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REFRAMING AGRICULTURAL SUSTAINABILITY: CULTURAL PRACTICES AND INTEGRATED PEST AND NUTRIENT MANAGEMENT FOR ENVIRONMENTAL PROTECTION

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ABSTRACT
Agricultural sustainability has become a necessity amid the environmental degradation, decline of soil quality, loss of biodiversity and limitations of input-intensive farming systems. This review focuses on the role of cultural agricultural practices, integrated pest management and integrated nutrient management on sustainable production of crops and environmental protection. It identifies the role of crop rotation, intercropping, polyculture, conservation tillage, cover crops, and organic amendments in enhancing soil health, ecosystem resilience, and efficiency of resource use. The review also discusses the significance of integrated pest and nutrient management in reducing dependence on synthetic agrochemicals, strengthening ecological balance, and supporting long-term agricultural productivity. In addition, it explores the growing importance of plant-derived bioactive compounds from sustainable agriculture and their nutritional, therapeutic, and pharmaceutical relevance. Emerging delivery technologies, including lipid-based nanocarriers, encapsulation systems, controlled release approaches, and plant-derived extracellular vesicles, further extend the value of these natural compounds. Despite promising progress, challenges related to standardization, scalability, formulation stability, and regulatory acceptance remain substantial. Overall, the review emphasizes that the integration of ecologically sound farming practices with advances in bioactive research and delivery technologies offers a promising pathway toward environmentally responsible agriculture and value-added utilization of plant resources.

KEYWORDS: agricultural sustainability, cultural practices, integrated pest management, integrated nutrient management, plant-derived bioactive compounds

1. INTRODUCTION
Food security, economic stability and provision of essential ecosystems are fundamentals of agriculture, which is a basic factor in maintenance of global food security. Nevertheless, increasing stress on the natural resources has cast a very important question regarding the sustainability of agricultural production systems in the long run. Agricultural sustainability refers to the ability of agriculture systems to be productive and at the same time be able to sustain environments, economy and social well being. This idea gives consideration to the principle of ecological balance, rational utilization of resources and capacity to withstand environmental pressures, and thus offers a significant guideline to the contemporary agricultural development policies[1]. Although increasing the awareness of the sustainability goals, the establishment of sustainability in agricultural systems is complicated due to the interconnection of the environmental, economic and technological variables to agricultural activities and resources management[2].
The principles that are used to develop sustainable agriculture are based on the principles of ecological stability, effective recycling of nutrients and reduced environmental disruption. These values support a sustainable use of soil, water, biodiversity and energy and a steady crop production. The contemporary sustainability models encourage agricultural systems which are less reliant on the external use of chemical inputs into the system and which enhance the operations of the natural ecosystems. Incorporation of ecological processes into agricultural management has therefore been needed to ensure the long-term agricultural productivity as well as conservation of the environmental resources[3]. The acceleration of conventional agriculture has contributed immensely to the degradation of the environment by over utilizing agrochemicals, unsustainable land management and the exploitation of natural resources. The result of such practices may be a higher pace of soil erosion, reduced soil fertility and the distortion of natural ecological balance, which, in its turn, may be a threat to the productivity of agriculture as well as to the balance of the ecosystem. Unsustainable land-use and ineffective resource management are commonly associated with environmental degradation in agricultural landscapes, and the adverse effects on biodiversity, water quality and climate resilience have been identified[4]. Moreover, the

anthropogenic agricultural activities are also causing bigger environmental problems like pollution, habitat damage and ecosystem degradation, and that is why there is a dire need to find more sustainable approaches to agriculture[5]. Agroecological strategies have emerged as viable channels of putting these sustainability concerns into practice. Agroecology is concerned with applying ecological principles in agricultural systems in a manner that improves the level of biodiversity, soil well-being, and the ecosystem becomes stronger. Sustainable whole-system approach to agriculture includes agricultural practices like crop diversification, conservation agriculture and ecological pest management since they help in improving the ecosystem services and minimizing the environmental risks associated with the conventional agricultural practices[6]. Integrated pest management (IPM) has been of significant interest amongst sustainable agricultural practices as a viable measure to reduce the ecological impact of pest control and management, although at the same time, it should be adopted to ensure crop productivity. IPM involves a combination of biological, cultural and mechanical ways of control alongside limited and controlled usage of chemical pesticides. Such a method can help reduce reliance on pesticides, input levels, and protect the beneficial species, as well as ensure the biodiversity of the agricultural ecosystems[7]. On the same note, there is also integrated nutrient management (INM) that is significant towards ensuring soil fertility and crop productivity. INM is a symbiotic application of organic nutrients, biofertilizer and inorganic nutrients to obtain the optimum plant nutrition with minimum pollution of the environment. This plan has been known to enhance the cycling of nutrients, enhance the soil structure, besides leading to agricultural sustainability in the long run[8]. The process of sustainable agricultural practices also influences the yield and quality of plant-derived bioactive compounds with enormous nutritional and therapeutic potential. Various secondary metabolites are synthesized by plants, and they comprise phenolics, flavonoids and alkaloids, and they are significant in plant defense and human health. These compounds can be biosynthesized better through ecologically sound farming techniques and improved nutrient management which makes the connection between sustainable agriculture and the production of nutritionally and pharmacologically useful plant resources[9]. The growing interest in natural bioactive products has only served to strengthen the connection between sustainable agriculture and pharmaceutical innovation, with a number of compounds of plant origin undergoing intensive research with regard to antimicrobial, antioxidant and therapeutic properties[10].

