., BharathwajChetty, B., Vishwa, R., Kunnumakkara, A.B., 2023. Curcumin Formulations for Better Bioavailability: What We Learned from Clinical Trials Thus Far? ACS Omega 8(12), 10713–10746. doi:10.1021/acsomega.2c07326.

[14] Helf, M.J., Buntin, K., Klančar, A., Rust, M., Petersen, F., Pistorius, D., Weber, E., Wong, J., Krastel, P., 2024. Scaling up for success: from bioactive natural products to new medicines. Natural Product Reports 41(12), 1824–1834. doi:10.1039/D4NP00022F.

[15] Indrayanto, G., 2024. Regulation and standardization of herbal drugs: Current status, limitation, challenge's and future prospective. Profiles of Drug Substances, Excipients and Related Methodology 49, 153–199. doi:10.1016/bs.podrm.2023.11.003.

[16] Jadhav, R., Das, J., Rajyaguru, S., Kyada, S., Kale, V., Teja, P.K., Bhutia, D.O., et al., 2025. Regulations, current development, and future prospects of phytopharmaceuticals, a new class of herbal medicines in India. Discover Pharmaceutical Sciences 1, 6. doi:10.1007/s44395-025-00006-4.

[17] Kaundal, R., Kumar, D., 2025. Current demands for standardization of Indian medicinal plants: A critical review. Medicine in Drug Discovery 27, 100211. doi:10.1016/j.medidd.2025.100211.

[18] Khosravi, M.A., Seifert, R., 2024. Clinical trials on curcumin in relation to its bioavailability and effect on malignant diseases: critical analysis. Naunyn-Schmiedeberg's Archives of Pharmacology 397, 3477–3491. doi:10.1007/s00210-023-02825-7.

[19] Kim, H.K., Kim, S.J., Gil, W.J., Yang, C.-S., 2025. Exploring the therapeutic potential of phytochemicals: challenges and strategies for clinical translation. Phytomedicine 145, 157090. doi:10.1016/j.phymed.2025.157090.

[20] Kothapalli, P., Vasanthan, M., 2024. Lipid-based nanocarriers for enhanced delivery of plant-derived bioactive molecules: a comprehensive review. Therapeutic Delivery 15(2), 135–155. doi:10.4155/tde-2023-0116.

[21] Liu, W., Chen, X., Li, H., Zhang, J., An, J., Liu, X., 2022. Anti-Inflammatory Function of Plant-Derived Bioactive Peptides: A Review. Foods 11(15), 2361. doi:10.3390/foods11152361.

[22] Madan, P., Janakiraman, K., Patel, S., Chandra, S., Sapaev, I., Priyan, S., Ganapathy, B., 2026. From Traditional Medicine to Modern Oncology: Mechanistic Insights into Plant-Derived Anticancer Agents. Natural Resources for Human Health 6(3).

[23] Maind, R., Halder, S., Bhat, A.R., Bhattacharya, D., Mujahid, M.H., Abu-Rayyan, A., Iqbal, M., Upadhye, V.J., Ahmed, S., Alam, M., Tataringa, G., 2025. Biomimetic green synthesis of ZnO nanoparticles using Cheilocostus speciosus and Gardenia gummifera with comprehensive characterization and bioactivity assessment. Scientific Reports 15, 44323. doi:10.1038/s41598-025-30720-z.

[24] McClements, D.J., 2022. Recent progress in the application of plant-based colloidal drug delivery systems in the pharmaceutical sciences. Current Opinion in Colloid & Interface Science 61, 102734. doi:10.1016/j.cis.2022.102734.

[25] Nasim, N., Sandeep, I.S., Mohanty, S., 2022. Plant-derived natural products for drug discovery: current approaches and prospects. Nucleus 65, 399–411. doi:10.1007/s13237-022-00405-3.

[26] Patil, B.K., Udugade, S.B., Kumar, H., Mazumder, A., Makhija, H., Anand, D.A., Soundararajan, K., Voronina, N., 2026. AI-Based Prediction of Pharmacological Activities of Plant-Derived Natural Products: Advances, Applications, Challenges, and Future Perspectives. Natural Resources for Human Health 6(3).

[27] Popovic, L., Rijkers, G.T., 2026. Phytochemicals: Principles and Practice. Biology 15(1), 18. doi:10.3390/biology15010018.

[28] Rasheed, H., Channa, I.S., Kainat, S., Tahir, M.A., 2026. Molecular Mechanisms and Therapeutic Implications of Oleuropein, a Multitarget Phytochemical in Lung Cancer. Majestic Journal of Pharmacology and Toxicology 1. doi:10.65080/mjpt.v1.CM2601113002.

