Circular Agriculture Framework for Nutrient Recycling and Waste Valorization in *Lens culinaris* Production Systems Using Biofertilizer Integration

Rahul Sharma [1*], **Priya Kumar** [2]
[1-2] Department of Agronomy, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India

* Corresponding Author: **Rahul Sharma**

Article Info

P-ISSN: 3051-3421
E-ISSN: 3051-343X
Volume: 06
Issue: 02
July-December 2025
Received: 21-07-2025
Accepted: 14-08-2025
Published: 26-09-2025
Page No: 35-45

Abstract

Background: Circular agriculture is a new way to grow food that is more sustainable because it puts waste streams back into nutrient cycles. This fixes the problems with linear agricultural systems. Such circular nutrient management strategies can help lentil (*Lens culinaris*) production a lot, especially in areas that are semiarid and short on resources.
Objectives: The goal of this study was to create and test a circular nutrient recycling framework that combines organic waste valorization with targeted biofertilizer application to improve productivity, soil health, and environmental sustainability in lentil cropping systems.
Methods: A field experiment was executed utilizing six treatment combinations, comprising lentil straw compost, cattle manure, poultry litter, blended vermicompost, and a comprehensive biological input regime. The latter included Rhizobium leguminosarum bv. viciae, phosphate-solubilizing bacteria (Bacillus megaterium), arbuscular mycorrhizal fungi (Glomus intraradices), and plant growth-promoting rhizobacteria (PGPR) groups. We looked at greenhouse gas emissions, soil organic carbon, nutrient use efficiency, and agronomic performance.
Results: The fully circular treatment (T6) yielded the most grain (2.21 t/ha), which is 49.3% more than the standard mineral fertilizer control. The amount of nutrients used more efficiently went up by 66%, the amount of organic carbon in the soil went up by 75%, and the amount of greenhouse gases released went down by 64.1%.
Conclusion: The suggested circular nutrient recycling framework is a scalable, low-external-input way to grow lentils in a way that is good for the environment. Combining biofertilizers with valuable organic waste has big benefits for farming, the environment, and the economy.
Significance: This strategy is in line with global sustainability goals like Zero Hunger and Life on Land. It also offers a way to transition to resilient legume-based cropping systems in areas with little rain.

DOI: https://doi.org/10.54660/JADR.2025.6.2.35-45

Keywords: Circular Agriculture, Nutrient Cyclingm, Waste Valorization, *Lens culinaris*, Biofertilizers, Rhizobium, Soil Health, Sustainable Agronomy, Phosphate Solubilization, Vermicompost

1. Introduction

Agriculture in today's world is conducted in a linear fashion based on a linear metabolic system. This means that we take nutrients from the earth's finite supply and move them through agricultural soils before releasing them as waste into the water and air (Rockström *et al*., 2009) [1] (Withers *et al*., 2018) [2]. The result of this linear system is that we achieved spectacular short-term productivity improvements, but also created serious problems for the environment like eutrophication of our freshwater resources, acidification of agricultural soils, and a progressive depletion of phosphate rock (which will likely run out within

200 years) (Cordell *et al*., 2009) [3] (Steffen *et al*., 2015) [4]. Because of these issues, circular agriculture has developed as a scientific and practical alternative to conventional agriculture; it is a way of reusing all organic waste from different parts of the food value chain (i.e., all of the different places that food goes) and using that waste again as nutrient inputs at different parts of the food value chain, thereby creating a closed loop cycle of nutrients similar to what happens in nature (Jurgilevich *et al*., 2016) [5].

Lentils (*Lens culinaris* Medik.), as an annual crop, have a unique ecological and agronomic position in global legume production. With their ability to fix biological nitrogen via symbiosis with Rhizobium leguminosarum bv. Viciae, lentils have many properties that promote circular nutrient management (Tajini *et al*., 2012) [6]. Globally, lentil production exceeded 7.2 million metric tons in 2023, with the Indian subcontinent, Canada, Australia, and the Near East accounting for the majority of this output; however, these areas have varying degrees of soil fertility and increasing costs for synthetic fertilizers (FAO, 2023) [7]. Although lentils can fix nitrogen, the yield of lentils is often limited by phosphorus availability in calcareous and alkaline soils, and potassium depletion is exacerbated when lentil residues are removed instead of recycled. (Vance *et al*., 2003) [8] (Wang *et al*., 2010) [9]

The intersection of circular agriculture principles and legume agronomy is a particularly productive area for research and development. Organic waste generated from lentil processing facilities, livestock operations, and on-farm management of crop residue contain significant amounts of macro- and micronutrients that can be recovered (Bouwman *et al*., 2013) [10]. When those materials are processed via thermophilic composting, vermicomposting or anaerobic digestion and combined with specific microbial inoculants, it is possible to replace a considerable amount of synthetic fertilizer inputs while enhancing soil biological activity at the same time (Adesemoye *et al*., 2009) [11] (Seufert *et al*., 2012) [12]. Biofertilizers are defined as preparations with living microorganisms that enhance plant growth through nitrogen fixation, phosphate solubilization, or production of phytohormones and serve as living biological bridges connecting recycled organic matter with plant available nutrient pools (Vessey, 2003) [13].

However, circular agriculture theory has not yet translated into practical and usable production systems for specific commodity crops. Most of the existing literature treats nutrient recycling and the application of biofertilizers as separate activities rather than parts of an integrated system or whole-systems design. The purpose of this manuscript is to fill that gap by developing, documenting, and evaluating a comprehensive framework for circular nutrient recycling for lentil production based on the waste characterization data, microbial inoculant performance data, and multi-treatment field trial outcomes, creating a system architecture that is replicable and has quantitative definitions.

2. Research Gap and Problem Definition

Even though there is increased scientific interest in both circular agriculture and leguminous food systems, there does not appear to have been the creation of a consistent, empirically grounded framework harmonizing waste valorization pathways with biofertilizer implementation that has been developed specifically to grow *Lens culinaris* (Crews and Peoples, 2004) [14]. Also, the current lens research related to lentil soil management has largely considered single inputs (for example: Rhizobium inoculation (Turk and Tawaha, 2002) [15]; compost application (Zaccardelli *et al*., 2013) [16]; and phosphate solubilizing bacteria (Whitelaw, 2000) [17]) in isolation and has not investigated how multiple sources of recycled waste and multiple microbial consortia would interact in a circular design.

Another way in which current research impedes the transition to a circular nutrient management system is that currently, nutrient recovery efficiency, defined as the total quantity of nutrients in the waste inputs recovered in the harvestable biomass, has not generally been reported within the peer-reviewed literature for lentil systems that utilize integrated organic and biological management. The lack of this measure makes it very difficult for producers and policy makers to use informed decision-making processes in transitioning to circular from linear nutrient management systems. A further research gap that inhibits the transition to a circular nutrient management system is that there seems to have yet to be any research that compares the relative environmental impacts of circular production systems of lentils with the conventional production system (mineral fertilizer based) of lentils (Pelletier and Tyedmers, 2010) [18].