In light of the environmental issues that have still been emerging with the use of conventional farming processes, it is notable to pass through the tests of sustainable practices, which seek to attain ecological balance as well as support the productive farming systems. This review thus argues the importance of cultural agricultural practices, integrated pest management and integrated nutrient management in ensuring agricultural sustainability and protection of the environment. It also highlights the potential relationship between the sustainable agricultural systems and the bioactive compounds of the plant origin production and their use in human health and pharmaceutical sciences.

2. REVIEW METHODOLOGY

This comprehensive review was prepared with a structured and theme-based evaluation of published literature available regarding agricultural sustainability, cultural practice, integrated pest management, integrated nutrient management, and plant-derived bioactive compounds in relation to their environmental and pharmaceutical importance. Topical relevance, scientific quality and contribution to the purpose of the review were used to screen relevant articles, reviews and book chapters that were found in peer-reviewed academic sources. First preference was given to the new and conceptually significant research on the problems dealing with the principles of sustainability, the ecological crop production, nutrient and pest regulation, as well as the bioactive application of plants. The selected literature was then grouped into large thematic categories to allow a critical synthesis of the existing knowledge and highlight the existing challenges and future research agenda on sustainable agriculture and associated bioactive innovation.

3. Agricultural Sustainability and Environmental Protection

3.1 Sustainability principles and conventional agriculture

Agricultural sustainability is founded on the principles of equalizing the needs of the environment, economic performance and social well-being in the farming systems. These principles are concerned with maximizing the utilization of resources, maintaining the soil fertility, biodiversity and resilience to environmental pressures. Setting up the standardized sustainability reference points provides a guideline to organize the evaluation of the agriculture practices and the management approaches towards the environmentally sound production systems[11]. On the other hand, modern agriculture has employed intensive modes of production like mechanization, monocropping and excessive application of synthetic fertilizers and pesticides in the past. As much as these methods have contributed to the increase in crop production and enhancing food supply globally, such methods are inclined towards prioritizing the short-term productivity over long-term ecological stability. Consequently, conventional agricultural regimes are able to impose environmental strains on the sustainability of agricultural landscapes[12].

3.2 Ecosystem services and land degradation

The agricultural systems provide most of the ecosystem services that are significant to environmental health and well-being of human beings. These services entail the formation of soil, the nutrient cycling, water regulation, pollination, and natural control of pests. Agricultural landscapes can potentially maintain these ecological functions and make the environment stable when they are well managed. Nevertheless, the excessive intensification and overexploitation of resources may augment the flaws and low stability of the agricultural systems in the ecosystem services[13]. Land degradation is one of the most severe impacts of unsustainable agricultural practices. Such activities as over-grazing, deforestation and improper cultivation may enhance soil erosion, reduce soil fertility and interfere with ecological processes. These transformations are harmful to biodiversity and an impediment to the ecosystem services that are important to support productive and environmentally viable agricultural systems[14].

3.3 Environmental impacts of agricultural intensification
Agricultural intensification has on many occasions been cited as one of the biggest causes of biodiversity loss in many sections of the world. Natural habitats and ecological communities may be seriously affected by the expansion of agricultural areas, increased utilization of agrochemicals, overuse of wells and soil degradation. These disruptions reduce the diversity of the species and disturb ecological interactions, which facilitate ecological stability and agricultural productivity in the ecosystem[15]. Another source of environmental degradation is chemical pollution as a result of agricultural activities. Massive application of pesticides and fertilizers along with other agrochemicals may lead to the pollution of soils and water bodies, the effects of which affect non-target organisms and alter the ecological processes. Such pollution may decrease the biodiversity and ecosystem goods and services and hence increase the environmental hazards in agricultural landscapes[16].

