

Review

Valorization of Agri-Food Waste to Promote Sustainable Strategies in Agriculture and Improve Crop Quality with Emphasis on Legume Crop Residues

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Abstract

The valorization of agri-food by-products represents a promising approach to advancing sustainable agriculture while contributing to climate resilience efforts. Leguminous crops, cultivated extensively across diverse agroecological zones, play a central role in global food systems and soil fertility dynamics. Waste from leguminous crops can contribute essential nutrients to the soil, such as nitrogen, helping the growth of associated or subsequent crops, thereby reducing the need for inorganic fertilizers. Additionally, they can help improve soil biological activity, physical soil properties, and increase nutrient availability. As nitrogen-fixing crops, the waste obtained after threshing pulses probably still contains large amounts of nutrients, which can replenish part of the nutrient needs required for other crops. However, there is little information available about the amount of nutrients these residues may contain, as well as their decomposition rate and release. In this review, we explore the role of agri-food waste, particularly leguminous residues, in promoting sustainable agricultural practices, identifying main knowledge gaps in legume crop residue characterization (i.e., nutrient content and decomposition rates). We also identify potential risks in using leguminous waste and discuss mitigation strategies for using these residues safely. Additionally, we propose new strategies to promote more sustainable agricultural practices and highlight future research directions.

Keywords: circular bioeconomy; common bean; crop quality; nutrient recycling; organic amendments; physiological performance; sustainability; recovery of leguminous waste; soil fertility



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1. Introduction

The agricultural sector is facing major challenges, mostly due to the increase in the global population and the adverse effects of climate change [1]. Climate change, particularly extreme weather events, has been impacting agriculture, reducing crop yields and productivity, and resulting in high economic losses [2]. For instance, Hari et al. [3] climatic projections for central Europe predict a seven-fold increase in drought events with a potential impact on 40 million hectares of agricultural lands from 2050 to 2100. As an

example, during the summer of 2022, Europe experienced one of the most severe droughts on record, resulting in an average yield reduction of 15% in maize, sunflower and soybean compared with the preceding five years [4]. According to climate projections these weather phenomena will continue to occur more frequently and intensely, leading to an increase in global warming, rainfall variability, and more frequent and severe episodes of both precipitation extremes and drought [5]. This scenario can compromise the ability to meet the world's food needs and food security.

To achieve high productivity and enough food availability under the constraints of climate change, the agriculture system was also changed, shifting from a traditional system production to more intensive systems. This actual agriculture system relies on intensive cultivation, using technology and high inputs of synthetic agrochemicals and water (irrigation) that provides increasing food production at affordable prices. However, the inadequate soil management practices, such as the excessive and inappropriate use of chemical fertilizers and pesticides, cause contamination of soils and water resources, reduce soil biodiversity and cause leaching processes and eutrophication of aquifers [6]. In fact, according to the model of Zhang et al. [7] approximately 70% of nutrient yields (mainly nitrogen and phosphorous) found in a headwater catchment were from chemical and fertilizer applications attributed to orchard plantations in an intensive agricultural area in China, and 70% of the nutrients reaching the catchment annually were driven by rainfall. This ultimately results in an imbalance of nutrient cycling and the degradation of the environmental conditions leading to negative impacts on ecosystems and human health.

Current concerns about climate change, sustainability and food security have definitely entered the global European Union (EU) agenda. Thus, the EU launched the Farm to Fork strategy, which is part of the European Green Deal and seeks to accelerate the transition to more sustainable food systems and achieve climate neutrality by 2050 [8]. This strategy aims to reduce the environmental impact of agriculture, help to adapt to climate change, ensure food security and public health [8]. For example, a reduction of 20% in the use of synthetic mineral fertilizers by 2030 and of 50% in the use of chemical pesticides by 2050 is expected [9].

Considering the challenges of the agricultural sector in the current climate change scenario and the objectives set by the European Green Deal, it is imperative to change current agricultural practices and develop new strategies to promote more sustainable agricultural systems, compatible with rational water management and a reduction in the use of agrochemicals, in order to contribute to the mitigation and adaptation to climate change [10]. The use of alternatives to mineral fertilizers, such as organic waste, agri-food and/or forest by-products are considered very promising to improve agricultural crop performance and can mitigate the negative effects of climate change on agriculture [11]. The quantity of biomass and macro nutrients provided by organic residues to the soil is highly variable and mainly depends on the type of crop/agri-food residues, on the dose applied, on whether residues are pure or in a mixture (very frequent) and on environmental conditions during crop production or residue decomposition. However, there is a consensus in the literature about using organic waste as a natural fertilizing alternative that can provide nutrients and reduce the need for synthetic mineral fertilizers application [12]. In addition, they can contribute to reduce soil nutrient loss, since the decomposition of some of these natural products is slow compared to inorganic fertilization, as is the case of crop waste (e.g., C/N values of 20–42 for legume crop residues [13]), and the availability of nutrients in the soil for plants is also gradual, which reduces a large loss of nutrients through leaching. Given these pressing challenges, this review explores sustainable agricultural practices and highlights the potential of agri-food waste, particularly from leguminous crops, as a pathway to more sustainable farming systems. Additionally, we identify key knowledge

gaps, highlight case studies demonstrating the potential of leguminous waste to enhance crop performance, and propose future research directions to support the development of innovative, climate-resilient agricultural strategies.