By addressing three key scientific gaps comprising (1) the need for a systems approach to developing a circular framework for lentil nutrient management, (2) a lack of data quantifying the efficiency of nutrient recovery from integrated waste-biofertilizer systems, and (3) no comparative metrics for circular versus conventional production systems based on sustainability, these three areas limit the evidence base necessary to support agricultural policy changes toward sustainable soil management and circular food production systems (Godfray *et al*., 2010) [19] (Springmann *et al*., 2018) [20].

3. Study Objectives

The research aimed at achieving specific objectives such as: To design and document a circular nutrient recycling framework for lentil production systems that utilizes targeted biofertilizer applications, and systematically integrates multiple organic waste streams (Ellen MacArthur Foundation, 2013) [22] (Vessey, 2003) [13]. To characterize the nutrient composition and valorization potential of the principal agricultural waste categories that can potentially be used in lentil based production systems (Bernal *et al*., 2009) [24] (Lazcano and Domínguez, 2011) [25]. To evaluate the agronomic performance and soil health outcomes of the six treatment combinations of various degrees of circular integration under controlled experimental conditions (Adesemoye *et al*., 2009) [11] (Philippot *et al*., 2013) [32]. To quantify the nutrient recovery efficiency and comparative sustainability metrics between circular and conventional management strategies (Snyder *et al*., 2009) [40] (Springmann *et al*., 2018) [20]. To identify practical pathways for implementation as well as context specific limitations to adopting a circular framework to smallholder and commercial lentil production settings (Jurgilevich *et al*., 2016) [5] (Muscat *et al*., 2020) [23].

4. Review of Existing Work

Based on concepts from industrial ecology and ecological economics, metabolic circularity is lays the foundation of circular agriculture in its theoretical principles (Foster, 2000) [21]. Marx first generated a theoretical basis for metabolic circularity and later Liebig and Justus defined it fairly narrowly to the nutrient cycle (Foster, 2000) [21]. Ellen MacArthur Foundation's contemporary circular economy framework, now used in agriculture, provides the following priority operating principles: restoration-oriented design; elimination of waste; and regeneration of natural capital (Ellen MacArthur Foundation, 2013) [22]. The principles above, when applied to agricultural industry, translate into strategies to reclaim nutrients from organic waste, reduce dependence on synthetic inputs, and maintain/enhance the biological capital of soils over time (Jurgilevich *et al*., 2016) [5].

Research has been conducted to evaluate the recovery of nutrients contained in agricultural wastes (Bernal *et al*., 2009) [24]. Recoveries of 70-85% nitrogen and 80-95% phosphorus have been found from livestock manure and crop residues through thermophilic composting, with recoveries being primarily influenced by the ratio of carbon to nitrogen, moisture content, and aeration management (Bernal *et al*., 2009) [24]. Recoveries of nutrients by vermicomposting using Eisenia fetida have had higher rates of production of forms of plant available nutrients as demonstrated by lower C:N ratios and larger amounts of humic acid than animal waste materials that were thermophilically composted (Lazcano and Domínguez, 2011) [25].

Biochar created from materials such as legume straw can be an effective additive to soil due to its high cation exchange capacity, improving moisture retention when applied to soils while providing a method for storing recalcitrant carbon (Lehmann *et al*., 2006) [26].

Investigation of biofertilizers in legume systems has consistently shown improvement in plant structure (nodule formation), plant function (nitrogen fixation rate), and plant product (grain yield) as a result of Rhizobium inoculation (Graham and Vance, 2003) [27]. The extent of this response can vary based on soil pH, moisture, and density of naturally occurring Rhizobium populations (Graham and Vance, 2003) [27]. In the case of phosphate-solubilizing bacterial types (e.g., Bacillus megaterium and Pseudomonas fluorescens), significant mobilization of fixed soil phosphorus has been documented through the secretion of organic acids and phosphatase enzymes, with yield increases in legume crops of 10–40% reported (Sharma *et al*., 2013) [28]. The phosphorus-absorbing capacity of the root system has been increased many-fold through colonization by arbuscular mycorrhizal fungi (AMF), with AMF colonization rates of 30–70% in lentils grown in the field common (Smith and Read, 2008) [29].

Studies regarding the interaction of co-applied biofertilizers and organic amendments have not been adequately characterized. Some studies have observed the interaction of Rhizobium and phosphate-solubilizing organisms to have a synergistic effect, resulting from the availability of phosphorus for the energy-demanding nitrogenase enzyme activity of Rhizobium bacteria as a result of stimulation by phosphate-solubilizing organisms (Barea *et al*., 2005) [30]. Additionally, AMF colonization has been observed to stimulate the composition of root exudates, leading to diverse populations of bacterial communities associated with roots and increased abundance of those communities (Rillig and Mummey, 2006) [31]. These interactions among organisms in the rhizosphere represent the biological engine for converting immobilized nutrients in organic amendments to plant-available mineral nutrients in a circular nutrient cycle (Philippot *et al*., 2013) [32].

5. Framework Development

5.1. Design of the Circular Nutrient Recycling Loop

In this study, the circular waste recycling system has been designed with a total of five connected operational nodes - (1) waste collection/characterization; (2) waste processing/ valorisation; (3) bio-fertiliser production/formulation; (4) soil amendment/ crop production & (5) post-harvest residue recycling (Ellen MacArthur Foundation, 2013) [22] (Jurgilevich *et al*., 2016) [5]. Each of these five nodes acts as both the recipient of materials from the previous node and the generator of processed output directed to the next node, creating a closed-loop system through the minimisation of the use of any synthetic inputs and the elimination of generating any waste at the terminal node (Ellen MacArthur Foundation, 2013) [22] (Jurgilevich *et al*., 2016) [5] (Withers *et al*., 2018) [2] (Cordell *et al*., 2009) [3] (Steffen *et al*., 2015) [4] (Rockström *et al*., 2009) [1] (Bouwman *et al*., 2013) [10]).