3.4 Sustainable management approaches
These environmental issues mean that sustainable agricultural management systems need to be adopted, which involves consideration of ecological, economic, and social issues. Some of the practices that are considered sustainable include good stewardship of the soil, maintenance of the biodiversity, efficient use of the nutrients and the reduced use of synthetic chemical inputs. These methods offer benefits to environmental conservation as well as sustainability in agriculture and enhance the welfare of the farmers, and eventually lead to the sustainability of agricultural systems[17]. The idea conceptual relationship among the principles of sustainable use, conventional agricultural pressures, environmental degradation and sustainable management paths are summarized in Figure 1.

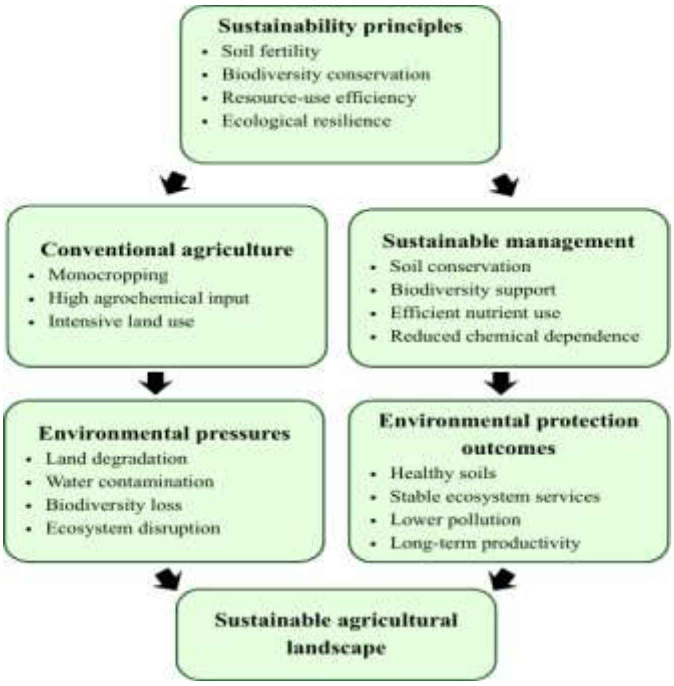

Figure 1. Agricultural sustainability framework and environmental protection

4. Cultural Agricultural Practices for Sustainable Crop Production
4.1 Crop rotation and diversification
Crop rotation is one of the simplest cultural practices with regard to increasing the diversity of the cropping systems as well as the resilience of the ecosystems that enhance the sustainability of agriculture. Rotational systems imply crops with alternative growing of crops on the same plot of land that allow keeping soil fertile, lessening pest and disease cycles, and enhancing the availability of nutrients. Crop diversifications ensure the system's robustness through stabilization of the productivity in the changing environmental factors and limits the susceptibility of the monoculture-based systems[18]. Recent research has indicated that diversified crop rotations are not only effective in enhancing productivity in agriculture, but they also lead to the sustainability of the environment. Rotational diversification is capable of improving soil health, increasing nutrient cycling and decreasing greenhouse gas emissions related to intensive farming systems. These systems enhance moderate use of nutrients and enhance biological activity in the soils, which eventually uphold the long-term crop production and environmental conservation[19].

4.2 Intercropping and polyculture systems

Intercropping and polyculture are significant cultural practices which enhance sustainable crop production by enhancing biodiversity in the agricultural fields. Intercropping entails the cultivation of two or more crops within one field; hence, crops are able to exploit the available resources more effectively. The systems increase the efficiency of resource-use, enhance the nutrient dynamics of soil and assist in stabilizing crop yields in varying environmental conditions[20]. Poly culture farming systems are based on this idea, only that several crop species are introduced into one agricultural environment to create multi-purpose agro-ecosystems. These types of diversified ecologies lower the level of pest pressure, increase the population of beneficial organisms, and increase the stability of the entire ecosystem. Adopting polyculture management, thus, does help in making agricultural development sustainable because it enhances ecological interactions and the achievement of balanced crop productivity[21].

4.3 Conservation tillage practices

Sustainable crop production also largely depends on soil management practices. Limiting soil disturbance through cultivation by conservation tillage has also received some concern as another effective measure to sustain the soil structure and minimize land degradation. Less tillage leads to preservation of soil organic matter, increases water retention and soil microbial activity, hence sustainable agricultural productivity[22]. Conservation tillage also helps in trapping carbon in the soils of agricultural land. Conservation tillage practices are beneficial to the soil by increasing carbon storage in the soil and decreasing carbon losses due to plowing systems that are conventional. This plays a crucial role in enhancing the quality of soil, besides helping in the reduction of climate change, since it minimizes carbon emissions to the atmosphere[23].

