



Journal of Agriculture Sustainability and Environment

ISSN: 2997-271X

Global Scientific Research

www.jescae.com

Journal of Agriculture Sustainability and Environment

Vol.4, No.2
December, 2025

Chief Editor	Dr. Abdullah Khan
Edited by	Global Scientific Research
Published by	Global Scientific Research
Address:	GLOBAL SCIENTIFIC RESEARCH (LIMITED COMPANY): 8206 Louisiana Blvd Ne, Ste A #2531 Albuquerque, New Mexico 87113, United States
Journal Link:	https://www.jescae.com/index.php/jase
Email	journals.gsr@gmail.com
Website	www.jescae.com

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REVIEW ARTICLE

Grain Legumes and Soil Health: Pathways to Sustainable Crop Production in Ethiopia: An Overview

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Received: 22 August, 2025, Accepted: 25 November, 2025, Published: 26 November, 2025

Abstract

Grain legumes are vital components of sustainable farming systems, owing to their unique ability to improve soil fertility and support resilient crop production. Through biological nitrogen fixation, organic matter enrichment, soil structure improvement, nutrient cycling, pest and disease suppression, erosion control, stimulation of soil microbial activity, and carbon sequestration, legumes deliver multiple ecosystem services that reduce dependence on external inputs. In Ethiopia, soil fertility depletion and declining crop yields remain critical challenges, largely driven by unsustainable land management and limited crop diversification. This review examines the role of grain legumes in Ethiopian farming systems, highlighting their contributions to soil fertility, biodiversity, food security, income, and climate resilience, while stressing the need for improved breeding and management to enhance nitrogen fixation and adaptability. Integrating legumes into crop rotations and agroecosystems emerges as a promising pathway to restore soil health, conserve natural resources, and strengthen the long-term sustainability of Ethiopian agriculture. Finally, this review uniquely synthesizes evidence on Ethiopian grain legumes, framing them not just as food or cash crops but as key to soil health, food security, and climate resilience, while outlining context-specific pathways for their integration into smallholder farming systems.

Key words: Legumes; Biological N-fixation; Cropping systems; Soil health; Sustainable agriculture

Introduction

The legume family (Fabaceae), comprising an estimated 20,000 species, represents the third largest group of flowering plants worldwide (Shafique et al., 2014). Beyond their vital role in enhancing global food security, legumes are recognized as one of the most important and widely consumed sources of dietary protein (Popoola et al. 2014; Mashungwa et al., 2019). Their high protein levels, when combined with cereals, provide complementary amino acids, helping to address protein quality deficiencies commonly observed in

smallholder farming systems. From an agronomic perspective, legumes are highly valued for their symbiotic associations with rhizobia and other nitrogen-fixing microbes. These interactions facilitate biological nitrogen fixation (BNF), converting atmospheric nitrogen into plant-available ammonia. This process improves soil nitrogen status, decreases dependence on chemical fertilizers, and contributes to long-term soil fertility (Bhatt et al., 2019; Kebede, 2021). In Ethiopia, practices such as legume-cereal rotations, intercropping, the use of legumes as green manure, and improved fallows have been widely reported to enhance soil health, increase nutrient cycling, suppress pests, and improve cereal yields (Kebede, 2021; Kebede et al., 2020).

Legumes are grown using a variety of cropping techniques, such as rotation, intercropping, and solitary cropping. Peterson et al. (2010) identified legumes and legume-based agricultural systems as viable remedies for food and nutrition insecurity in a range of populations. Similarly, this authors explained as legumes and crops derived from them are promoted for smallholder farmers in most developing nations. Smallholder farmers in Asia, Africa, and Latin America have long engaged in intercropping, which is now becoming more popular due to its ability to preserve space and yield large yields with little input (Yu et al., 2015). For instance, because pigeon peas can withstand drought, farmers in drought-prone areas have long utilized them as an intercrop with cereals (Semahegn, 2022). Nonetheless, due to land constraints, the majority of small-scale farmers cultivate legumes as intercrops for basic cereals, especially maize. As intercrops, legumes and cereal crops have a symbiotic biological commensalism that benefits farmers. Cereal crops develop and yield more when legumes fix N and add more organic matter to the soil (Yuvaraj et al., 2020). When intercropping, farmers should take into account elements including suitable species, planting time, physiological traits of the intercrop, growth patterns, canopy, root architecture, and water and fertilizer requirements (Semahegn, 2022). It is not recommended for farmers to grow legumes as single crops since they can lead to a decrease in soil fertility and a rise in pest and disease problems.