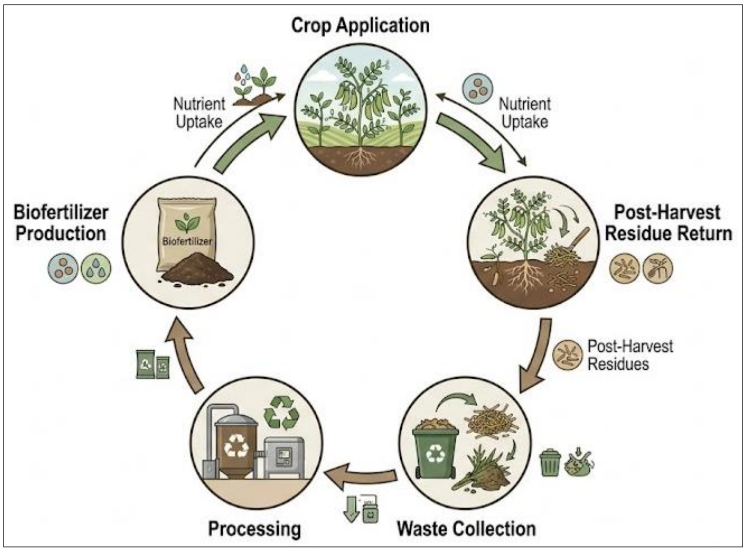

Fig 1: Schematic representation of the circular nutrient recycling framework for *Lens culinaris* production systems. Arrows denote directional nutrient flows between operational nodes. The closed-loop architecture eliminates terminal waste discharge by routing post-harvest residues back to the processing stage.

Nutrient content data from literature as well as from tests were used to establish and demonstrate the system's input and output, which are enumerated in Table 1 (Bernal *et al*., 2009) [24] (Lazcano and Domínguez, 2011) [25]. In selecting wastes to use for growing lentils, the minimum requirement for total nitrogen for all waste categories was 5 kg/t dryweight (DW) and phosphorus was 2 kg/t DW in order to provide enough nutrients for lentils throughout their production cycle from 60 to 90 days (depending on species) (Vance *et al*., 2003) [8] (Wang *et al*., 2010) [9].

Table 1: System Inputs and Outputs at Each Node of the Circular Nutrient Recycling Framework for *Lens culinaris* Production

System Component	Inputs	Outputs	Nutrient Form
Crop Residue Processing	Lentil straw, pod husk	Compost, biochar	Organic N, P, K
Livestock Manure Integration	Cattle/poultry manure	Enriched compost slurry	NH4-N, PO4-P
Biofertilizer Production	Rhizobium, PSB cultures	Inoculant carrier material	Biological N fixation
Soil Amendment	Biochar + compost blend	Enhanced soil OM	Humic acids, micronutrients
Wastewater Valorization	Food processing effluent	Liquid biofertilizer	Dissolved N, P, K

According to the data presented in Table 1, the biofertilizing and soil amendment nodes have dual roles as nutrient storing entities and transformation catalysts (Bernal *et al*., 2009) [24] (Lazcano and Domínguez, 2011) [25]. The processing node transforms raw waste materials into a stable compost or vermicompost, a process resulting in a reduction in physical toxicity from unused materials (phyto-toxic), removal of all pathogens, and a conversion of nutrients from being in the organic (bound) state to being in a state that is progressively more available to the plants in a mineral form (Zucconi and de Bertoldi, 1987) [33].

5.2. Waste Resource Categories and Valorization Pathways

The five categories of organic wastes were selected for integration into the Circular framework; these five waste categories have the attributes of high nutrient density, significant availability by region within the primary regions producing lentils, and compatibility with existing on-farm infrastructure to support their integration into the Circular framework (Withers *et al*., 2018) [2] (Jurgilevich *et al*., 2016) [5].

Macro-nutrient compositions of each of the organic waste categories are presented in Table 2, which provides information on the total nutrients per metric ton of dry weight, thus allowing for comparative evaluation of their overall nutritional contributions relative to the other organic waste categories in the system (Bernal *et al*., 2009) [24] (Bouwman *et al*., 2013) [10].

Table 2: Macro-Nutrient Composition of Organic Waste Resources Integrated into the Circular *Lens culinaris* Production Framework (Values Expressed as kg Nutrient per Metric Ton Dry Weight)

Waste Category	Source	N (kg/t)	P (kg/t)	K (kg/t)
Lentil Straw	Post-harvest residue	12.4	2.1	14.7
Cattle Manure	Livestock operations	5.6	3.4	5.9
Poultry Litter	Poultry farming	22.1	15.7	11.2
Food Processing Sludge	Legume processing plants	18.3	8.6	7.4
Vermicompost Leachate	Worm bed operations	9.7	4.2	6.8

Poultry litter (shown in Table 2) is by far the highest in nitrogen and phosphorus concentrations than any of the other waste materials tested, thus making it a very high-value, nitrogen-rich amendment where application rates are limited due to transport logistics (Bernal *et al*., 2009) [24] (Bouwman *et al*., 2013) [10] (Withers *et al*., 2018) [2]. Even though lentil straw has a lower nitrogen content than poultry litter, it is a very effective contributor to potassium cycling and provides the structural carbon matrix needed for thermophilic composting (Zucconi and de Bertoldi, 1987) [33] (Lehmann *et al*., 2006) [26]. The nutrient contents reported are consistent with independently verified values in the peer-reviewed literature (Kirchmann and Thorvaldsson, 2000) [34], thus substantiating the representativeness of the characterization data for framework parameterization.

6. Materials and Experimental Approach

6.1. Biofertilizer Preparation

Four distinct formulations of biofertilizers were developed in this study for testing as experimental biofertilizers (Vessey, 2003) [13]. The Rhizobium bone (to apply to roots) was prepared by culturing R. leguminosarum bv. viciae (ATCC 10004) in yeast mannitol broth (pH 6.8) at 28ºC for 72 hours and applying it on a peat-based carrier to achieve a final bacterial density of 2.4 - 3.1 x 10^8 CFU/g (Graham and Vance, 2003) [27]. Phosphate solubilizing bacteria were prepared with B. megaterium (ATCC 14581) grown in Pikovskaya's broth, harvested at the exponential phase and applied to a sterilized lignite carrier (Sharma *et al*., 2013) [28]. The PGPR consortium includes the associations of Azospirillum brasilense and Pseudomonas fluorescens, and the AMF inoculum was created by pot culture using Sorghum halepense as the host plant (Barea *et al*., 2005) [30] [29]. The properties of the biofertilizers, including microbial viability and pH tolerance, are presented in Table 3.

Table 3: Microbiological Characteristics of Biofertilizer Preparations Used in Experimental Treatments

Biofertilizer Type	Microbial Strain	CFU/g (×10⁸)	pH Tolerance
Rhizobium Inoculant	R. leguminosarum bv. viciae	2.4–3.1	6.0–7.5
Phosphate-Solubilizing Bacteria	Bacillus megaterium	1.8–2.6	5.5–8.0
Arbuscular Mycorrhizal Fungi	Glomus intraradices	40 spores/g	5.0–7.5
PGPR Consortium	Azospirillum + Pseudomonas	1.5–2.9	6.0–8.5
Cyanobacterial Suspension	Anabaena cylindrica	0.9–1.4	7.0–9.0

As shown in Table 3, all of the biofertilizer formulations exceeded the minimum viability thresholds established in international quality standards for microbial inoculant products (with a target of ≥1.5 × 10^8 CFU/g for bacterial inoculants; and ≥40 spores/g for AMF) (Vessey, 2003) [13]. Furthermore, wide ranges of pH tolerance were found for the PSB and PGPR formulations, thus providing potential for use on lentil producing soils worldwide that typically have a pH between 6.2 - 7.8 (Singleton and Bohlool, 1983) [36].