4.4 Cover crops and organic amendments

Organic amendments and cover crops are generally known as practices that are useful in enhancing soil health and ensuring crop productivity. Cover crops save the soil against soil erosion, augment soil nutrient cycling, and boost soil organic matter. When used in the agricultural systems, such crops enhance the soil texture, foster soil microbial activities and maintain soil fertility in the long run, which is a critical aspect when it comes to sustainable agricultural crop production[24]. The amendments by organic material like compost and plant residues also increase soil properties by enhancing the availability of nutrients and conditions of soil biology. Cover crops and organic inputs, when used together, can have a great effect on enhancing the properties of the soil and yields, along with a decrease in the use of synthetic fertilizers. These activities, consequently, add up to sustainable farming systems by promoting the health of the soil and improving its productivity in general[25].

4.5 Cultural practices and ecological balance

Cultural agricultural traditions have traditionally insisted on ecological balance and the use of resources. Most traditional and indigenous agricultural systems have employed crop diversification, natural management of nutrients and ecological methods of pest management that have ensured a balance between agricultural production and environmental protection. These strategies put emphasis on the need to combine environmental science with contemporary farming techniques to realize sustainable food production and environmental safeguarding[26]. Figure 2 shows the key cultural agricultural practices and their role in ensuring long-term crop production. Table 1 gives the main agronomic and environmental advantages of the principal cultural agricultural practices.

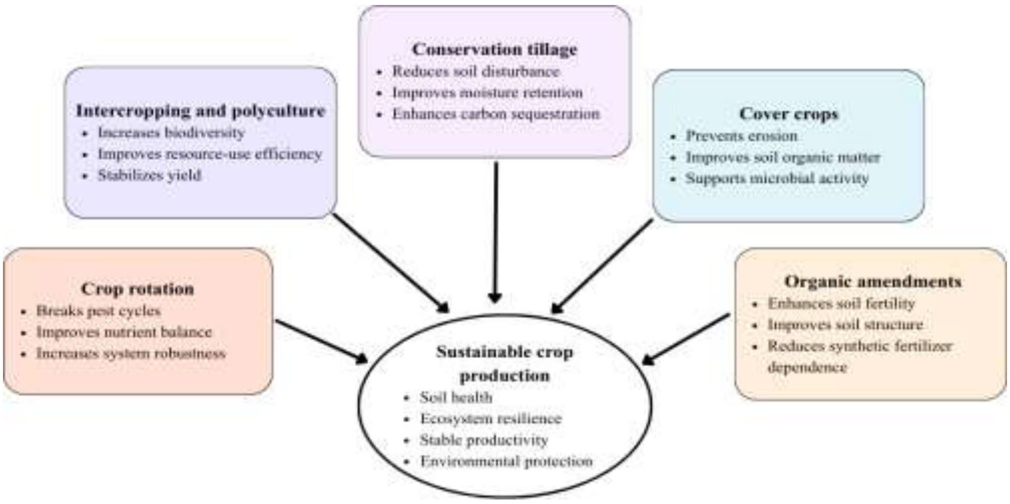

Figure 2. Cultural practices supporting sustainable crop production

Table 1. Major cultural agricultural practices and their sustainability benefits

Practice	Main function	Agronomic benefit	Environmental benefit

Crop rotation	Sequential cultivation of different crops	Improves nutrient balance and yield stability	Reduces pest pressure and supports soil health
Intercropping	Simultaneous cultivation of multiple crops	Enhances resource-use efficiency	Increases field biodiversity
Polyculture	Integration of diverse crop species	Improves system resilience	Strengthens ecological interactions
Conservation tillage	Minimal soil disturbance	Preserves soil moisture and structure	Reduces erosion and supports carbon retention
Cover crops and organic amendments	Soil protection and nutrient enrichment	Improves fertility and crop performance	Enhances organic matter and reduces external input reliance

5. Integrated Pest Management (IPM)

5.1 Concept and sustainability of IPM

Integrated pest management (IPM) is an ecologically friendly, economically viable and socially acceptable crop protection plan aimed at reducing the population of pests. Instead of focusing on the use of chemical pesticides only, IPM integrates preventative, monitoring-friendly, and intervention-based approaches to ensure that pest populations remain below pest-damaging economic levels. Whereas it is well-known that IPM is a sustainable framework, its application in practice is frequently limited in terms of how it can be adopted by farmers, how the knowledge can be transferred, and how complex the system itself is[27]. More recent developments have, however, strengthened IPM as a fundamental sustainability-oriented crop protection strategy involving the combination of ecological concepts with current technologies and management on a decision-based basis[28].