Crop rotation methods, which cultivate a variety of crop species consecutively on the same plot of land, have been known to employ legumes. Crop rotation has repeatedly been demonstrated to lower soil erosion, improve water consumption efficiency, and sustain high yields (Shah et al., 2021; Yang et al., 2023). For instance, a two-crop rotation uses maize (*Zea mays*) and soybean (*Glycine max*) or maize and alfalfa (*Medicago sativa*) in alternate years to provide complementary inorganic nitrogen in the soil for succeeding crops. Mixtures of legumes, grains, or tubers can also be created using legumes. This farming system benefits from combining growth elements such as soil nutrients, light, and water, fewer pests and diseases, and reduced soil erosion. This cropping strategy increased yield stability and biomass production. Legume production has become more of a focus due to growing awareness and concern about the security of food and nutrition for humans and animals as well as declining environmental health, particularly in smallholder farms (ICRISAT (International Crops Research Institute for Semi-Arid Tropics), 2016). Legumes are an essential source of food and nutrition, and using them in a production system can lower pest and disease levels, stop soil erosion, and boost crop yields (FAO, 2016; Neda, 2020). In order to encourage pulse farming, the Food and Agriculture Organization (FAO) of the United Nations (UN) proclaimed 2016 to be the International Year of Pulses (FAO, 2016).

Despite their agronomic and environmental benefits, legume adoption and productivity in Ethiopia remain below potential due to technical, economic, and institutional constraints. Yields are low, mainly because of limited use of improved varieties, poor agronomic practices, and restricted access to quality seeds and inputs (Atnaf et al., 2015). High input costs, weak seed systems, and insufficient extension support further hinder adoption (Ferede et al., 2014; Kebede et al., 2020). Farmers also face poor market infrastructure, unstable prices, and limited linkages, which discourage investment in legume production (Asfaw et al., 2010). Environmental stresses such as soil acidity, drought, and climate change, combined with pests and diseases

like faba bean gall, further reduce yields (Atnaf et al., 2015; Kassa et al., 2024). Moreover, legumes are often regarded as “secondary crops” compared to cereals, resulting in limited research, policy attention, and investment (Ferede et al., 2014). In general, legume production in Ethiopia is constrained by interlinked biophysical, economic, and institutional factors. Addressing these challenges is essential for harnessing the full potential of legumes to improve soil fertility, enhance food security, and promote sustainable crop production. Accordingly, this review aims to highlight the significance of legumes in advancing sustainable agriculture and soil health in Ethiopia.

The concepts of legume crops

Grain legumes are members of the angiosperm family Fabaceae (Leguminosae). Recognized for their distinctive floral structure, compound leaves, and pod-like fruits, legumes are a botanically varied and economically significant group of plants. Beans, peas, lentils, and chickpeas are examples of legume grain crops that are well-known for their capacity to fix atmospheric nitrogen through rhizobial bacterial symbiosis. Furthermore, a crucial ecological trait promoting soil fertility and sustainable agriculture is their capacity to establish symbiotic partnerships with bacteria that fix nitrogen (Doré et al., 2011). They are thought to be abundant in high-quality proteins and have a big impact on people's diets, nutrition, and general health all over the world (Popoola et al., 2019). These are the edible seeds of plants belonging to the legume family, and they all develop into pods. They are gathered, allowed to reach maturity, dried, refrigerated for extended periods of time, and then sold in a dry state for use as food, feed, or in the creation of other goods (Getachew, 2019). Legumes are therefore significant for a variety of reasons, such as economic advantages, nutrition, agricultural, and environmental sustainability.