2. Methodology

This review employed a narrative approach to describe sustainable strategies for agricultural practices, and to synthesize the existing literature on the valorization of agri-food waste in sustainable agriculture, with a particular focus on leguminous crop residues. A comprehensive search was conducted across scientific databases including Scopus, Web of Science, Google Scholar, and ScienceDirect using keywords such as “sustainable agriculture”, “sustainable agriculture practices”, “agri-food waste”, “legume crop waste or residue”, “legumes nutrient source” and “legumes soil quality”. Studies were selected based on their relevance, novelty, and alignment with the European Union’s sustainability goals, particularly the Farm to Fork strategy. Priority was given to scientific peer-reviewed publications from 2000 to 2025, supplemented by governmental and institutional reports to capture recent policy developments.

The search yielded approximately 120 articles that were reviewed, with particular emphasis on nutrient composition, decomposition dynamics, and effects on soil health. The findings were thematically categorized into strategies for waste valorization, nutrient management, and sustainability outcomes.

3. General Sustainable Strategies for Agricultural Practices

Sustainable agriculture practices must be based on ecological strategies that preserve natural resources, build resilience and guarantee the development of future generations [14]. Some of the strategies used to maintain ecosystem’s biodiversity and sustainability include, for example, the use of a wide diversity of species and crop rotation, implementing agroforestry systems, maintaining tillage conservation, applying an ecosystem-based strategy to manage disease, pest and weeds, the use of natural products and cover crops, and renewable energies (Figure 1).

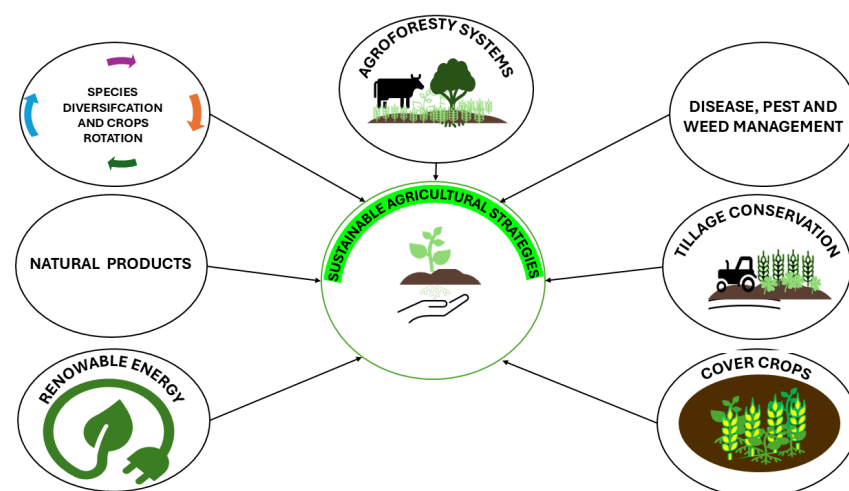


Figure 1. Main agricultural strategies that preserve natural resources and maintain biodiversity and sustainability of ecosystems.

3.1. Species Diversification and Crop Rotation

Sustainable agriculture should prioritize the cultivation of diverse crops within the same farm or across different regions, instead of relying only on one crop. Crop diversification provides a sustainable approach to increase resilience and can mitigate the risks

associated with monocultures. Several strategies can be adopted, such as spatial diversification (where different crops are cultivated in distinct fields), temporal diversification (applying crop rotation throughout different years or seasons), genetic diversification (using different crop varieties), and intercropping (growing several crops together in the same field) [15].

The use of a variety of plant species enhances the ability of the agricultural system to withstand and recover from environmental stress and can help to adapt to climate variability [15]. Diverse cropping systems can bring several benefits, like increasing soil health (quality and characteristics) and pest management, promoting biodiversity, reducing the need for pesticides and synthetic fertilizers, and can reduce financial risks if one crop is lost [15,16]. For instance, cultivating many varieties of the same crop, enhancing genetic diversity but also helps in the management of some pests and diseases that can only affect specific varieties [15]. Also, the use of several atmospheric nitrogen-fixing cover crops or the rotation of nitrogen-fixing legumes with cereals can help to improve soil quality, through the enrichment with nutrients and organic matter, reducing the need for fertilizer use [17].

3.2. Agroforestry Systems

Agroforestry practices offer the opportunity for multifunctional land use, since they benefit simultaneously food production for humans and animals, and provide biodiversity and environmental benefits and protection [18]. The challenge for the agroforestry systems lies in finding a balance between maximizing the productive capacity of farming systems and preserving environmental benefits, both essential for promoting sustainable agriculture and resilient agroecosystems [19].

