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Enhancing lentil productivity through residue management and biofertilizers: A review

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Abstract

The present review envisages available information regarding the importance of the incorporation of crop residues and biofertilizers in enhancing the growth and yield of lentil. The productivity of lentil varies considerably with the soil conditions and therefore, sustainable soil management practices play a key role in maintaining good production. Incorporation of crop residues increases soil organic carbon, water retention, aggregation and microbial activity, thus increasing the proper cycling and availability of nutrients. Nonetheless, temporary problems like immobilization of nitrogen and allelopathic activity can arise based on the quality of residues and the rate of decomposition. Biofertilizers (especially *Rhizobium*-based inoculants) also play a role in nutrient availability, namely, biological fixation of nitrogen and enhancement of soil fertility. Research have shown that combined methods of using residue management and biofertilizers are very beneficial in improving yield parameters like pods per plant and grain yield, particularly where moisture is limiting. To get maximum benefits and long-term sustainability of lentil based cropping systems, site specific management strategies are crucial.

Keywords: Crop residue, residue incorporation, soil health, soil organic carbon, conservation agriculture

Introduction

Lentil (*Lens culinaris* Medik) is one of the most important pulse crops produced in semi-arid and rainfed soils because of its high protein level, ability to grow in marginal soils and its possible ability to enhance the fertility of soils by fixation of nitrogen through biological means. It has a significant contribution to food and nutrition security in poor countries where pulses are one of the primary sources of dietary protein (FAOSTAT, 2023; Sahithi *et al.*, 2023)^[6, 22]. The lentil farming is also significant in the context of sustainable cropping systems as in addition to nutritional value, it improves the soil health, increasing the amounts of nitrogen in the soil and improving the soil structure (Zhao *et al.*, 2022)^[29]. However, lentil have low and erratic productivity due to low soil fertility, erratic rainfall, ineffective use of inputs, and ineffective crop management measures. (Kumar *et al.*, 2023)^[9].

In cereal systems like rice-lentil farming, the management of the crop residues is essential for ensuring that the soils remain healthy and productive. The residue integration also increases the nutrient availability and cycling through increase in soil organic carbon, soil aggregation, water infiltration, and microbial activity. (Lal, 2020; Liu *et al.*, 2024)^[11, 14]. Furthermore, conservation agricultural practices like no-tillage and retention of the residue are found to have a strong advantage over the traditional tillage systems in terms of improving soil moisture dynamics, decreasing soil erosion, and improving the utilization of nutrients (Layek *et al.*, 2022)^[13]. In spite of having good benefits, poor residue management may cause allelopathic effects, slowed nutrient mineralization and temporary immobilization of nitrogen all of which may impact early crop development (Scavo *et al.*, 2021)^[25]. Biofertilizers such as *Rhizobium* and phosphate-solubilizing bacteria (PSB) have become a potential substitute to chemical fertilizers by boosting the accessibility of nutrients and the fertility of soil through the promotion of biological processes (Sansinenea, 2021; Rai *et al.*, 2020)^[23, 18]. Such microbial inoculants improve nodulation, fixation of nitrogen and solubilization of phosphorus and overall plant growth. In addition, biofertilizers enhance the sustainability of agricultural systems on a long-term basis and an increased degree of soil microbial diversity (Kumar *et al.*, 2023)^[9]. Residue management

and the use of biofertilizers, particularly when there are limited moisture and resources, is a sustainable and synergistic solution to the increase in lentil production (Ali *et al.*, 2022; Lal, 2020) ^[2, 11].

Review of Literature

Agricultural Residue Management

In developing countries where, there are limited organic inputs and soil erosion is becoming a very frequent phenomenon, efficient agricultural crop residue management plays an important role in sustainable agriculture. The impact of the crop residues on the soil properties and crop yield depends on whether the residues remain on the surface of the soil or incorporated into the soil. Among these, the retention of residue and absorption is well known to have benefited the nutrient cycling, carbon sequestration and the organic matter accumulation of soil, all of which have long-term effects on the soil fertility. Residue management also enhances the dynamics of soil moisture, by reducing the losses of evaporation, increasing soil infiltration, and controlling soil temperature. These benefits are particularly important in rainfed systems, in which water supply is a major constraint (Liu *et al.*, 2024) ^[14]. Also, retention of residues enhances the soil structure and aggregate stability and decreases soil erosion by protecting the soil surface against the effects of a raindrop and runoff (Raju *et al.*, 2025) ^[19]. The improvement of the physical conditions of the soil promotes better root development and assimilation of nutrients, which ultimately leads to the increase of crop yields. In addition to the physical benefits, the residue absorption enhances soil biological activity by providing substrates for the microbial growth, which enhances nutrient mineralization and decomposition activities (Lal, 2020) ^[11]. Nevertheless, residues if managed poorly can cause issues like the short-term immobilization of nitrogen, reduced soil temperature in the initial stages of development and increase in infestation of insects and diseases (Zhao *et al.*, 2021) ^[28]. To maximize benefits and reduce potential constraints, site-based residue management methods that include quality of the residue, type of soil, climate and type of cropping practices are essential. Residue management can be further integrated with other sustainable methods such as conservation tillage and integrated nutrient management to enhance crop productivity and sustainability.