Opportunities in Adopting Legume Production in Ethiopia

Despite the challenges, Ethiopia has significant opportunities to enhance legume production and unlock its full potential. Ethiopia is endowed with a diverse range of agro-ecologies, making it suitable for cultivating a wide variety of legume species. This geographical advantage allows for the production of different legumes, including faba beans, chickpeas, lentils, and haricot beans, which can be adapted to specific regions and climatic conditions (Getachew, 2019). There is a high and increasing demand for legumes, both domestically and internationally, driven by a growing population and urbanization. Legumes are a staple in the Ethiopian diet and a cost-effective source of protein, making them crucial for household food security (Getachew, 2019). Legumes have the unique ability to fix atmospheric nitrogen in the soil, which improves soil fertility and reduces the need for synthetic fertilizers. This makes them a critical component of sustainable and climate-smart agricultural systems, especially when used in crop rotation. Increased legume production can create opportunities for local value-added processing, stimulate domestic demand, and provide off-farm employment and income sources for smallholder farmers (Kebede, 2020). Legumes are also a major export commodity, providing a source of foreign exchange for the country. Legumes provide high-quality feed for livestock, which can enhance animal nutrition and productivity. Integrating legumes into mixed crop-livestock systems can improve nutrient cycling and overall farm productivity. Continued agricultural research and the development of new, improved legume varieties that are drought-tolerant and disease-resistant offer a significant opportunity to increase productivity. This is complemented by initiatives and projects aimed at deploying these technologies to farmers (ICARDA, 2022).

Ethiopia has considerable opportunities to enhance legume production due to its diverse agro-ecologies, which support a wide range of species such as faba beans, chickpeas, lentils, and haricot beans. Rising

domestic and international demand, driven by population growth and urbanization, underscores their importance as a staple food and affordable protein source. Beyond nutrition, legumes improve soil fertility through nitrogen fixation, reduce fertilizer needs, and play a vital role in sustainable, climate-smart agriculture. Expanding production can also boost exports, create value-added processing opportunities, generate off-farm employment, and strengthen mixed crop-livestock systems by providing high-quality feed. Furthermore, ongoing research and the development of improved, stress-tolerant varieties offer strong potential to increase productivity and resilience.

Empirical Evidence on legume production

Ethiopia is both a major producer and an important trader of pulses, and national policy recognizes legumes as a strategic lever for soil restoration and sustainable intensification. Pulses account for large national production volumes and figure among exported commodities, while government technical guidance on Integrated Soil Fertility Management (ISFM) explicitly promotes legume integration to address widespread soil fertility decline and low crop yields (ITD, 2022/23; Manzoor et al., 2025). National ISFM manuals and field guides have been used in extension and restoration programs to mainstream legumes as part of multi-pronged soil health packages (ITD, 2022/23).

Field experiments and on-farm research across Ethiopian agroecologies provide strong, locally relevant evidence that legume-to-cereal rotations deliver measurable agronomic and soil-fertility benefits. A Mesfin et al. (2023) field study in northern Ethiopia reported that preceding wheat with faba bean, field pea and lentil increased subsequent wheat grain yield by $\sim 1.1\text{--}2.2\text{ t}\cdot\text{ha}^{-1}$ (2196, 1616, 1254 and 1065 $\text{kg}\cdot\text{ha}^{-1}$ for faba bean, “dekeko”, field pea and lentil respectively) and substantially increased N uptake relative to continuous wheat - a clear, locally measured “rotation dividend” for smallholder systems. Similar rotation benefits (yield gains of $\sim 5\text{--}7\%$ relative to continuous wheat) have been reported in the central highlands and southern Ethiopian trials, demonstrating that the legume yield dividend is robust across contrasting highland contexts (Mesfin et al., 2023).