Agroforestry encompasses several specific agricultural approaches; the most common is the silvopastoral (combining trees and livestock), the silvoarable (horticultural crop is integrated with long-term tree crops), and the agro-silvopastoral (integrating horticultural crop with long-term tree crops and livestock) [20]. The integration of these approaches offers several benefits, such as improved soil fertility (favoring nitrogen cycling and carbon storage), physical properties, water infiltration and water holding capacity [21]. This leads to increased soil organic matter and root activity, favoring productivity. These strategies also promote soil microbial processes and decomposition, leading to increased release of nutrients from organic matter [21]. Moreover, they also enhance biodiversity, help in the control of erosion, reduce pests and weeds, and improve the aesthetics of agricultural landscapes [21,22].

3.3. Tillage Conservation

Tillage conservation is the name given to soil management practices that aim to preserve natural resources [23]. This practice has gained high importance due to climate change and the increasing need for soil preservation.

This practice relies on the minimization of the frequency and intensity of soil disruption through tillage operations, reducing the risks of soil erosion, and minimizing evaporation processes leading to increased soil water retention [24,25]. Tillage conservation allows the nutrients from crop residues and the organic matter to remain in fields, promotes microbial activity and biomass production, and also reduces carbon dioxide and greenhouse gas emissions [25]. The conservation of carbon and also nitrogen in the soil surface layer favors soil structure promoting resilience to extreme weather [25,26]. The reduction of soil tillage can also decrease the dependence on machinery and equipment and can reduce the overall cost with fuel and labor. However, the yield loss due to weed competition and problems with seed germination are sometimes the arguments against tillage conservation practice.

3.4. Disease, Pest and Weed Management

An ecosystem-based strategy to control pests and disease in agricultural areas should focus on long-term prevention, and combination of methods such as the use of biological control, biopesticides, mechanical control and resistant crop varieties [27]. Biological control uses an organism to reduce the population density of another. This method offers several advantages, particularly because it targets a specific group of pathogens and therefore has a small impact on the ecosystem and reduces the allocation of plant resources in defense response, shifting more energy for agronomic traits [27]. However, the efficacy of some biological controls strongly depends on biotic and abiotic factors, and their effectiveness when changes occur in the pathogen poses some concerns [27]. Biopesticides are naturally occurring organisms or compounds that suppress the progression of pests and diseases using several mechanisms of action. However, the high cost associated with the production, the low action, the interference of environmental factors with their activity, the lack of standard method of preparations and dose determination of active ingredients, are some examples of the reduced use of biopesticides [28]. Mechanical and physical control kills directly a pest. For example, this includes handpicking and killing, hand net, physical beating and shaking, mechanical traps, attractants, tillage, flaming, flooding, and row covers, etc. Increasing the diversity of genotypes can also reduce disease and pest abundances, and at the same time increase crop yield [29]. Moreover, cultivating plant species more resistant to specific diseases and pests will increase the survival until crop harvest.

To control weed growth and dispersion, multiple and combined management actions must be applied for effective control [30]. For instance, the introduction of a crop rotation system together with different growth cycles can disrupt weed growth associated with a particular crop [31]. Also, changing the plant pattern by early planting crops will provide a competitive advantage over the weed. Mechanical weed control (tillage, small disruption with machinery, hands tools, cutting and mowing) and thermal control (flaming and steaming), destroy weeds or reduce their competitive ability [30,32]. Mulching, covering the soil with plant residues or synthetic materials can prevent weed seed germination and/or block seedlings growth [31]. The adoption of cover crop cultures suppresses weeds by occupying the ecological area or competing for resources. Cover crops improve soil quality and carbon sequestration, leading to higher microbial activity, as well as plant and animal biodiversity [31]. In addition, allelopathic crops (those that interfere with other organisms by releasing chemical compounds into the environment) and/or the application of phytotoxic natural compounds through mulches, green manures or plant extracts can also suppress weeds while reducing synthetic herbicide inputs [33]. The use of livestock is an under-explored method that has been proved very efficient for the control of weeds [31,32].

3.5. Natural Products: Organic Fertilizers and Biostimulants

Sustainable agriculture practices must prioritize the use of natural products over synthetic inputs in order to preserve soil health, biodiversity, and ecological balance.

Concerning the organic fertilizers, they can be derived from organic sources, including organic compost (cattle manures and domestic sewage), green manure and composted agricultural wastes. Also, organic waste from agriculture and by-products from the agri-food industry can be used as natural fertilizers, since they provide organic matter and essential nutrients (e.g., nitrogen, phosphorous and potassium) for the soil. Organic fertilizers when incorporated into the soil improve soil structure (by increasing soil microbial activity), fertility, nitrate use, water retention capacity and, consequently, the production of agricultural food [34,35].

In turn, biostimulants are also natural compounds or microorganisms, but they enhance nutrient uptake and stimulate the antioxidant system of plants, leading to better

growth and yield, as well as biotic stress tolerance [36]. There is a high variety of biostimulants, but the most used are those derived from seaweeds (e.g., *Ascophyllum nososum*), protein hydrolysates, humic substances and microorganisms (e.g., plant growth-promoting bacteria and arbuscular mycorrhiza fungi), and those prepared with nanoparticles or nanomaterials [37]. The specific mode of action of biostimulants is not well understood, but it seems that they act as priming agents, triggering several molecular and physiological mechanisms that enhance plant's defense and protection against stressors.

All of these natural products, biostimulants and organic waste can provide several benefits to soil and plants and lower the necessities of chemical fertilizers inputs in agriculture while maintaining high crop yield.