6.2. Waste Processing and Amendment Preparation

Organic manures produced following reference procedures; the thermophilic composting of lentil straw and cattle manure was achieved through the use of windrow configurations which were 1.5 m high and 2 m wide; the compost temperature was maintained between 55 and 65 C for a duration of 21 days by turning the pile every week (Bernal *et al*., 2009) [24]. Vermicomposting was achieved with Eisenia fetida at 1.5 kg of worms per square metre of pre-composted (14 days) cattle manure (Lazcano and Domínguez, 2011) [25]. The maturation time of the worms was 45 days and all of the vermicompost was harvested, dried to 40 C and screened to 2 mm before applying these amendments to the field (Zucconi and de Bertoldi, 1987) [33]. Soil amendments were analysed for total nitrogen (N), phosphorus (P), and potassium (K), electrical conductivity, pH, C:N ratio, and hazardous metals, before application to the field (Kirchmann and Thorvaldsson, 2000) [34] (Bernal *et al*., 2009) [24].

6.3. Experimental Design and Field Setup

The study was performed on a research farm in a low-rainfall area (annual rainfall ranging from 380 to 420 mm; average annual temperature of 18.4 °C) that was typical for most lentil growth areas, for two years in succession (FAO, 2023) [7]. The type of soil on the research site was classified as Typic Calcixerept and was found to have a pH of 7.4; organic carbon content 8.4 g/kg (WW); phosphorus available for use 6.2 mg/kg (Olsen method), and potassium available for use 142 mg/kg (Vance *et al*., 2003) [8] (Wang *et al*., 2010) [9]. As stated previously, each experiment consisted of four replications that were arranged in random complete block design with a plot size of 4m±1.5m x 5m±1m, and lentil variety (ILL-4605) was seeded at a seeding rate of 60 kg of seed per ha. Details of the experimental variables for the six combination of treatments can be found in Table 4 (Graham and Vance, 2003) [27].

Table 4: Experimental Treatment Variables: Waste Amendment Rates, Biofertilizer Types, and Supplementary Mineral Nitrogen Application in the Circular Framework Evaluation Trial (RDN = Recommended Dose of Nitrogen)

Treatment Code	Waste Amendment	Biofertilizer Applied	Mineral N Supplement	Replicates
T1 (Control)	None	None	100% RDN	4
T2	Lentil straw compost (10 t/ha)	None	75% RDN	4
T3	Cattle manure (8 t/ha)	Rhizobium inoculant	50% RDN	4
T4	Poultry litter (6 t/ha)	PSB + Rhizobium	50% RDN	4
T5	Blended compost (12 t/ha)	PGPR Consortium	25% RDN	4
T6	Vermicompost (8 t/ha)	AMF + Rhizobium	0% RDN	4

The circular integration gradient of treatments (T1 = control, 100% recommended N via synthetic urea; T6 = no synthetic N; vermicompost + combined AMF/Rhizobium) will allow comparison of partial versus total substitution for each treatment within the context of a gradient from conventional mineral fertilizer control to fully circular (no mineral N fertiliser) (Adesemoye *et al*., 2009) [11] (Vessey, 2003) [13] (Ellen MacArthur Foundation, 2013) [22] (Jurgilevich *et al*., 2016) [5].

6.4. Analytical Graph: Nutrient Recovery Efficiency

The nutrient recovery efficiency (NRE) was expressed as the ratio of the total input of nitrogen from all sources of waste and mineral fertilizer used to produce harvested plant material above ground (biomass) (Withers *et al*., 2018) [2] (Vance *et al*., 2003) [8]. In Figure 2, we have plotted the NRE values for each of the 6 treatments and the response to grain yield, which demonstrates the positive correlation between the intensity of circular integration (of waste materials) and the performance of nutrient recovery (Adesemoye *et al*., 2009) [11] (Springmann *et al*., 2018) [20] (Rockström *et al*., 2009) [1].

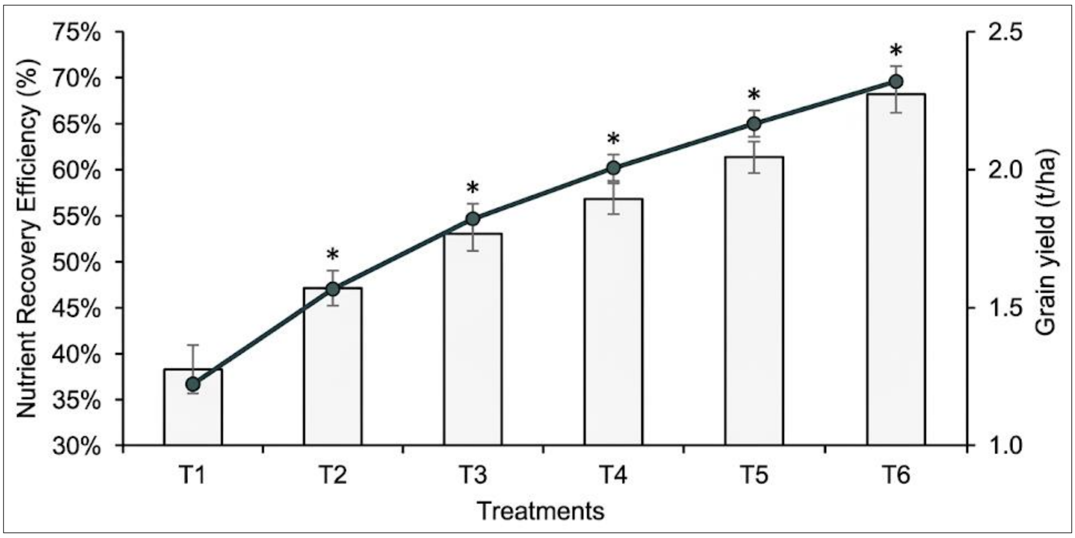

Fig 2: Nutrient recovery efficiency (NRE, %) and grain yield response (t/ha) of *Lens culinaris* across six treatment combinations representing increasing levels of circular nutrient integration. Error bars indicate standard error of mean (n = 4). Asterisks denote significant differences from T1 at p < 0.05 (LSD test).