[29] Sahoo, H.P., Sahoo, R.K., Parida, S., Sahoo, B.M., Gochhi, M., Dash, P., Das, C., Ghosh, G., Rath, G., Kar, B., 2026. Phytochemicals as Promising Therapeutics in Cancer Prevention and Treatment: Mechanisms and Applications. Current Cancer Drug Targets 26(8), 925–945. doi:10.2174/0115680096451740260311114647.

[30] Saldívar-González, F.I., Aldas-Bulos, V.D., Medina-Franco, J.L., Plisson, F., 2021. Natural product drug discovery in the artificial intelligence era. Chemical Science 13(6), 1526–1546. doi:10.1039/d1sc04471k.

[31] Saxena, P., Sharma, P., Balasundaram, S., Barman, B., Panda, B.K., Srivastava, K., Khaitov, F., Karimova, M., 2026. Systems Biology Approaches for Understanding the Therapeutic Mechanisms of Medicinal Plants. Natural Resources for Human Health 6(3).

[32] Shete, A.S., Singh, G., Mukhamadieva, N., Sapaev, I., Tiwari, Y., Sonavale, R., Bhati, H., Sundarasamy, K., 2026. Integrating Network Pharmacology and Molecular Docking to Discover Novel Therapeutic Phytochemicals. Natural Resources for Human Health 6(3).

[33] Shoaib, S., Ansari, M.A., Al Fatease, A., et al., 2023. Plant-Derived Bioactive Compounds in the Management of Neurodegenerative Disorders: Challenges, Future Directions and Molecular Mechanisms Involved in Neuroprotection. Pharmaceutics 15(3), 749. doi:10.3390/pharmaceutics15030749.

[34] Singh, K., Gupta, J.K., Chanchal, D.K., Shinde, M.G., Kumar, S., Jain, D., Almarhoon, Z.M., Alshahrani, A., Calina, D., Sharifi-Rad, J., Tripathi, A., 2025. Natural products as drug leads: exploring their potential in drug discovery and development. Naunyn-Schmiedeberg's Archives of Pharmacology 398(5), 4673–4687. doi:10.1007/s00210-024-03622-6.

[35] Suryavanshi, N.J., Wani, T.A., Sapaev, I., Arumugam, M., Krishnamoorthy, P., Mittal, C., Kapoor, T., 2026. Green Nanotechnology and Functional Foods: Emerging Opportunities in Human Health. Natural Resources for Human Health 6(3).

[36] Talib, W.H., Atawneh, S., Shakhatreh, A.N., Shakhatreh, G.N., Rasheed Aljarrah, I.S., Hamed, R.A., Banyyounes, D.A., Al-Yasari, I.H., 2024. Anticancer potential of garlic bioactive constituents: Allicin, Z-ajoene, and organosulfur compounds. Pharmacia 71, 1–23. doi:10.3897/pharmacia.71.e114556.

[37] Thyagarajan, R., Varshney, S., Kaushik, V., Vignesh, J., Yaxyayeva, K., Priyadharshini, G., Durga, B., Della, M.E.S., 2026. Advances in Phytochemical Research: Sustainable Utilization of Medicinal Plants for Pharmaceutical and Nutraceutical Applications. Natural Resources for Human Health 6(3).

[38] Wang, Y., Wang, F., Liu, W., Geng, Y., Shi, Y., Tian, Y., Zhang, B., Luo, Y., Sun, X., 2024. New drug discovery and development from natural products: Advances and strategies. Pharmacology & Therapeutics 264, 108752. doi:10.1016/j.pharmthera.2024.108752.

[39] Wani, T.A., Sudhakar, K., Sapaev, I., Parthasarathy, R., Shanmugapriya, V., Bera, K., Mittal, S., 2026. Bioactive Peptides and Polyphenols as Next-Generation Nutraceuticals: Mechanisms, Bioavailability, and Clinical Prospects. Natural Resources for Human Health 6(3).

[40] Washida, H., Yoshinaka, K., Yamada, O., Ookawa, S., Yuki, M., 2025. Toward the commercialization of recombinant pharmaceuticals expressed in plants. Plant Biotechnology 42. doi:10.5511/plantbiotechnology.24.1130a.

[41] Wu, C., Lee, S.-L., Taylor, C., Li, J., Chan, Y.-M., Agarwal, R., Temple, R., Throckmorton, D., Tyner, K., 2020. Scientific and Regulatory Approach to Botanical Drug Development: A U.S. FDA Perspective. Journal of Natural Products 83(2), 552–562. doi:10.1021/acs.jnatprod.9b00949.