3.6. Cover Crops

Cover crops are crops that are incorporated between the growth cycles of two cash crops, offering several benefits to agroecosystems through surface coverage and crop diversification. These benefits include provisioning (e.g., food and feed production), regulation (e.g., carbon storage, pest, disease and weed control, and climate mitigation), and support (e.g., improvement of soil physical features, stabilization and erosion control), but they can also provide other environmental and cultural benefits, like biodiversity conservation, improvement of landscape aesthetics, carbon sequestration and water purification [38].

For instance, legume cover crops can enhance soil nutrition through biological nitrogen fixation, and non-legume cover crops can improve soil structure and root penetration, supporting the well-developed root systems of primary crops [39]. Additionally, cover crops accelerate the formation of microbial-derived carbon by providing diverse residues (e.g., other plant wastes) for soil microorganisms [39]. However, some cover crops can also negatively affect the yield of subsequent crops by competing for soil moisture and nutrients, and they contribute to increased nitrous oxide and methane emissions due to enhanced microbial metabolism [38,39]. It is fundamental to optimize cover crop practices (e.g., selection of cover crops, producing mixture of cover crops) to balance food security and environmental benefits.

3.7. Renewable Energy

To achieve sustainable agriculture, the use of clean, efficient and renewable energy is also crucial to mitigate environmental harm tied to agriculture [40]. Environmentally clean agricultural practices have the advantage of generating more livelihood opportunities and quality food without jeopardizing agricultural productivity and environmental balance in relation to the reduction of natural resources [40].

Examples of renewable energy and energy efficiency can include solar energy, wind power, biomass, and hydroelectric power [41]. Solar energy can be used through photovoltaic systems to produce electricity for farmers, that can be used in milking machines, water pumps and irrigation systems [40]. Particularly in places with good wind conditions, the implementation of wind turbines can generate energy, and hydroelectric power can be harnessed from streams or water systems [40,41]. Also, anaerobic digestion or biomass gasification of agricultural by-products or waste, food processing industry waste, and animal manure can be transformed into bioenergy, that can be used to generate electricity and heat [40]. In addition, the use of energy-efficient technologies, such as LED illumination, or taking advantage of the insulation, and applying smart controls are actions that can be implemented in farm infrastructure and contribute to reaching a sustainable agriculture system.

4. Potential Contribution of Agri-Food Waste for Sustainable Agriculture

Agri-food waste is defined as the residues of raw agricultural products [42] and includes, among others, non-marketable parts of animals and crops, waste obtained from growing and processing, losses from the food supply chain [43]. The amount of agri-food waste has largely increased as a result of agricultural production and agro-industrial activity, with waste from vegetables, fruits, cereals, roots and tubers, oil crops, and pulses being the major contributors [43]. The waste generated globally is now a major concern for policymakers due to its impact on increasing environmental, economic and social problems [44]. In many regions, agri-food waste is still primarily disposed of through landfilling or incineration [45] despite emerging recycling efforts. Concerning this problem, the EU presented the Circular Economy plan followed by the Food Losses and Waste platform and, later, the Farm to Fork strategy [46,47] to prevent food losses and waste production. Specifically, EU guided the principles in the Waste Framework Directive (Directive 2008/98/EC) [48] and measures to be applied in a Communication [49] to avoid food losses and waste. As a result, EU established a 10% reduction in food losses due to processing and manufacturing and a 30% per capita reduction in waste generated throughout the retail and consumption chain by 2030 [47]. The EU's rationale is to convert linear economic processes into circular ones by recycling, recovering and reusing waste to protect the environment and human health and reduce dependence on primary resources.

4.1. Agri-Food Waste as an Alternative Source of Biofertilizers

The transition of agricultural lands to more efficient and resilient systems requires the adoption of sustainable strategies [50]. One of them is reducing reliance on the excessive use of external synthetic inputs, such as chemical fertilizers, responsible for environmental pollution [50]. The valorization of agri-food waste as a source of nutrients can help achieve this objective, complying with regulations and market demand and fostering circularity and sustainability in agriculture (Figure 2). Despite this, the fertilizer industry has shown some reluctance to feed on renewable raw materials due to technological and production issues [22], which is expected to change in the near future. Transforming agri-food waste into a base of renewable biofertilizers has attracted increasing attention due to the recent rise in prices of mineral fertilizers from non-renewable resources and a disruption in the supply chain caused by the COVID-19 pandemic or the war in Ukraine [22]. Post-harvest residues represent approximately 80–90% of crop biomass still retaining organic matter, most available nutrients (e.g., carbon, nitrogen, phosphorus, potassium, calcium, magnesium, silicon) and other components [51,52], that can be recycled into the soil as fertilizer (Figure 2). Agricultural or agri-food waste can be incorporated into the soil directly or more frequently after transformation by hydrothermal, pyrolysis, composting and vermicomposting or anaerobic fermentation for nutrient stabilization [22]. Once incorporated, waste can improve soil properties and plant performance, resulting in beneficial effects at environmental and economic levels (Figure 2). For example, a circular-successful study entering rose-waste compost into the production system was recently conducted in Kenya [53]. This study found that rose-waste compost improved the content of organic matter and short-term nutrient availability in soil, as well as facilitated long-term nutrient release without compromising the commercial value of roses. The application of combinations of different agricultural waste products is also possible, with crops achieving economic yields similar to those obtained with commercial organic fertilization (e.g., [54]). Another important aspect of using agricultural waste products is that nutrients are released slowly compared to mineral fertilization during the crop growth process [55], which reduces nutrient losses by leaching, but it also requires a better understanding of the best application timing to avoid nutrient deficiency in crops.