5.2 Biological control strategies

One of the pillars of IPM is biological control, which entails the use of natural predators, parasitoids, and pathogens to control the increase of pests. The strategies assist in long-term suppression of pests with minimal disturbances to the environment and the conservation of non-target organisms. The key to biocontrol success is a selection of control agents, management of the habitat and compatibility with local agroecosystems[29]. Biological control has been shown in both organic and conventional agricultural systems to have significant potential in minimizing pest outbreaks and supplementing larger IPM initiatives, thus enhancing ecological stability and minimizing the dependency on synthetic inputs[30].

5.3 Botanical and bio-based inputs

The plant-derived compounds have gained more and more attention in IPM, whose pesticidal, repellent, and growth-inhibitory effects are considered. Plant-based bioactive compounds, including essential oils, may operate independently or in combination with synthetic pesticides and other bioactive molecules, enhancing the efficacy of pest control and potentially reducing the dose of chemicals used[31]. The botanical pesticide is thus the prospective solution to sustainable pest management since most of them are biodegradable, target-specific, and can be used in conjunction with environmentally responsible agricultural production, but there are still some challenges associated with formulation stability, consistency and field performance[32].

5.4 Microbial and biopesticide approaches

Another significant aspect of IPM is biopesticides that are made out of biological agents. These involve microbial formulations and other biologically developed pest control products that have provided a selective and environmentally friendly alternative to traditional pesticides. Biocontrol agents were rather promising in controlling insect pests and plant pathogens, as well as complementing integrated crop protection systems[33]. Particularly important among them are microbial biopesticides, such as bacteria, fungi and viruses, due to their specificity, lower environmental persistence, and coexistence to other IPM practices[34].

5.5 Reduced pesticide dependence

One of the primary tasks of the IPM is to decrease pesticide reliance by means of the enhanced management of crops and pests. Through a combination of cultural, biological, botanical and microbial practices, IPM reduces the level of application of synthetic pesticides, therefore, the level of chemical residues, environmental pollution and also the hazard to useful organisms. Introducing crop management strategies that enhance the health of the plants and interfere with pest development will significantly reduce the necessity of chemical actions, and IPM is an invaluable way to go towards a sustainable and ecologically friendly agricultural practice[35].

6. Integrated Nutrient Management (INM)

6.1 Concept and role

One balanced method of plant nutrition is known as integrated nutrient management (INM), which is the combination of organic, inorganic and biological nutrients to maintain the productivity of crops without causing soil degradation. In contrast to the input-intensive nutrient management, which relies primarily on the use of synthetic fertilizers, INM is the quest to achieve maximum nutrient availability, enhanced nutrient-use efficiency and permanent soil fertility. This method is becoming a major strategy in ensuring sustainable agriculture since it favors crop production as well as the physical, chemical, and biological properties of the soils[36].

6.2 Effects on yield and quality

The great benefit of INM is that it has a positive effect on nutrient uptake, crop production, and the quality of produce. Combining various sources of nutrients, the crops get a more balanced provision of the key factors during the growth process, enhancing physiological activities and harvest results. Investigations in potato growth have demonstrated that INM can lead to better nutrient uptake and crop yield as well as improvement in crop quality indicators, which means that it can be of practical use in providing sustainable and efficient cultivation of crops[37].

6.3 Organic and bio-based inputs

The INM systems are comprised of organic amendments and biologically derived inputs. When incorporated into a combination of nutrient strategies, biochar and compost can enhance the carbon conditions in soils, increase microbial activity, and make the poor soils active again. These inputs also aid in the enhanced maintenance of soil structure, soil moisture and buffering capability of nutrients, which is mostly applicable in weak or nutrient-deprived environments[38]. Besides that, microbial inoculants like useful bacteria and fungi can enhance the solubility of nutrients and their uptake, which enhances the crop functionality and enables the maintenance of more biologically active and sustainable soil systems[39].

6.4 Precision nutrient management

New developments in nutrient management have also put focus on the site-selective and precision-based strategies. Precision agriculture can be used to apply nutrients selectively to the crop based on the needs of the crop in relation to space and time to minimize nutrient loss and maximize input efficiency. Site-specific crop nutrient management is also compatible with the principles of INM since it is a method that enables integrated sources of nutrients to be put more efficiently, reducing environmental pollution and enhancing productivity in a variety of conditions in the field[40].