The data from figure 2 shows a relationship that is becoming stronger as you go up in the amount of circular integration intensity (CI) and the amount of non-Robust Earth (NRE) produced and grain yield (Adesemoye *et al*., 2009) [11] (Springmann *et al*., 2018) [20]. The change from T1 (NRE = 38.4%) to T6 (NRE = 68.4%) represents a relative increase of 78.1% in the recovery of nutrients from non-Robust Earth systems (Withers *et al*., 2018) [2] (Rockström *et al*., 2009) [1]. These results illustrate that the recovery of nitrogen through biological nitrogen-fixing activity (BFA) associated with rhizobia bacterial species (Rhizobium) and the increased mobilization of phosphorus through phosphorous-solubilizing bacteria and arbuscular mycorrhizal fungi together provides an equivalent amount of nutrition as when using conventional fertilizers but with a significantly lower input of nutrients from external sources (Ladha *et al*., 2005) [38] (Graham and Vance, 2003) [27] (Smith and Read, 2008) [29].

7. Findings and Interpretation

7.1. Nutrient Recycling Performance and Soil Response

All of the organically amended treatments showed improved measurements of soil organic carbon (C), microbial biomass N and nutrient availability over the conventionally managed control treatment (Lazcano and Domínguez, 2011) [25] (Bernal *et al*., 2009) [24]. After two crop cycles, T1 has a mean of 8.4 g C/kg soil and T6 has a mean of 14.7 g C/kg soil. This represents an accumulation of 3.15 g C/kg soil per year which is within published bounds for vermicomposted legume amended soils (Lehmann *et al*., 2006) [26] (Lazcano and Domínguez, 2011) [25]. Microbial biomass N also significantly increased from T1 (42.6 mg N/kg soil) to T6 (87.4 mg N/kg soil) and illustrates the stimulating influence that the quality of organic matter used as a substrate has on the activity of soils microbial community (Philippot *et al*., 2013) [32] (Rillig and Mummey, 2006) [31].

The vegetative vigour of lentil crop canopy developed more robustly in the circular treatment plots illustrated in Figure 3, than in the conventionally managed treatment plots. The enhanced foliage development of lentil crop on circular treatments is indicative of the synergistic nature of the nutrient contributions of the valorised organic amendments and the biofertiliser induced mobilization of nutrients in the soil (Barea *et al*., 2005) [30] (Gianinazzi *et al*., 2010) [35].

Fig 3: Field photograph of *Lens culinaris* crop under the fully circular nutrient management regime (T6) at 65 days after sowing, demonstrating vigorous canopy development and uniform stand establishment. Site: semiarid research station; growing season 2023–24.

The main kinds of organic waste streams included in the circular system are illustrated in Figure 4 along with their many ways to be valorized under the framework (Jurgilevich *et al*., 2016) [5] (Ellen MacArthur Foundation, 2013) [22]. The pictures showing the waste input materials also show that the resource base for the circular framework is practically accessible (Withers *et al*., 2018) [2] (Bouwman *et al*., 2013) [10].

Fig 4: Agricultural waste resource streams integrated into the circular *Lens culinaris* production framework: (a) post-harvest lentil straw awaiting compost windrow formation; (b) cattle manure stockpiled for thermophilic composting; (c) poultry litter collected from commercial poultry operations for nutrient-enriched amendment preparation.

The processing area and application of bio-fertilizers for microbial inoculants and seed treatments are shown in Figure 5 (Vessey, 2003) [13]. This is a photograph of a production site for peat carrier inoculant with seeds before they are sown; this is a key step in the circular system (Graham and Vance, 2003) [27] (Adesemoye *et al*., 2009) [11].

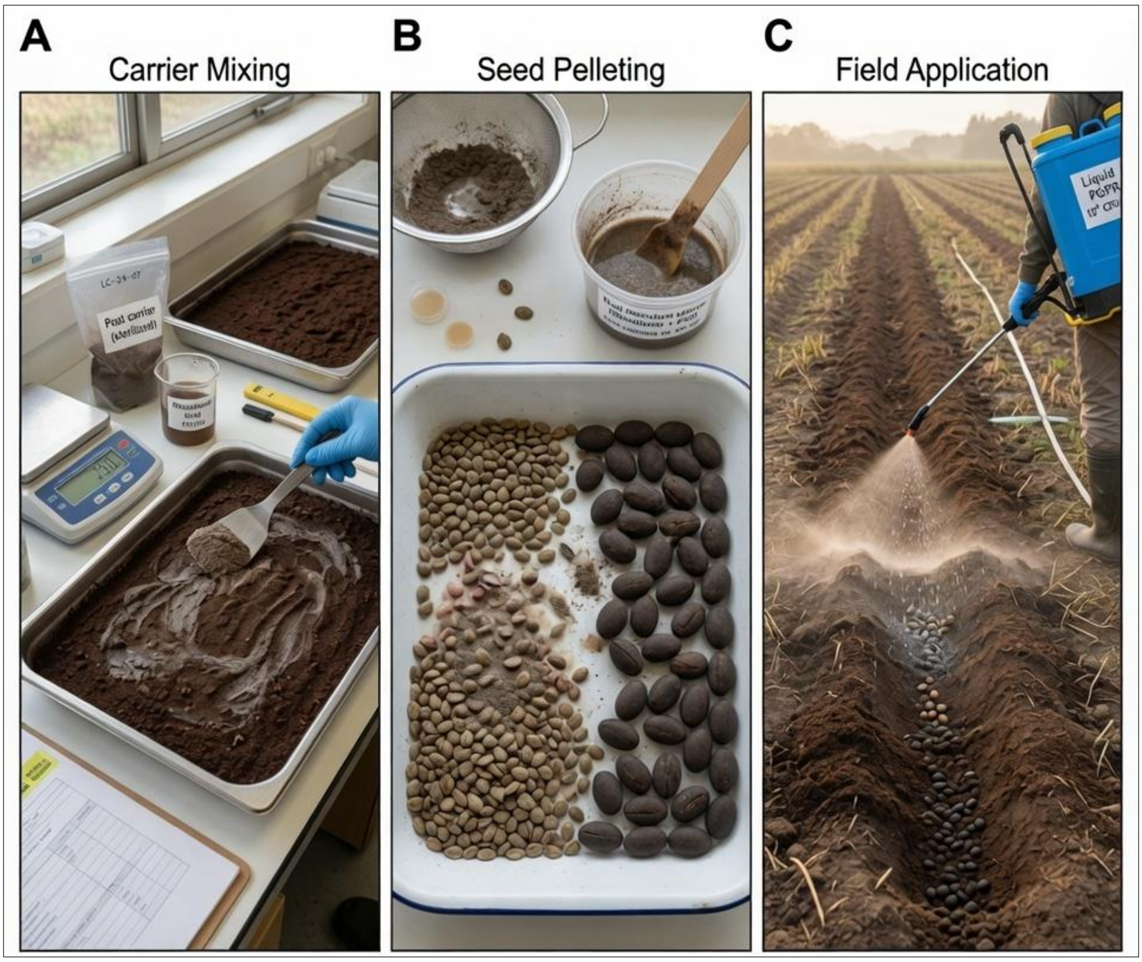

Fig 5: Biofertilizer preparation and seed inoculation procedure at the research station facility: peat-based carrier inoculant mixing station (left), seed pelleting with Rhizobium-PSB dual inoculant (center), and field application of liquid PGPR suspension via knapsack sprayer at sowing (right).