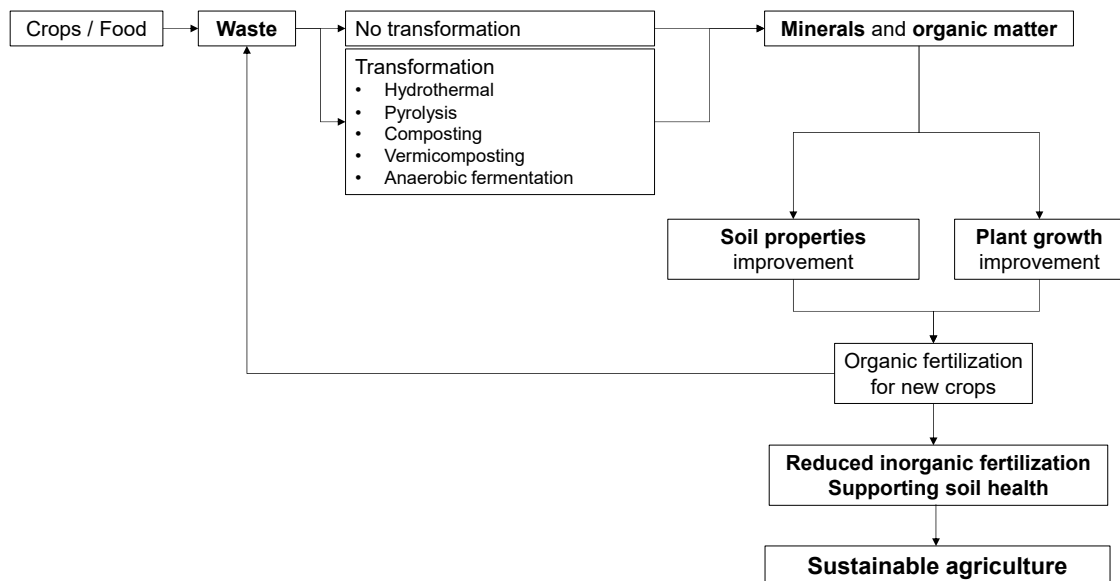


Figure 2. Resource utilization path of agri-food waste to foster circularity and sustainability in agriculture.

4.2. Agri-Food Waste as Soil Amendment

Simultaneously with fertilization properties, agricultural waste also improves soil health and quality by positively influencing its physical, chemical and biological properties (Figure 2) [56,57]. Compost application is related to the improvement of soil structure and a reduction in bulk density [56,57], which favors the formation of stable aggregates, increasing water infiltration and water-holding capacity [56,58]. Agricultural waste can also increase soil pH, soil organic matter and cation exchange capacity and reduce the bioavailability of heavy metals in contaminated soils [59]. Furthermore, the application of agricultural waste as compost also enhances enzymatic activities by promoting diverse groups of rhizospheric microorganisms, and micro- and macro-fauna [56], ensuring proper functioning of biochemical functions and reactions, nutrient cycling and thus soil health (Figure 3). A comparative study assessing the effect of non-legume (*Lolium perenne* L.) and legume (*Astragalus sinicus* L.) green manures found that both organic amendments positively affected soil pH, nitrogen availability and microbial biomass carbon compared with fallow treatments, while differentially affecting the activity and diversity of soil microbes [60].

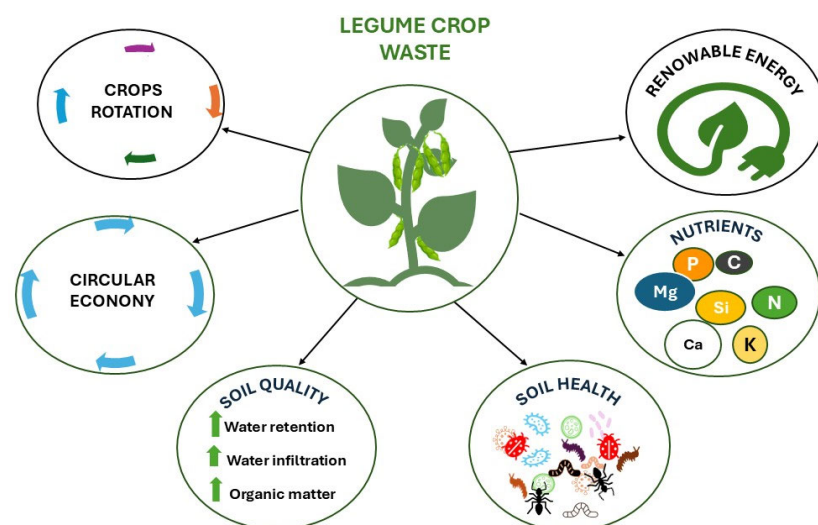


Figure 3. Potential of legume crop waste for agricultural sustainable practices.