6.5 Benefits and constraints

INM has a number of benefits to sustainable agriculture, such as better soil fertility, better crop performance, reduced reliance on chemical fertilizers, and less risk to the environment. It plays its part in the cycling of nutrients, long-term productivity, and the sustainability of farming systems due to the use of balanced resources. It might, however, be limited in its uptake by the availability of organic inputs, inadequate technical expertise and inconsistency in its application at the field level. Nonetheless, INM is an efficient strategy that is sustainable and environmentally friendly in its endeavors to get sustainable agricultural production[41]. Table 2 compares the integrated pest management with the integrated nutrient management in sustainable agriculture.

Table 2. Comparison of IPM and INM in sustainable agriculture

Component	IPM	INM	Shared sustainability outcome
Primary focus	Pest suppression	Nutrient optimization	Improved crop productivity
Main inputs	Biological control, botanicals, microbial biopesticides, cultural methods	Organic amendments, fertilizers, biofertilizers, microbial inoculants	Reduced input inefficiency
Key environmental role	Lowers pesticide dependence and non-target toxicity	Reduces nutrient loss and soil degradation	Lower environmental pollution
System-level effect	Supports biodiversity and ecological pest regulation	Improves soil fertility and nutrient cycling	Greater agroecosystem resilience
Major limitation	Adoption complexity and monitoring demand	Input availability and field-level variability	Need for technical knowledge and management support

7. Plant-Derived Bioactive Compounds from Sustainable Agriculture

7.1 Bioactives and one health

There is growing interest in plant-derived bioactive compounds due to their significance in the agricultural, human and environmental sustainability. These compounds relate to plant resilience, ecosystem stability, and therapeutic value, and, in a One Health view, are not specific to primary metabolism. The application of their role in sustainable agriculture is not only in aiding plant defense and adaptation but also in giving valuable molecules for nutritional and pharmaceutical us[42].

7.2 Major secondary metabolites

Especially important are the secondary metabolites phenolics, flavonoids and alkaloids, terpenoids and other specialized compounds, which are among the plant biomolecules important as bioactives. These metabolites are critical in tolerance of stress, defense, and adaptation to unfavorable environmental conditions in plants. It is identified that phenolic compounds, especially, have been identified as major but not fully appreciated plant-based resilient factors to biotic and abiotic stresses, leading to their relevance to sustainable agricultural systems[43]. Plant-derived secondary metabolites also have extensive biological, agricultural, and pharmaceutical capabilities and, thus, they are at the core of the interface between sustainable crop production and value-added bioresource use[44].

7.3 Bioactivity and phytochemical value

Plant secondary metabolites have been mostly reported to be biologically active in various plant species. These compounds have antioxidant, antimicrobial, anti-inflammatory, and other protective properties, which increase their usefulness as functional food ingredients and antibiotic agents[45]. Phytochemical composition may be different in a range of plant species, genotype, extraction, post-harvest process, and as a result, phytochemical profiling becomes pivotal to high-value plant material identification and transformation to added-value products[46].

7.4 Influence of farming practices

Plant-based bioactive substances have a high level of concentration and composition that is sensitive to agricultural practices. The low-input and sustainable systems are able to alter the metabolic processes of plants and consequently change the phytochemical accumulation. Comparisons of conventional and organic agricultural systems have demonstrated that the cultivation strategy may influence the phytochemical composition of crops, which reveals that the farming systems are intimately correlated with the nutritional and functional quality of plant materials[47].

7.5 Therapeutic and drug potential

Bioactive compounds in plants are becoming a biologically relevant therapeutic option, especially in treating chronic and complex diseases. Their neuroprotective, antioxidant, and anti-inflammatory effects have caught a lot of interest in the neural degenerative disease studies, whilst the obstacles with their stability, bioavailability, and mechanism of action are yet to be overcome[48]. On a larger scale, natural products derived from plants remain an invaluable source of drug discovery with structurally diverse and biologically active molecules of good pharmaceutical potential[49].

8. Emerging Technologies for Delivery of Plant-Derived Bioactives

8.1 Lipid-based nanocarriers

Nanocarriers made of lipids are being considered as promising vectors in the enhancement of the delivery of bioactive molecules derived from plants. These carriers improve solubility, prevent degradation of sensitive phytochemicals, and increase bioavailability, making them more therapeutic and functional. They are also highly flexible in their structure, which can more readily incorporate the hydrophobic plant compounds and thus are useful platforms in the effective delivery of natural bioactives[50].