[42] Xie, S., Zhan, F., Zhu, J., Xu, S., Xu, J., 2025. The latest advances with natural products in drug discovery and opportunities for the future: a 2025 update. Expert Opinion on Drug Discovery 20(7), 827–843. doi:10.1080/17460441.2025.2507382.

[43] Zhang, A., Huang, J., Liu, Y., Gong, H., Guan, F., Li, W., Han, F., Wang, Y., 2024a. Hyaluronic acid application strategies for plant bioactive component delivery: A review. International Journal of Biological Macromolecules 282, 137129. doi:10.1016/j.ijbiomac.2024.137129.

[44] Zhang, N., Zhang, S., Dong, X., 2024b. Plant-derived bioactive compounds and their novel role in central nervous system disorder treatment via ATF4 targeting: A systematic literature review. Biomedicine & Pharmacotherapy 176, 116811. doi:10.1016/j.biopha.2024.116811.

[45] Sawarkar, P.G., Pote, A., Khan, M.A., Abed, M.H., Hadi, A.A., Smerat, A., Khishe, M. 2025: Sustainable geopolymer concrete evaluation using machine learning and PDP analysis: Comparative insights into strength prediction.: Hybrid Advances 11, 100569.

[46] Sohail, M., Nazir, U., Mahariq, I., Elmasry, Y. 2025: Implementation of FEM and Taguchi analysis on blood flow for Casson fluid inclusion of di- and tri-Hamilton Crosser nanofluid through the cylinder with a rough surface.: Mechanics of Time-Dependent Materials 29.

[47] Marouani, I., Hassan, W.H., Singh, P.K., Hasan, M., Boujelbene, M., Mahariq, I., Channuie, P., Atamurotov, F., Yuennan, J., Diab, M.A. 2025: Construction of a novel coffee husk-derived biochar-supported Ce2Sn2O7-Sb2O3 composites for enhanced visible light-driven photocatalytic degradation of metronidazole and H2 production.: Journal of Water Process Engineering 75, 107935.

[48] S. N. Raju et al., "GeoDisasterAINet: An Explainable Deep Ensemble Framework for Real-Time Urban and Rural Disaster Classification and Resilience," in IEEE Access, vol. 13, pp. 97944-97974, 2025, doi: 10.1109/ACCESS.2025.3574451.

[49] Benaziza, N., Kezzar, M., Rashid, F.L., Shah, N.A., Idris, S.A., Sari, M.R., Mahariq, I. 2025: Statistical and numerical investigation on heat transfer of MHD ternary hybrid nanofluid flow in convergent–divergent channel via Taguchi analyses.: Journal of Thermal Analysis and Calorimetry 150, 10201–10220.

[50] Galal, A.M., Idris, S.A., Abbas, M., Saydaxmetova, S., Ali, A.H., Kanwal, H., Mahariq, I., Akgül, A. 2024: Comparison study of modified and classical Hamilton–Crosser models for electrophoretic and thermophoretic particle deposition in stagnation point flow of diamond –SiC–Co3O4/diathermic oil-based trihybrid nanofluid.: Journal of Thermal Analysis and Calorimetry 150, 2195–2208.

[51] Aoudia, M., Abbas, M., Marzouki, R., Norberdiyeva, M., Bayram, M., Akgül, A., Faqihi, A.A., Mahariq, I. 2025: Tribology thermal-solutal analysis of oxytactic and gyrotactic microorganisms in ternary hybrid nanofluid with local thermal non-equilibrium effects.: Journal of Thermal Analysis and Calorimetry 150, 16701–16717.

[52] Rehman, W.U., Koondhar, M.A., Afridi, S.K., Albasha, L., Smaili, I.H., Touti, E., Aoudia, M., Zahrouni, W., Mahariq, I., Ahmed, M.M.R. 2025: The role of 5G network in revolutionizing agriculture for sustainable development: A comprehensive review.: Energy Nexus 17, 100368.

[53] Tanveer, M.U., Munir, K., Raza, A., Abualigah, L., Garay, H., Gonzalez, L.E.P., Ashraf, I. 2025: Novel transfer learning approach for detecting infected and healthy maize crop using leaf images.: Food Science & Nutrition 13, e4655.

[54] Singla, M.K., Gupta, J., Kumar, R., Jangir, P., Louzazni, M., Giri, N.C., Al-Gburi, A.J.A., Ei-Kenawy, E.I.-S.M., Alharbi, A.H. 2025: Enhancing solid oxide fuel cell efficiency through advanced model identification using differential Evolutionary mutation Fennec Fox algorithm.: International Journal of Computational Intelligence Systems 18.