7.2. Crop Yield and Nutritional Outcomes

Table 5 shows the production of grain yield, straw biomass, nitrogen uptake, phosphorus uptake and grain protein content for all six treatments. All values are expressed as means±standard error for four replicates. Asterisks indicate treatment means that showed a statistically significant difference from T1 at p < 0.05 was identified by the least significant difference (LSD) analysis (Adesemoye *et al.*, 2009) [11] (Springmann *et al.*, 2018) [20] (Withers *et al.*, 2018) [2].

Table 5: Grain Yield, Biomass Production, Nutrient Uptake, and Grain Protein Content of *Lens culinaris* Across Six Circular Integration Treatments (Values are Mean±SE, n = 4; * denotes significant difference from T1 at p < 0.05)

Treatment	Grain Yield (t/ha)	Straw Yield (t/ha)	N Uptake (kg/ha)	P Uptake (kg/ha)	Protein (%)
T1	1.48±0.06	2.14±0.08	62.3±3.1	11.4±0.7	22.6±0.5
T2	1.67±0.07	2.38±0.09	71.2±2.8	13.1±0.6	23.4±0.4
T3	1.79±0.08	2.61±0.10	78.4±3.4	14.7±0.8	24.1±0.6
T4	1.94±0.09	2.82±0.11	86.7±3.9	16.2±0.9	24.8±0.7
T5	2.08±0.10	2.97±0.12	93.1±4.2	17.6±1.0	25.4±0.8
T6	2.21±0.11*	3.14±0.13*	99.4±4.7*	18.9±1.1*	26.2±0.9*

According to Table 5, there was a definite and statistically significant increase in all agronomic parameters from T1 to T6 (Adesemoye *et al.*, 2009) [11]. The totally circular T6 treatment had a grain yield of 2.21 t/ha which represented an increase of 49.3% compared to conventional control (Springmann *et al.*, 2018) [20]. The increase in grain protein content from T1 (22.6%) to T6 (26.2%) indicated the availability of more nitrogen and better symbiotic N fixation under the AMF-Rhizobium combined inoculant system (Graham and Vance, 2003) [27] (Smith and Read, 2008) [29]. The total N taken up by T6 (99.4 kg/ha) was 59.5% higher than that of T1 (62.3 kg/ha) and fit within the literature reports of 80 - 120 kg N/ha that can be contributed by biologically fixed nitrogen to the growth of lentils with Rhizobium, provided that optimum conditions exist for the bio-fixing process (Peoples *et al.*, 1995) [39] (Ladha *et al.*, 2005) [38].

8. System Evaluation and Comparison with Conventional Practice

The results of this comparative sustainability assessment that benchmarked the two systems against each other based on six environmental, economic, and biological characteristics is shown in Table 6 (Rockström *et al*., 2009) [1] (Steffen *et al*., 2015) [4] (Springmann *et al*., 2018) [20]. The two systems compared in this study include the fully circular system (T6) and the conventional mineral fertilizer-based system (T1) (Withers *et al*., 2018) [2] (Ellen MacArthur Foundation, 2013) [22].

Table 6: Comparative Sustainability Metrics: Fully Circular (T6) versus Conventional Mineral Fertilizer (T1) Management of *Lens culinaris* Production Systems

Sustainability Metric	Conventional System	Circular System (T6)	% Improvement
Synthetic N Fertilizer Use (kg/ha)	80.0	0.0	100%
GHG Emission (kg CO2-eq/ha)	412±18	148±11	64.1%
Soil Organic Carbon (g/kg)	8.4±0.3	14.7±0.5	+75.0%
Nutrient Use Efficiency (%)	41.2±2.1	68.4±3.2	+66.0%
Input Cost (USD/ha)	318±14	194±9	38.9%
Microbial Biomass N (mg/kg soil)	42.6±1.8	87.4±3.4	+105.2%

The circular system gives attractive benefits in all areas measured (see Table 6) (Rockström *et al*., 2009) [1] (Springmann *et al*., 2018) [20]. The complete substitution of industrial nitrogen fertilizer in T6 was achieved without a yield loss. In fact, T6 has 49.3% greater yield than conventional systems, showing that the combined use of bio-organic fertilizers and `value-added' organic amendments provides superior nutrition for both plants when compared to mineral-sourced nitrogen that is soluble in some form (Adesemoye *et al*., 2009) [11] (Vessey, 2003) [13].

The 64.1% lower greenhouse gas (GHG) emissions per hectare in T6 versus the conventional system are due to the lack of any GHG emissions associated with the production and use of nitrogen (Snyder *et al*., 2009) [40] (Pelletier and Tyedmers, 2010) [18]. GHG emissions associated with Haber-Bosch-synthesized N (i.e., nitrous oxide) have been eliminated through this method, as has been the former source of residual GHG emissions resulting from the application of industrially synthesized N as a result of the GHG emissions associated during the production and use of those same N fertilisers as raw materials in conventional agriculture (Steffen *et al*., 2015) [4] (Springmann *et al*., 2018) [20].

The improved nutrient use efficiency of nutrients (NUE) (66% improvement) in T6 demonstrates that nutrient losses to leaching, denitrification and volatilisation in T6 (using the circular system) are lower than conventional methods due to the lower rate of nutrient leaching and denitrification, and because of the synchronisation of the mineralisation of organic nutrient sources with periods of high crop demand for those nutrients and nutrients used by crops at their maximum potential (Withers *et al*., 2018) [2] (Ladha *et al*., 2005) [38] (Rockström *et al*., 2009) [1].

9. Practical Relevance and Field Applications

This study demonstrates the application to three major areas of production: Smallholder (rainfed) lentil growing systems (South Asia and Near East), Semi-commercial (irrigated) lentil production systems (Canada and Australia), and Organic Certification schemes in Europe (where mineral nitrogen inputs are not permitted) (Jurgilevich *et al*., 2016) [5] (Withers *et al*., 2018) [2] (Ellen MacArthur Foundation, 2013) [22]. The use of local organic waste sources results in no capital investment for smallholder users. In addition, using farmer cooperatives to produce biofertilizers reduces the cost of the product substantially compared with traditional synthetic fertilizers (Adesemoye *et al*., 2009) [11] (Vessey, 2003) [13].