Beyond immediate yield effects, Ethiopian studies highlight genotypic variation and management interactions that determine how much soil benefit a legume will deliver. Recent work on faba bean shows considerable genotypic variation in symbiotic N_2 -fixation traits and differential responses to phosphorus supply and rhizobial inoculation-implicating that breeding and targeted management (P fertilization, inoculants) can enhance the BNF contribution of legumes under Ethiopian soil conditions. Trials examining phosphorus responses, inoculation and seed/variety choice have recorded large differences in biomass, grain yield and estimated N contributions, indicating clear avenues for improving legume performance through both breeding and adaptive agronomy (Abu et al., 2024). Programmatic and policy enablers are beginning to align. CGIAR and national partners (e.g., ICRISAT activity in Ethiopia) have invested in improved legume germplasm, seed system strengthening, and seed policy support; these actions increase farmer access to improved varieties that better express BNF and yield potential. At the same time, major climate and landscape restoration investments (including Climate Investment Funds / World Bank-backed programs) are channeling funds into land restoration, soil health regeneration and sustainable farming, creating opportunities to scale legume-based interventions at landscape scale (Jessop, 2024).

Critical constraints remain and shape realistic expectations for scaling legume benefits in Ethiopia. Seed system gaps, weak extension reach for pulses, constraints in access to inoculants and phosphorus, and heterogeneity in farmer objectives limit adoption and the full expression of legume ecosystem services. National ISFM manuals and seed policy briefs emphasize these gaps and recommend integrated interventions-combining breeder and agronomy work, seed system reform, tailored extension, and incentives that recognize

both food-security and soil-restoration benefits (ICRISAT, 2022-2024). Table 1 summarize the empirical evidence underscores that Ethiopia has significant untapped potential to enhance legume productivity. Closing the yield gap requires integrated interventions that strengthen seed systems, expand access to inputs and services, and promote market linkages. Such measures, coupled with location-specific research and gender-responsive extension, are essential for realizing the dual benefits of improved household welfare and sustainable agricultural intensification.

Table 1: The summary of empirical evidences on legume production and productivity from Ethiopia

No	References	Location / context	Experiment / design	Main result (headline)
1	Mesfin S., (2023)	Northern Ethiopia (trial)	Field experiment: legume (faba bean, field pea, lentil) → wheat rotations vs continuous wheat	Wheat yield increased by 1.06–2.20 t·ha ⁻¹ after legumes; large increases in N uptake.
2	Mekonnen and Endrias (2023)	Central highlands, Southern Ethiopia	Crop rotation trial (faba bean/field pea → wheat vs continuous wheat)	Wheat yield +5–7% after faba bean/field pea relative to continuous wheat.
3	Abu et al., (2024)	Multi-site faba bean trials (Ethiopian contexts)	Genotypic evaluation for symbiotic N ₂ fixation under contrasting P regimes	Significant genotypic variation in BNF traits; responses to P indicate breeding + P management improve fixation.
4	Jithesh et al., 2024	Review including Ethiopia-relevant studies	Synthesis of BNF enhancement strategies (inoculation, fertilization)	Rhizobial inoculation and P optimization commonly increase BNF and yield-actionable in Ethiopian settings.
5	Negasa and Dobocha (2025).	On-station Faba bean P response trial, (Ethiopia)	P fertilizer gradients + management	40 kg P·ha ⁻¹ increased biomass and seed yield substantially (headline yield responses reported).
6	MoA (2020)	National / extension context	Technical manual and field guide promoting ISFM	Legumes recommended as ISFM component to restore soil fertility and improve smallholder resilience.
7	ICRISAT / CGIAR seed-system reports (2022–2024).	Programmatic (seed systems)	Variety dissemination, seed system strengthening	Improved pulses varieties and seed system activities show progress in supply and adoption enablers.
8	Jessop (20224)	Climate Investment Funds or National investment / restoration program	CIF and partners backing large restoration programs	\$37–500M funding endorsement for land restoration, soil health and sustainable farming-political and finance window to scale legume interventions.