5. The Importance of Using Leguminous Crop Waste for Crops

Legumes are one of the most widely produced foods worldwide (around 92 million tons) [61], including lentils (*Lens culinaris* Medik.), chickpeas (*Cicer arietinum* L.), common beans (*Phaseolus vulgaris* L.), soybeans (*Glycine max* L.), broad beans (*Vicia faba* L.) and peas (*Pisum sativum* L.) [62]. Legumes are rich in proteins, fiber, bioactive compounds and several minerals, particularly nitrogen [63]. The processing of these pulses into various products generates a significant amount of waste that can be converted into a low-cost resource [64]. The use of legume crop waste presents a promising strategy for advancing sustainable agriculture by delivering both ecological and economic benefits. Rich in nitrogen and other essential nutrients, these residues can be effectively utilized as organic fertilizers or substrates for renewable energy production (Figure 3) [65]. When applied to the soil, legume crop waste improves soil health by enhancing microbial activity, increasing organic matter content, improving soil structure, and boosting water retention (Figure 3) (e.g., [58,62,63,66]). Additionally, its integration into crop rotation systems supports plant growth and can enhance resilience under stress conditions such as drought, and reduces reliance on synthetic inputs (Figure 3) (e.g., [58,64,66,67]). This practice aligns closely with circular economy principles by transforming agricultural byproducts into valuable resources, thus closing nutrient cycles and minimizing environmental impact (Figure 3) [63].

In Portugal, for instance, legume production has increased, but the amount produced is still deficient [68]. The most widely grown legumes in Portugal are peas, broad beans, chickpeas and common beans [69,70]. Chickpea and common bean production have been increasing since 2015, achieving 2890 and 2531 tons, respectively, in 2020 [69]. The production of peas and broad beans in 2020 was 15,846 and 4500 tons, respectively [69]. Thus, waste from leguminous crops are common in Portugal and also in other European countries, but it is currently undervalued. Its use as fertilizers and soil amendments can improve efficiency and sustainability in agriculture [71].

5.1. Source of Nutrients in Crop Rotations

Legumes help improve soil fertility due to their ability to fix atmospheric nitrogen. The introduction of leguminous crops in polyculture systems favors the supply of nitrogen to the soil and subsequent crops, both in the short- and long-term, and contributes to increasing the organic matter content in soil (Figure 3) [72,73]. For instance, rotation experiments in low nitrogen soils in Pakistan have shown that mung bean (*Vigna radiata* (L.) R. Wilczek)—wheat (*Triticum aestivum* L.) and lentil—summer cereal sequences followed by the incorporation of above-ground residues into the soil improved the nitrogen economy of the agricultural system and increased the productivity of non-leguminous crops [74]. Similarly, leguminous waste from common beans and pigeon pea (*Cajanus cajan* L. (Millsp.)) crops can be used as nitrogen fertilizers in low-input farming systems in Africa for subsequent crops [75]. Covering leguminous crops and their waste left on the topsoil also increase the amount of phosphorus (mainly the labile fraction) in soils [76]. They can help increase the soil's capacity to store carbon and restore poor and degraded soils (Figure 3) [68]. In addition, crop rotations such as broad bean crop plus its aerial waste followed by wheat favor soil microorganisms related to nutrients and plant growth in wheat crops compared to other rotations, suggesting a protective effect of soil after the leguminous crop against soil pathogens [77].

Since legumes favor all dimensions of sustainability, their inclusion in agri-food systems is fundamental to achieving the Sustainable Development Goals [78]. Some farmers use leguminous waste to feed animals or distribute them on agricultural fields. However, farmers lack knowledge of the potential value of legume crop waste as a fertilizer, including

the mineral content it contributes to the soil and its rate of decomposition. In general, waste from legume crops exhibit lower C/N ratios compared to those from non-legume crops, resulting in a more readily decomposable substrate that enhances mineralization and nitrification, thereby accelerating decomposition [79]. Nevertheless, the incorporation of legume residues must be carefully timed and appropriately managed for each cropping system. Otherwise, the rapid decomposition of the residues can hinder crop development due to a high availability of nutrients over a short period or nutrient losses through runoff [80]. Additionally, several factors influence the decomposition and mineralization of legume residues in soil, which in turn affect nutrient release and availability to subsequent crops. The rate and extent of decomposition are governed by both biotic and abiotic factors, including the structural composition of the residues, residue management practices (e.g., incorporation vs. surface application), soil temperature, moisture, aeration status (flooded vs. aerobic), and key physical and chemical properties of the soil [81]. A low C/N ratio and high nitrogen content generally enhance decomposition and nutrient release, while adverse moisture conditions, such as prolonged saturation or drought, can suppress microbial activity [82]. While the presence of lignin and polyphenolic compounds can affect decomposition by interfering with microbial activity, tissue nitrogen concentration, the C/N ratio, and soil water content are widely recognized as the principal drivers of mineralization [81,83]. According to Kebede [81], understanding the interactions among these variables is critical, as they collectively determine the timing and magnitude of nutrient release and availability in soil. For the optimal utilization of minerals provided by legume wastes in subsequent cropping systems, a thorough understanding of the decomposition and mineralization dynamics of different residues is essential. Due to the complexity and variability of these processes, driven by factors such as residue composition, environmental conditions, soil characteristics and microbial activity, significant knowledge gaps remain. Further research is necessary to develop predictive models and optimized residue management strategies that enhance nutrient cycling and improve crop productivity.