Chemical and Physical characteristics of residue

Crop residues decomposition behaviour, patterns of nutrient release, and overall effect on soil fertility are all greatly influenced by their chemical and physical characteristics. Nutritional composition, bulk density, electrical conductivity, lignin content and carbon to nitrogen (C: N) ratio of residues differ tremendously, and they all influence the rate at which they will decompose and decide nutrient available to crops (Sadiq *et al.*, 2025) ^[21].

The rapid breakdown of the residues containing high levels of nitrogen and low C:N ratio enhances the mineralization rate of the nutrients and elevates their uptake by plants. Conversely, those residues that contain a high C:N ratio such as cereal straw tend to decompose slowly and temporarily absorb nitrogen, which restricts its supply to crops in their initial growth stages (Lal, 2020) ^[11]. Lignin and polyphenols also have impacts on the rate of breakdown since they influence the microbial activity and the stability of residue.

Nitrogen, Phosphorus, Potassium, Calcium, Magnesium, and trace elements are among the macro and micronutrients found in

organic residues such as farmyard manure, compost, crop wastes, and agro-industrial by-products (Bhatia, 2025) ^[4]. Nevertheless, in order to prevent soil salinity and toxicity, the residues with high electrical conductivity or sodium level, including some industrial wastes, should be efficiently monitored before use.

Microbial colonization and breakdown rates are strongly influenced by physical attributes such surface area, moisture content, and particle size. Although larger leftovers degrade more slowly, smaller particle sizes can enhance microbial activity and accelerate degradation. Another important element affecting microbial activities and nutrient release is moisture availability.

Residual characteristics have to be adequately characterized and managed in order to maximize their use in nutrient management systems. Biofertilizers or other organic amendments that are combined with leftovers may lead to better health of the soil, its nutrient availability and its decomposition performance that can all contribute to sustainable agricultural production systems (Sansinenea, 2021; Kumar *et al.*, 2023) ^[23, 9].

Impact of Residue Incorporation on Soil Properties

Through enhancing physical, chemical, and biological properties of the soil, incorporation of the residue is vital in enhancing soil health. It enhances soil organic carbon significantly, improves soil structure, and improves water-retaining capacity, all of which are essential in sustaining agricultural production under rainfed conditions (Lal, 2020; Fu *et al.*, 2021) ^[11, 7]. The introduction of organic wastes enhances better root penetration and aeration, reduces bulk density and increases porosity and formation of stable soil aggregates. These changes in the physical characteristics of the soil are especially crucial in deteriorated and compacted soils. Residue integration enhances nutrient availability by increasing cation exchange capacity and promoting nutrient mineralization processes. Vital nutrients such as potassium, phosphorus and nitrogen are also released by the breakdown of wastes and are gradually made available to the plants (Oyebiyi *et al.*, 2026) ^[16]. This slow and steady discharge of nutrients contributes to maintaining the soil fertility and also reduces the amount of nutrients lost through leaching. Moreover, the residue incorporation increases the pH stability and soil buffering capacity, which is necessary to achieve the optimal nutrient absorption (Lal, 2020) ^[11].

Biologically, the absorption of residues enhances the activity of the microorganisms as it is a good source of nutrition to the soil microorganisms. There is enhanced microbial biomass and enzyme activity that increases soil biological activity, decomposition of organic matter and recycling of nutrients (Fu *et al.*, 2021) ^[7]. Also, the existence of diverse microbial communities contributes to the health of the plants and reduction of soil-borne diseases.

Moreover, the residues reduce the crusting of the soil surface, reduce soil erosion and enhances soil resistance to environmental stresses such as drought and salt among others, which alleviate soil degradation (Naorem *et al.*, 2023) ^[15]. The incorporation of residue enhances the conservation of moisture in the soil, particularly under conditions of water scarcity. Overall, these benefits help to improve the ecosystem operation, sustainable soil management and the crop yield in lentil-based cultivation systems.