Importance of legumes

The foundation of a balanced diet and sustainable agriculture is legume crops. They are a priceless tool for advancing environmental sustainability, food security, and economic stability due to their beneficial effects on soil health and the ecosystem. Growing more legumes is essential to replenishing nutrient-deficient soils and providing people and animals with the necessary protein, minerals, and vitamins. Globally, legumes can help smallholder farmers make a better living (Yuvaraj et al., 2020). Furthermore, given of their market demand and cheaper input costs for pesticides and fertilizers, they can be very profitable crops for farmers. Thus, healthier populations and a more sustainable world can result from increasing the amount of legumes in diets and agricultural systems.

Legumes in human nutrition

With a protein level ranging from 17 to 40%, grain legumes (such as pigeon pea, chickpea, soybean, or mung bean) are a true source of protein. Farmers and their families can enhance their diets and achieve protein stability by consuming grains together with cereals. Legumes seeds are a rich source of vital vitamins and minerals, including folic acid and Vitamin B. They also include significant amounts of minerals, such as calcium, zinc, and iron, and nutritional vitamins (Yuvaraj et al., 2020). Legumes also contribute significantly to food security by offering a dependable source of protein and other nutrients, especially in poorer nations where access to animal protein may be restricted. All things considered, adding a range of legumes to the diet can greatly improve its nutritional value and promote general health. As key parts of a balanced diet, they supply vital nutrients, help avoid chronic diseases, and provide a sustainable source of protein.

Legumes for animal nutrition

The productivity of healthy animals was significantly boosted by cereal crop wastes supplemented with feed legumes. For instance, it has been noted that adding protected pulse grains to poultry feed boosted egg output. Legume flora leftovers can improve the digestibility and quality of cereal crop residues when added to cattle feed. For instance, adding leguminous flora will increase animal nutrition because maize residues often contain low levels of proteins and large levels of carbohydrates (Yuvaraj et al., 2020). Therefore, incorporating fodder crops based on legumes into livestock systems can support sustainable farming methods. Additionally, using legume cover crops and rotational grazing can enhance soil health, give farmers more revenue streams, and lower greenhouse gas emissions from livestock operations.

Legumes for crop and soil improvement

Plants need mineral nutrients, the most important of which is nitrogen, to produce the maximum amount. Because exhausted soils frequently have low nitrogen contents, farmers typically use inorganic fertilizers. Farmers struggle to achieve enough yields, though, as fertilizer costs rise. Legumes can be added to cropping systems to help with this issue. Leguminous plants are closely associated with *Rhizobium*, a type of bacterium that fixes nitrogen. Thus, legumes offer an incredibly affordable way to alter soil nitrogen, enhance soil fertility, and increase crop yields in the future by naturally fixing nitrogen levels in the soil (Yuvaraj et al., 2020).

Role of grain legumes to sustainable crop production

Due to the existing severe pressure on water and land, the fast expanding population is having an impact on food and nutrition security. Degradation due to global warming, pollution, and loss of soil fertility are some of

the negative effects on soil health (Swaroop and Lal, 2018). When incorporated into crop rotations and intercropping schemes, legumes can serve as substitutes to promote soil stability under such circumstances. Legumes fix atmospheric N₂ in symbiosis with rhizobial bacteria, which makes them a valuable component of integrated soil fertility management. Moreover, these crops supply inputs of organic matter that enhance crop yields and have a good impact on the chemical, physical, and biological characteristics of the soil (Bashir et al., 2021).