5.2. The Improvement of Soil Moisture

Extreme and more frequent drought events are expected under climate change conditions, mainly in the Mediterranean Basin. There is an urgent need to find strategies that reduce the amount of irrigation water while minimizing the effects on crop yields. Besides nutrient properties, and as an organic material, legume crop waste may help improve physical soil properties, water penetration, decrease evaporation and increase the water retention capacity of soils (Figure 3). This is a key topic that has only recently started to receive attention. For instance, soils amended with green manures from broad bean plants conserved moisture better than unamended soils under well-watered conditions [84]. More interestingly, Sifola et al. [66] found that legume green manuring from *Vicia villosa* Roth increased the water retention capacity of soils in deficit-irrigated tobacco crops, supporting a deficit irrigation strategy. On the contrary, the rapid decomposition of leguminous residues due to their low C/N ratio prevents the maintenance of soil moisture for subsequent crops [85]. Further studies assessing different legume crops, doses and decomposition rates of legume waste may contribute to overcoming this shortcoming.

5.3. Potential of Legume Crop Waste for Improving Crop Performance: Cases Studies

Vicia faba L. (broad bean) is a key leguminous crop in many parts of the world and its production is likely to increase [86]. Recent research has proven both phytotoxic and fertilizing properties for broad bean waste. Fresh aboveground biomass (excluding pods) incorporated into the soil initially reduced weed biomass in maize (*Zea mays* L.) crops by half. However, once the phytotoxic effects diminish, both maize and weed growth are

stimulated [84]. Álvarez-Iglesias et al. [84] suggested that the broad bean biomass releases nutrients, particularly nitrogen, that promote maize growth. Similarly, [87] reported that the application of broad bean waste increased maize yields, probably due to greater nutrient availability. Alternatively to maize crops, broad bean waste alone or mixed with field pea (*Pisum sativum* L.) waste also produced the highest yield of mushrooms when compared with other agricultural waste [88], or the incorporation of dry broad bean pods into the soil enhanced *Sorghum bicolor* (L.) Moench biomass production [89]. Dry broad bean pods also improved the plant water content, fresh foliar biomass and plant height of young olive trees (*Olea europea* L.), achieving similar levels to those obtained with organic commercial fertilization [90].

Similarly to broad bean waste, applying *Vigna radiata* (L.) R. Wilczek (mung bean) residues significantly enhanced plant length, stem diameter, number of branches and leaves, tuber weight, leaf area, dry tuber weight, and yield traits such as number, length, and diameter of tubers of sweet potato (*Ipomoea batatas* (L.) Lam.) under both greenhouse and field conditions [91]. Taking all this information together, the incorporation of broad bean, field pea, and mung bean waste into agricultural soils could enhance crop growth (Table 1) through the release of nutrients, while also reducing external inorganic fertilization and improving sustainability in agriculture. However, the decomposition rate of these wastes in soil and the quantities of nutrients provided are not clear.

Table 1. Legume crop residues focused on crop performance and effects observed.

Waste	Culture	Effects	Reference
<i>Vicia faba</i>	Maize	Growth stimulation	Álvarez-Iglesias et al. [84]
<i>Vicia faba</i>	Sorghum	Enhance biomass production	Al-Chammaa et al. [89]
<i>Vicia faba</i>	Maize	Increase yield	Iqbal et al. [87]
<i>Vicia faba</i> <i>Pisum sativum</i>	Mushrooms	Increase yield	Gebru et al. [88]
<i>Vicia faba</i>	Olive tree	Improve water content, fresh biomass and plant height	Lee [90]
<i>Vigna radiata</i>	Sweet potato	Enhance plant length, stem diameter, number of branches and leaves, and leaf area. Increase the number, length, and diameter of tubers as well as dry weight	Ghassan et al. [91]

Phaseolus vulgaris L. (common beans) is another of the most cultivated crops in the world and one of the most important legumes for human consumption [92]. The aerial waste after threshing contains large amounts of nutrients that can be returned to the soil and partially cover the nutrient requirement for subsequent crops [74]. This waste contains 0.6–1.5 Mg ha^{−1} of dry matter, 5–12 kg ha^{−1} of nitrogen and 0.4–1.0 kg ha^{−1} of phosphorus, representing on average 15% of nitrogen and 11% of phosphorus accumulated by the crop during bean maturation [93,94]. Excluding carbon, stems and pod straw are rich in potassium, while senescent leaves are rich in nitrogen (Table 2) [94]. However, the decomposition rate of this waste in the soil is slow and influenced by the C/N ratio of the residue (Table 2), with a gradual release of nitrogen, carbon and phosphorus, but also a faster release of potassium [94,95]. Decomposition is faster for pod straw, followed by senescent leaves, and then stems (Table 2) [94]. The information about the nutrient content and release is relevant to match the waste type with a specific crop requirement. However, although nutrient data are available, the potential application of this waste as fertilizer for crop production remains largely unexplored.