8.2 Plant-derived nanomaterials

Nanomaterials made of plant materials are becoming popular due to their precise biological uses in the medical field and intelligent farming. The advantages of nanoscale delivery and the inherent biological compatibility of plant-based materials give rise to such materials. Their use provides further possibilities to provide precision, biologically regulated interaction and safer use of the solutions concerning the environment and increases the contribution of the innovations of plant-based use to the bioactive use sustainability[51].

8.3 Controlled release systems

The second technology that is emerging as a vital one in the delivery of the plant-derived bioactives is the controlled-release technologies. They are designed to release active compounds over a given rate in a given period of time, making them more stable, efficient and targeted. The idea of controlled release was first implemented in biomedicine, but it is also being translated into the agricultural and plant-based sector, and it has the potential to improve the bioactivity of compounds in numerous processes[52].

8.4 Encapsulation technologies

The principle of encapsulation is widely used in order to maintain the bioactive phytochemicals against degradation in the environment and increase their manipulation, stability, and controlled release. The use of plant-based matrices has demonstrated specific potential of serving as encapsulating materials since they can promote the retention and functionality of phytochemicals and facilitate their use in food and associated systems. Encapsulation is thus a powerful method of maintaining the biological activity of plant-derived compounds and expanding their application to practice[53].

8.5 Targeted delivery strategies

Precise delivery strategies have also increased the possibilities of using plant-based bioactives in pharmacological use. Nanocarriers made of plants have demonstrated the potential of improving selective drug delivery, especially in cancer therapy, by increasing the targeting capabilities and minimizing the side effects on host tissues[54]. Moreover, plant-derived extracellular vesicles have become a current hot developing topic since they can be used both as the source of bioactive compounds and as carriers, which forms a synergizing approach to further therapeutic uses[55]. Figure 3 presents the spectrum between sustainable agricultural production and extraction, and the development of bioactive and advanced delivery platforms. The significant classes of plant-based bioactive compounds, their applicability, and the new delivery technologies are highlighted in Table 3.

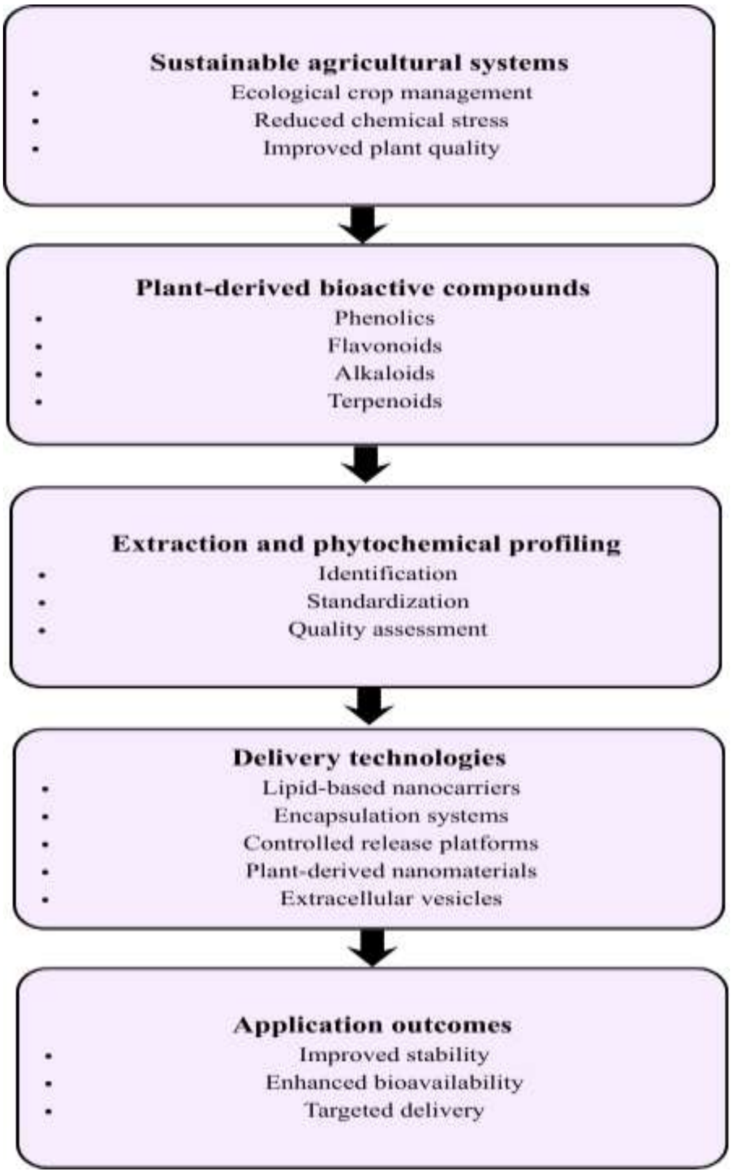

Figure 3. From sustainable agriculture to advanced delivery of plant-derived bioactives