Impact of Biofertilizers on Growth of Lentil

Biofertilizers play a critical role in the growth of lentil by enhancing nutrient availability, fertility of soil and overall health

of plants. The inoculation of leguminous crops such as lentil with *Rhizobium* is particularly important as it enhances root nodulation and biological fixation of nitrogen that is helpful in fulfilling the nitrogen demand of the crop and reduces the use of synthetic fertilizers (Kumar & Singh, 2025) ^[10]. Higher availability of nitrogen also stimulates the synthesis of chlorophyll thereby increasing the vegetative growth and ultimately the biomass and grain yield.

Phosphate-solubilizing bacteria (PSB) also helps in improving the growth of plants by secreting organic acids and enzymes that convert insoluble forms of phosphorus to available forms that plants can use (Rai *et al.*, 2020) ^[18]. The availability of phosphorus is crucial to higher yields, as it is a crucial nutrient for root development, energy transfer (ATP) and reproductive growth. In addition, other useful microorganisms such as arbuscular mycorrhizal fungi (AMF) enhances nutrient uptake, particularly under drought conditions or deficiency of nutrients (Lata *et al.*, 2025) ^[12].

Also, biofertilizers enhances the diversity of the soil microbes and enzymes, contributing to the biological fertility of the soil, organic matter degradation and nutrient cycling (Sansinenea, 2021) ^[23]. The enhanced microbial activity leads to improved root-microbe interactions that increase flowering and stress tolerance in plants via enhanced soil structure. Moreover, biofertilizers have been found to enhance the resilience of plants to abiotic stresses and in part soil-borne diseases, resulting in more stable yields under adverse conditions.

Several studies have shown that the use of biofertilizers along with crop residues or organic amendments significantly enhances the lentil yield, nutrient uptake and economic gains in comparison with chemical fertilizers (Kumar *et al.*, 2023; Rakesh *et al.*, 2022) ^[9, 20]. Biofertilizers are a safe, cost-effective and long-term solution to nutrient management in Cropping systems using lentil because integrated methods do not only enhance yield of crops, but also enhances the health and longevity of soils.

Mechanical impacts on the Resource Availability of Lentil

Environmental factors that have a great influence on lentil production include drought which is a severe limitation in rainfed and semi-arid regions. Residue management and the use of biofertilizers is crucial to enhance resource availability by enhancing soil moisture retention, nutrient dynamics and plant physiological responses (Lal, 2020) ^[11]. Residue retention on the soil's surface increases water usage efficiency by acting as a mulch and lowering soil evaporation, regulating soil temperature and enhancing water penetration (Liu *et al.*, 2024) ^[14]. These effects are particularly important during critical stages of development such as blooming and pod formation when moisture stress can cause a large decrease in production.

Biofertilizers enhance the availability of resources by making the nutrient intake more efficient and stimulating root development. *Rhizobium* in combination with other microbe inoculation helps to increase the root surface area and root development, allowing plants to exploit deeper layers of soil and utilize water and nutrients better (Rai *et al.*, 2020) ^[18]. Drought resistance entails the necessity to have better root architecture including increased root density and rooting depth.

Moreover, residue integration and biofertilizer application affect plant physiological processes, such as stomatal conductance, transpiration efficiency and photosynthetic activity. Improved soil moisture and nutritional status allow for better control of stomatal opening, reducing water loss but not compromising carbon uptake. Higher microbial activity also helps in the

production of bioactive compounds that enhances plant growth, including phytohormones, which enhances plant tolerance to stress (Sansinenea, 2021) ^[23].

Enhanced soil moisture availability, improved nutrient uptake and optimized physiological responses together increases yield stability and resilience in lentil-based cropping systems under rainfed conditions. Additionally, these practices improve soil-plant-microbe interactions, resulting in more effective nutrient cycling and decreased environmental stress impacts.

Consequences on Lentil Phenology and Biomass

Residue management and biofertilizers greatly influence the phenology and biomass accumulation of lentil by modifying the microenvironment of the soil and the availability of resources. The increase in soil moisture and nutrient levels enhances germination, early seedling Vigor, vegetative growth and reproductive development, contributing to the enhanced crop establishment and productivity (Kumar *et al.*, 2023) ^[9]. The incorporation of residues enhances soil organic matter and promotes the continued release of nutrients, which is essential to long-lasting growth at different phenological stages.