Table 2. Content of macronutrients, C/N ratios and half-life period of different types of residues from common bean crops (*Phaseolus vulgaris* L.) [94].

Residue Type	Carbon (kg kg ⁻¹)	Nitrogen (g kg ⁻¹)	Phosphorus (g kg ⁻¹)	Potassium (g kg ⁻¹)	C/N	Half-Life (Days)
Stems	0.54	6.8	0.49	15.3	79	133–179
Pod straw	0.53	8.0	0.50	33.1	66	64
Senescent leaves	0.48	20.4	1.54	9.3	24	70–80

It is important to emphasize that, despite the potential of leguminous waste for improving crop performance, this topic remains significantly underexplored in the scientific literature. Existing studies are scarce and often fragmented, limiting our understanding and practical applications in agriculture. In this review, we compiled the limited available evidence (Table 2) and aim to draw attention to the urgent need for more systematic research in this area.

6. Risks, Mitigation Strategies and Future Directions

As described above, the incorporation of legume residues into the soil is a promising strategy for improving soil fertility and supporting sustainable agricultural practices [12]. However, this practice can also present some agronomic and environmental risks that must be properly addressed through appropriate management strategies to ensure long-term benefits. Some examples of potential risks and mitigation strategies are presented:

- Certain legume species release allelopathic or phytotoxic compounds during decomposition, which can negatively affect seed germination or early crop development [96,97]. To mitigate this, it is advisable to select species with low allelopathic potential and/or allow sufficient time between residue incorporation in soil and planting to permit initial decomposition and detoxification;
- Legume residues may also serve as hosts for pests or pathogens [98], especially in monoculture systems or short crop rotations. Preventive measures can include rotating with non-host crops and using healthy and disease-free legume material;
- Legumes cultivated in soils contaminated with heavy metals may accumulate these elements in their tissues, and when residues are incorporated into the soil, they can contribute to the long-term accumulation of metals in the soil. Monitoring and testing the metal content of legume biomass before soil incorporation, especially in regions near mining sites, industrial zones, or areas irrigated with wastewater, is advised;
- In conventional farming systems, legumes are often treated with pesticides. Residual agrochemicals can persist in plant tissues and be introduced into the soil when residues are incorporated. To mitigate this, preference should be given to organic or low-input legume production systems to obtain residues destined for soil incorporation and/or to allow a waiting period after pesticide application before harvesting residues could reduce the toxicity of the residue. Also, promote composting or pre-treatment of legume biomass to enhance pesticide degradation before field application.
- Incorporation of legume residues in soil can, in some cases, increase GHG emissions, particularly N₂O and CO₂ [79,99,100]. Avoid incorporating residues into poorly drained or flooded soils, and implement proper drainage management and soil aeration strategies. Also, monitor the full GHG profile in integrated systems.

Future research should explore more extensively the effectiveness of using legume crop residues as a nutrient source for subsequent crop cultivation. Key areas of investigation include the decomposition and mineralization dynamics of different legume species (and different parts of the legumes), the optimization of residue application timing and

methods, and the impact on nitrogen use efficiency, soil organic matter accumulation, drought prevention, and crop productivity. Additionally, studies assessing environmental outcomes, such as greenhouse gas emissions or nitrate leaching associated with residue incorporation, will be essential to validate the agroecological benefits of this practice. Finally, promoting circular bioeconomy approaches, where legume residues are recycled within local food systems to reduce external inputs and sustainably improve soil health, is crucial for advancing resilient and low-input agricultural systems.

7. Conclusions

The agricultural sector is facing significant challenges due to the necessity to produce enough food for the growing global population under the scenario of climate change. It is already recognized that intensive farming systems, despite their high production and profitability, strongly contribute to environmental degradation and climate change. Therefore, a shift toward a more sustainable and environmentally friendly agricultural system is essential. Reusing the waste generated from agricultural production and agro-industrial activity, agri-food waste, can help increase the sustainability of the agricultural sector and combat climate change. For instance, legumes are one of the most widely produced foods in the world. However, crop waste is still undervalued. According to the sustainable strategies for agricultural practices, waste from legumes can contribute, at least, to enhancing crop rotation and cover crops, soil fertility and health, improving soil moisture, and represents a source of new natural products including some essential nutrients for crop growth. Despite the growing body of the literature highlighting the beneficial effects of incorporating legume crop residues into agricultural systems, there is still limited knowledge regarding which nutrients are released from these residues, the quantity and the decomposition process, especially in the case of the most widely cultivated crops for human and animal consumption. For this reason, further studies are required on various aspects of the utilization of legume crop waste to standardize utilization conditions. Such studies should include the investigation of decomposition rates under different environmental conditions, the release and availability of minerals in soil for a wide variety of crops, and the mineral profile of different legume crop residues, including varieties.

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Abbreviations

The following abbreviations are used in this manuscript:

EU	European Union
LED	Light Emitting Diode
pH	Potential of Hydrogen
C/N	Carbon to Nitrogen ratio

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