Legumes increase productivity as intercrops on maize farms while maintaining nutrient availability, claim Choudhary and Choudhury (2018). As part of a grain legume maize-based cropping system, Chimonyo et al. (2019) observed an improvement in soil fertility and water-holding capacity, which they linked to a rise in maize productivity. This makes sense given that systems of legume cropping increase soil fertility, improve soil health, and increase soil resistance to several types of erosion (Kintl et al., 2015). By boosting beneficial soil microorganisms and increasing soil biodiversity, the use of legumes in farming systems improves ecosystems (Meena et al., 2014). These crops ensure protection from pests and diseases, improve nearby plants, and lessen soil erosion through mineralization (Lal, 2013). According to Sugiyama and Yazaki (2012), legumes have large root systems and emit exudates that greatly enhance the dynamics, structure, and quality of the soil's nutrients. These legumes also help to recycle nutrients, such as nitrogen, phosphorus, and carbon. Many legumes, such as lupin (*Lupinus angustifolius* L.), vetches (*Vicia sativa* L.), and velvet bean (*Mucuna pruriens* Bak.), fenugreek (*Trigonella foenum-graecum* L.), clover (*Trifolium* sp.), showy rattlebox (*Crotalaria spectabilis*), and water bean (*Sesbania rostrata*) have also been used as green manure (Swaroop and Lal, 2018). These crops provide good sources of nutrients for plants by increasing soil organic matter and nutrient availability when applied as green manure. Consequently, adding these crops to a rotational system would increase the amount of nitrogen available for plantings that come after them (Hauggaard-Nielsen and Jensen, 2005).

It is difficult to achieve sustainable productivity, especially in underdeveloped countries. The improper use of agrochemicals has made matters worse by negatively affecting the health of the soil. Shahid et al. (2020) claim that improper and needless application of fungicides to prevent soil-borne illnesses and boost crop yields negatively impacts soil fertility, microbial composition, and grain yield. Therefore, crop rotation based on legumes is a more effective way to preserve the ecosystem. Crop rotation greatly enhances the microbiological state of the soil because legume leftovers provide a food source for soil biota, which enhances productivity, nutrient mineralization, and soil functions. Because they address the issues associated with low productivity, legumes play a significant impact in increasing productivity (Shahid et al., 2020).

Grain legume production systems

Systems for producing grains and legumes are essential to sustainable agriculture and offer advantages in terms of economy, nutrition, and ecology. To maximize crop productivity and sustainability, effective management techniques are essential. These practices include crop selection, soil management, and integrated pest and weed control, and efficient water usage. Farmers may contribute to food security, environmental sustainability, and improved soil health by growing legumes in a variety of cropping systems. Depending on the climatic and edaphic circumstances as well as the planned end use, grain legumes are generated in a variety of methods, including dry grain, green feed, arable silage, and green manure (Watson et al., 2017). Various species of legumes are grown: pea (*Pisum sativum* L.), lupins (*Lupinus* spp.), faba bean (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), common bean (*Phaseolus vulgaris* L.) and soybean (*Glycine max* (L.) Merr.) (Vanlauwe et al., 2019). Legumes can be grown as standalone crops or as intercrops with cereals such as maize.

Intercropping

Growing two or more crops from different families and species is known as intercropping. The main crops are the only ones that are important, and the other crops are grown as secondary crops that enhance the soil and fix nitrogen. Numerous legumes offer great chances for resource efficiency by intercropping with early maturing crops. According to Meena et al. (2014), intercropping encourages species interactions, boosts biological variety, and aids farmers in adjusting to climatic irregularities. The primary crop, the variety of legumes available, the maturity period, the height of growth, and the farmers' preferences all influence the choice of legume intercrop. Planting arrangement and spacing are determined by species, the potential for automation, the growing status of intercrops and primary crops, current climate, and soil fertility. Comparing legume-based intercropping systems to monocropping systems, higher production is obtained from the same field, and natural resource efficiency is enhanced (Inal et al., 2007). Fustec et al. (2010) claim that leguminous crops outperform monoculture farming systems because they enhance soil functions through biological nitrogen-fixing. Legume-based intercropping is a sustainable agricultural production technique that is environmentally friendly and requires little in the way of inorganic nitrogen (Ashoka et al., 2017). This demonstrates that intercropping is a sustainable farming method that boosts crop yield, strengthens the health of the soil, and encourages ecological balance. Thus, intercropping improves biodiversity, controls weeds, and lessens the burden of pests and diseases by diversifying crop production. By supplying a variety of revenue streams and stabilizing yields, it helps farmers monetarily. By decreasing the demand for chemical inputs and increasing the resilience to climate change, intercropping promotes environmental sustainability. All things considered, intercropping is an essential technique for developing sustainable agricultural systems.