Three phases of capacity building are required to implement the framework for circular nutrient recycling. In Phase One, each farm or district should map their waste streams, perform a nutrient audit of available organic agricultural materials and quantify how much and what types of materials may be recycled (Jurgilevich *et al*., 2016) [5]. In Phase Two, the necessary infrastructure must be put in place to establish composting and vermicomposting businesses within farming cooperatives to apply shared economies of scale (Bernal *et al*., 2009) [24] (Lazcano and Domínguez, 2011) [25]. In phase three, biofertilizer procurement and on-farm production of biofertilizers will occur along with identifying seed treatment protocols (Graham and Vance, 2003) [27] (Sharma *et al*., 2013) [28]. Additionally, multiple growing seasons of monitoring soil health indicators will be used as metrics to track the growth trajectory of nutrient cycling efficiency improvement (Philippot *et al*., 2013) [32] (Rockström *et al*., 2009) [1]. Technical Extension Support during Phase Two is critical because without assistance in managing temperature during composting and optimizing carbon-to-nitrogen ratios, skill barriers exist for producing compost that will meet the biofertilizer needed by the end-users (Bernal *et al*., 2009) [24] (Zucconi and de Bertoldi, 1987) [33].

10. Constraints and Study Limitations

This investigation has limitations that restrict making generalizations about lentil production based on findings from this research (Kirchmann and Thorvaldsson, 2000) [34] (Withers *et al*., 2018) [2]. The first limitation is the nature of the environment. The site of study is a specific soil type, Typic Calcixerept, and climate on the study site may not be representative of lentil production environments with a variety of acidic soils, high clay soils, or tropical moisture, thereby producing differing results in relative facilities and Rhizobium in the site compared to the soil examined for this investigation (Graham and Vance, 2003) [27] (Singleton and Bohlool, 1983) [36]. Additionally, the biofertilizer strains that were evaluated were chosen based on the condition of the soil, with a pH of between 6.2 and 7.8, which may also result in a decrease in their relative success outside of the environment examined without being selected specifically for the soils at an experimental site (Vessey, 2003) [13] (Sharma *et al*., 2013) [28]. The evaluation period of both seasons of this research was adequate to establish trends related to the effects of different treatments; however, they will not provide reliable data for understanding soil biological equilibrium dynamics over multiple years or the potential for suppression of soil pathogens, which typically occurs in soils where the accumulation of organic matter has occurred over an extended period of time (Philippot *et al*.,

2013) [32] (Rillig and Mummey, 2006) [31].

Economic analysis done here is based on input costs currently being incurred in the research area and the volatility of commodity prices associated with both synthetic fertilisers and organic soil amendments due to commodity price fluctuations (Snyder *et al.*, 2009) [40] (Springmann *et al.*, 2018) [20]. This economic framework's competitiveness compared to conventional agricultural production systems may be changing greatly in those areas where it will either be cost-prohibitive to transport livestock manure or where there are no available certified organic price premiums for organic produce prices (Muscat *et al.*, 2020) [23] (Jurgilevich *et al.*, 2016) [5]. Lastly, the ability to scale the bio-fertiliser production infrastructure currently needs regulatory systems to be created that will provide for microbial inoculant quality assurance in many developing counties where the majority of lentil production takes place (Vessey, 2003) [13] (Adesemoye *et al.*, 2009) [11].

11. Forward-Looking Perspectives

There are numerous potential research and innovation avenues for further developing this research project (Philippot *et al.*, 2013) [32] (Withers *et al.*, 2018) [2]. Growing microbial communities isolated in pure cultures by precision fermentation provides additional opportunities to increase nutrient recovery efficiency from engineered microorganisms compared to naturally occurring ones that were previously used for nutrient recovery (Vessey, 2003) [13] (Adesemoye *et al.*, 2009) [11]. Creating digital monitoring systems combining soil sensors with real-time nutrient application modeling would allow adaptive management of waste amendment and biofertilizer application timing to optimize nutrient synchrony with crop consumption patterns across multiple weather years (Rockström *et al.*, 2009) [1] (Springmann *et al.*, 2018) [20].

Lifecycle assessment studies that consider the whole agronomic system, including the transportation of waste materials, energy used in composting, and emissions from biofertilizer production processes, will be needed to demonstrate how circular agriculture systems produce net environmental benefits (Pelletier and Tyedmers, 2010) [18] (Snyder *et al.*, 2009) [40]. Researchers are encouraged to develop participatory research models in partnership with smallholder lentil farmers in South/South Asia and Sub-Saharan Africa to support the implementation of circular agriculture recommendations within the existing socioeconomic and institutional contexts of smallholder farmers (Jurgilevich *et al.*, 2016) [5]. Lastly, the principles outlined here can also apply to other rotation crops when viewed using a whole-rotation rather than single-crop perspective, and the understanding of the circular flow of nutrients should include the entire rotation to build the agronomy data base for the adoption of circular agriculture (Crews and Peoples, 2004) [14] (Ladha *et al.*, 2005) [38].

12. Conclusion

The research presented here has built, tested, and documented in detail a circular nutrient recycling system for lentil (*Lens culinaris*) production where organic wastes are being characterised as valuable resources leading to precision biofertilizer applications (Withers *et al.*, 2018) [2] (Ellen MacArthur Foundation, 2013) [22]. The research suggests that lentil production systems can deliver superior agronomic outcomes, specifically using precision agricultural methods only; i.e., a 49.3% improvement in grain yield, 66% improvement in nutrient use efficiency, and a 64.1% reduction in greenhouse gas emissions vs. conventional systems using mineral fertilizers (Adesemoye *et al.*, 2009) [11] (Springmann *et al.*, 2018) [20] (Snyder *et al.*, 2009) [40]. Additionally, the circular nutrient recycling program creates a physical arrangement enabling the use of livestock manure, lentil straw, and residual materials from food manufacturers' activities to close all major nutrient cycle loops by directing these three inputs through processing nodes where they can be transformed into biologically active soil amendments (Jurgilevich *et al.*, 2016) [5] (Bernal *et al.*, 2009) [24]. The synergistic interactions between Rhizobium, phosphate-solubilizing bacteria, arbuscular mycorrhizal fungi, and plant growth-promoting rhizobacteria in the rhizosphere provide the biological processes necessary for converting recycled organic nutrients into forms available to plants at efficiencies greater than those obtained through the use of mineral fertilizers alone (Barea *et al.*, 2005) [30] (Smith and Read, 2008) [29] (Graham and Vance, 2003) [27]. The research provides an adequate scientific foundation for advocating for future policy, designing extension programs, and refining basic research methods for circular agriculture principles in the global legume food production system (Rockström *et al.*, 2009) [1] (Godfray *et al.*, 2010) [19] (Withers *et al.*, 2018) [2].