Table 3. Plant-derived bioactives and emerging delivery technologies

Bioactive class/technology	**Representative examples**	**Main functional relevance**	**Delivery/application relevance**
Phenolics and flavonoids	Phenolic acids, flavonoids	Antioxidant and protective effects	Require stabilization and bioavailability enhancement
Alkaloids and terpenoids	Alkaloids, terpenes	Therapeutic and defensive activity	Suitable for targeted or controlled delivery
Phytochemical profiling	Extract characterization and standardization	Identifies high-value plant materials	Supports formulation quality and consistency
Nanocarrier systems	Lipid-based nanocarriers, plant-derived nanomaterials	Protect sensitive bioactives	Improve solubility, targeting, and release behavior
Advanced delivery platforms	Encapsulation, controlled release, extracellular vesicles	Enhance functional performance	Expand nutraceutical and pharmaceutical applicability

9. Challenges and Future Perspectives

Although there is an increase in the interest of bioactive compounds obtained through plant sources, there have remained a number of scientific and practical challenges that restrict their further use in sustainable agriculture and pharmaceutical manufacturing. Fluctuation of plant sources, poor extraction yields, unstable active molecules and variability of biological performance are major challenges. Also, producing and using bioactive peptides and other natural compounds of plant origin are often associated with difficulties in the standardization, scalability, and maintenance of functional activity, which limits their application to large-scale use after experimental research[56]. The recent progress in the research of bioactive compounds of plant origin has provided new opportunities to use them as nutraceutical and pharmaceutical agents. Better methods of analysis and phytochemical profiling, as well as bioactivity screening, are widening the horizons of these compounds and bringing to light new candidates with therapeutic possibilities. Such advances indicate that future studies are directed at determining the high-value plant resources, understanding the mechanisms of action, and optimal processing and formulation techniques to improve the functional and commercial value of bioactives in plants[57]. The other major obstacle is regulatory and translational pathway of the herbal and plant-based bioactive formulations. The regulatory systems of such products are likely to be dry owing to the differences in the composition, the variations in the quality standards, and the need to demonstrate the safety, efficacy, and consistency. This consideration is particularly true for the formulations to be administered pharmacologically since there is a need to be standardized, quality assured and meet the requirements of the regulation. The resolution to these will be of paramount value in increasing the acceptance, commercialization and actual application of plant-based bioactive systems in the future to sustainable and therapeutic uses[58]. Future research should be in the direction of improving the standardization, stability and large-scale application of bioactive compounds of plant derivation in sustainable agriculture and pharmaceutical practice. Instead, they should pay increased attention to the best methods of extracting, certain phytochemical characterization and formulation technologies to advance bioavailability and functional efficacy. The translation of plant bioactives into products would require interdisciplinary approaches between agronomy, phytochemistry, nanotechnology, and the science of drug delivery. Also, better harmonization of regulatory frameworks, quality control and field to formulation validation is needed to help in commercialization. These developments could reinforce the position of sustainable agriculture as a consistent and high-value bioactive feedstock.

10. CONCLUSION

Sustainable agriculture and farming systems necessitate the shift of the input-intensive production system towards ecologically balanced production methods that safeguard the natural resources and, at the same time, maintain crop yields. In this review, it has been indicated that cultural practices (crop rotation, intercropping, conservation tillage, cover cropping and organic amendments) enhance the health of the soil, biodiversity, and ecosystem resilience. Simultaneously, integrated pest management and integrated nutrient management help to decrease the use of synthetic chemicals and enhance the efficiency of resource use and environmental protection in the long term. Another observation made by the review is that sustainable farming systems have the potential to determine the production of bioactive compounds of plant origin that have nutritional, therapeutic, and pharmaceutical properties. New methods of delivery, such as nanocarriers, controlled release system and encapsulation methods, continue to increase the usage of these natural compounds. Although the integration of sustainable agriculture and bioactive innovation still faces various obstacles associated with standardization, scalability, and regulation, there is a promising avenue that may bring the integration of the two closer to an environmentally friendly production and value-added use of plant resources. The next step will involve the incorporation of ecological agriculture with better formulation science and translational frameworks.

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