Residue retention on the soil surface helps to control soil temperature by reducing daily variations and protecting the soil against extreme temperatures either hot or cold. This enhances the coordination of key phenological stages such as flowering, pod development and grain filling by providing a favourable environment for root development and the presence of microbes (Lal, 2020) ^[11].

Biofertilizers also lead to enhanced phenological development by improving nutrient absorption and plant growth by the production of phytohormones including auxins, gibberellins, and cytokinins (Sansinenea, 2021) ^[23]. Such growth-promoting chemicals accelerate the developmental processes, resulting in earlier flowering and improved reproductive performance. Increased nodulation and fixation of nitrogen also contribute to increased biomass accumulation and better partitioning of assimilates to grain development.

Residue incorporation can enhance lentil yield by up to 20-25% in situations where moisture is the limiting factor, based on the simulation and field research (Liu *et al.*, 2024) ^[14]. Other advantages of high biomass production are the increased photosynthetic activity and an improved harvest index. The lentil-based cropping systems ultimately lead to high biomass accumulation and grain production through better soil conditions, nutrient availability, and physiological control.

Synergistic Effects of Residue Incorporation and Biofertilizer

Residue incorporation combined with the application of biofertilizers may provide synergistic solution in enhancing the productivity of lentil crop. Residue Incorporation enhances physical properties of soil that support the survival of the soil microorganisms. Moreover, the use of crop residues as organic matter in the soil offers the advantage of providing organic substrates to the beneficial microbes in the biofertilizer to grow and increase the biological fixation of nitrogen and phosphorus in the soil (Rai *et al.*, 2020) ^[18]. The microbes that are inoculated with the biofertilizer treatment will decompose the organic material in the crop residue more rapidly and provide nutrients which can be utilized by the lentil crop.

The interaction between these two agricultural practices creates a synergistic effect that enhances biological properties of the soil, including microbial biomass, diversity, and enzymatic activity all of which are indicators of better soil fertility. The

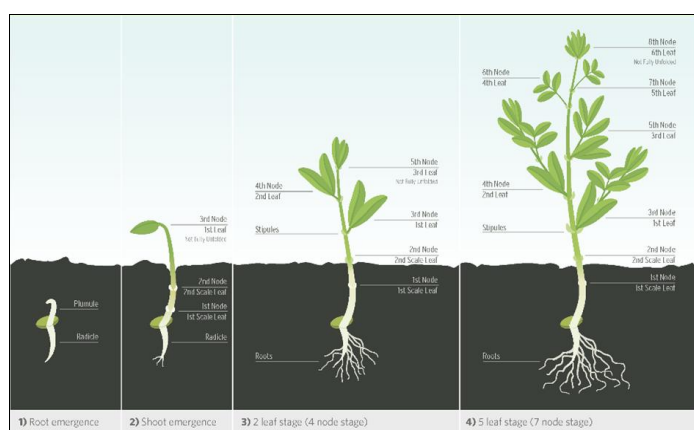
increased microbial activity aids in converting organic nutrients into nutrients available to plants and in the generation of growth-promoting substances by the soil microbes (Sansinenea, 2021)^[23]. These biological functions enhance the development and uptake of nutrients by lentil.

When lentil crop is treated together with crop residues and biofertilizers, the nutrient and water use efficiency is greatly enhanced. The leftover of the crops also helps to retain the soil moisture and increases supply of nutrients to the plant resulting in efficient utilization of available resources. The practice is particularly useful in rainfed lentil production system, where water and nutrients are most constraining growth determinants.



Source: Antara Ag (n.d.)^[3]

Fig 1: Characteristics of residue incorporation.



Source: Saskatchewan Pulse Growers (n.d.)^[24]

Fig 2: Lentil Phenology.

Conclusion

Incorporation of residues and application of biofertilizers are the key measures towards increasing the lentil production and the sustainability of soils. The ecofriendly practices have shown increased soil organic carbon, water retention, nutrient availability, and microbial activity that has resulted in better crop performance (Lal, 2020)^[11]. Residue quality and quantity may pose a challenge that could lead to issues like nitrogen immobilization, but these can be addressed by efficient management practices. Biofertilizers also increase the cycling of nutrients and minimize reliance on chemical fertilizers. Combination of such practices offers a sustainable solution in enhancing the lentil production especially in rainfed areas. The need to find site-specific management and deep knowledge of the soil-plant-microbe interactions to maximize productivity should be addressed in future research.

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