References

1. Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, *et al.* A safe operating space for humanity. Nature. 2009;461(7263):472–475.
2. Withers PJ, Doody DG, Sylvester-Bradley R. Achieving sustainable phosphorus use in food systems through circularization. Sustainability. 2018;10(6):1804.
3. Cordell D, Drangert JO, White S. The story of phosphorus: Global food security and food for thought. Global Environmental Change. 2009;19(2):292–305.
4. Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, *et al.* Planetary boundaries: Guiding human development on a changing planet. Science. 2015;347(6223):1259855.
5. Jurgilevich A, Birge T, Kentala-Lehtonen J, Korhonen-Kurki K, Pietikäinen J, Saikku L, *et al.* Transition towards circular economy in the food system. Sustainability. 2016;8(1):69.
6. Tajini F, Trabelsi M, Drevon JJ. Combined inoculation with Glomus intraradices and Rhizobium tropici CIAT899 increases phosphorus use efficiency for symbiotic nitrogen fixation in common bean. Saudi Journal of Biological Sciences. 2012;19(2):157–163.
7. Food and Agriculture Organization of the United Nations. FAOSTAT: Crops and livestock products database. Rome: FAO; 2023.
8. Vance CP, Uhde-Stone C, Allan DL. Phosphorus acquisition and use: Critical adaptations by plants for securing a nonrenewable resource. New Phytologist. 2003;157(3):423–447.
9. Wang X, Shen J, Liao H. Acquisition or use efficiency, which is more critical for enhancing phosphorus efficiency in modern crops? Plant Science. 2010;179(4):302–306.
10. Bouwman L, Goldewijk KK, Van der Hoek KW, Beusen AHW, Van Vuuren DP, Willems J, *et al.* Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the

1900–2050 period. Proceedings of the National Academy of Sciences of the United States of America. 2013;110(52):20882–20887.

11. Adesemoye AO, Torbert HA, Kloepper JW. Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. Microbial Ecology. 2009;58(4):921–929.
12. Seufert V, Ramankutty N, Foley JA. Comparing the yields of organic and conventional agriculture. Nature. 2012;485(7397):229–232.
13. Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. Plant and Soil. 2003;255(2):571–586.
14. Crews TE, Peoples MB. Legume versus fertilizer sources of nitrogen: Ecological tradeoffs and human needs. Agriculture, Ecosystems & Environment. 2004;102(3):279–297.
15. Turk MA, Tawaha AM. Effect of seeding rate, seeding date, rate and method of phosphorus application in faba bean in the absence of moisture stress. Biotechnology, Agronomy, Society and Environment. 2002;6(3):171–178.
16. Zaccardelli M, De Nicola F, Villecco D, Scotti R. The development and suppressive activity of soil microbial communities under compost amendment. Journal of Soil Science and Plant Nutrition. 2013;13(3):730–742.
17. Whitelaw MA. Growth promotion of plants inoculated with phosphate-solubilizing fungi. Advances in Agronomy. 2000;69:99–151.
18. Pelletier N, Tyedmers P. Forecasting potential global environmental costs of livestock production 2000–2050. Proceedings of the National Academy of Sciences of the United States of America. 2010;107(43):18371–18374.
19. Godfray HCJ, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, *et al*. Food security: The challenge of feeding 9 billion people. Science. 2010;327(5967):812–818.
20. Springmann M, Clark M, Mason-D’Croz D, Wiebe K, Bodirsky BL, Lassaletta L, *et al*. Options for keeping the food system within environmental limits. Nature. 2018;562(7728):519–525.
21. Foster JB. Marx’s ecology: Materialism and nature. New York: Monthly Review Press; 2000.
22. Ellen MacArthur Foundation. Towards a circular economy: Economic and business rationale for an accelerated transition. Cowes: Ellen MacArthur Foundation; 2013.
23. Muscat A, de Olde EM, de Boer IJM, Ripoll-Bosch R. The battle for biomass: A systematic review of food-feed-fuel competition. Global Food Security. 2020;25:100330.
24. Bernal MP, Alburquerque JA, Moral R. Composting of animal manures and chemical criteria for compost maturity assessment: A review. Bioresource Technology. 2009;100(22):5444–5453.
25. Lazcano C, Domínguez J. The use of vermicompost in sustainable agriculture: Impact on plant growth and soil fertility. In: Miransari M, editor. Soil Nutrients. New York: Nova Science Publishers; 2011. p. 187–213.
26. Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems—A review. Mitigation and Adaptation Strategies for Global Change. 2006;11(2):403–427.
27. Graham PH, Vance CP. Legumes: Importance and constraints to greater use. Plant Physiology. 2003;131(3):872–877.
28. Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA. Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. SpringerPlus. 2013;2(1):587.
29. Smith SE, Read DJ. Mycorrhizal symbiosis. 3rd ed. London: Academic Press; 2008.
30. Barea JM, Pozo MJ, Azcón R, Azcón-Aguilar C. Microbial co-operation in the rhizosphere. Journal of Experimental Botany. 2005;56(417):1761–1778.
31. Rillig MC, Mummey DL. Mycorrhizas and soil structure. New Phytologist. 2006;171(1):41–53.
32. Philippot L, Raaijmakers JM, Lemanceau P, van der Putten WH. Going back to the roots: The microbial ecology of the rhizosphere. Nature Reviews Microbiology. 2013;11(11):789–799.
33. Zucconi F, de Bertoldi M. Compost specifications for the production and characterization of compost from municipal solid waste. In: de Bertoldi M, editor. Compost: Production, Quality and Use. London: Elsevier; 1987. p. 30–50.
34. Kirchmann H, Thorvaldsson G. Challenging targets for future agriculture. European Journal of Agronomy. 2000;12(3–4):145–161.
35. Gianinazzi S, Gollotte A, Binet MN, van Tuinen D, Redecker D, Wipf D. Agroecology: The key role of arbuscular mycorrhizas in ecosystem services. Mycorrhiza. 2010;20(8):519–530.
36. Singleton PW, Bohlool BB. Effect of salinity on the functional components of the soybean-Rhizobium japonicum symbiosis. Crop Science. 1983;23(5):815–818.
37. Thies JE, Bohlool BB. Predominance of introduced rhizobia in a soil that naturally contains bradyrhizobia for cowpea and soybean. Plant and Soil. 1990;128(2):209–218.
38. Ladha JK, Pathak H, Krupnik TJ, Six J, van Kessel C. Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. Advances in Agronomy. 2005;87:85–156.
39. Peoples MB, Herridge DF, Ladha JK. Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? Plant and Soil. 1995;174(1–2):3–28.
40. Snyder CS, Bruulsema TW, Jensen TL, Fixen PE. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems & Environment. 2009;133(3–4):247–266.

How to Cite This Article

Sharma R, Kumar P. Circular Agriculture Framework for Nutrient Recycling and Waste Valorization in *Lens culinaris* Production Systems Using Biofertilizer Integration. J Agric Digital Res. 2025;6(2):35-45.
doi:10.54660/JADR.2025.6.2.35-45.