Crop rotation

Crop rotation, as opposed to monoculture which is the continuous growth of one crop on the same land, is a system in which various crop kinds are cultivated on the same land in recurrent and specific sequences (Zhao et al., 2020). Crop rotation can increase productivity and sustainability in crop production systems where legumes are included in maize/sorghum production systems (Keeler et al., 2009). Grain legumes are an alternate crop that can be grown in rotation farming to promote soil recovery and production diversification. This lowers the prevalence of pests and illnesses while also increasing soil fertility and biodiversity. To increase soil sustainability and productivity, grain legumes are planted as part of crop rotation (Watson et al., 2017). Crop rotation increases biological variety and decreases dependency on chemical fertilizers, which increases crop yields and the sustainability of production systems. It also enhances soil permeability, microbial activity, water-holding capacity, and organic matter. According to Knight (2012), the frequency at which legumes are generated has an impact on soil microbial activity and nitrogen fixation. However, Brouwer (2006) claims that there is a trend in agricultural production systems toward specialization, which has led to a progressive loss of diversity. Therefore, biological processes like using pesticides in place of ecological pest control or biological nitrogen fixation (BNF) in place of mineral fertilizers are affected (Zander et al., 2021). It is recommended that farmers cultivate a variety of crop species with varying life cycles to optimize pest and disease control and concurrently leverage nutrient availability via crop rotation (Cook, 2013). Crop yield and sustainability can benefit greatly from crop rotation, an established agricultural technique. It improves the health of the soil, breaks down the cycles of disease and pests, controls weed growth, and supports environmental sustainability. Crop rotation is one way that farmers can create more resilient and sustainable agricultural systems that will guarantee ecological balance and long-term productivity.

Mixed cropping

Mixed cropping, which involves growing legumes, cereals, or tuber crops, is a typical approach in marginal agro-ecological areas. This cropping method serves several purposes, including the complementary utilization of growth elements such as soil nutrients, light, and water (Doré et al., 2011). This approach also decreases pests, illnesses, and soil erosion while increasing biomass and overall yields (Staniak et al., 2014). Furthermore, the combinations are easily adaptable to account for variables such as the timing of the rainy season or soil fertility levels in different areas (Weltzien et al., 2017). Legume cereal mixes require less nitrogen fertilizer than cereal crops do. As a result, there was an increase in the protein content of cereal seeds. Zarea et al. (2008), while working on the effects of forage legumes mixed crops on biomass production and bacterial community structure, found that mixed cropping enhanced the number of bacteria, free-living N_2 -fixing bacteria, and *Azotobacter* in the rhizosphere. Studies on cropping mixtures of yellow lupine with wheat and oats have indicated the competitive potential of a single legume compared to a single cereal plant (Staniak et al., 2014). Mixtures of legumes and cereals create allelopathic conditions that may significantly influence the plant stand and yield output.

Monocropping

Monocropping is the practice of planting only one crop on the same plot of land each year. This approach is prohibited since alternate agricultural systems based on legumes, rather than monoculture production, have superior economic and environmental outcomes and reduce the prevalence of pests, illnesses, and weeds (Nigli et al., 2008; Doré et al., 2011; Kebede, 2020).

Table 2: Summary on seed yields (kg ha^{-1}) of castor as influenced by sole cropping, alley cropping, green leaf manures, and nitrogen levels

Treatment	No	N40	N80	Mean
Sole cropping	263	470	570	434
No green leaf manuring				
Leucaena green leaf manuring	349	618	679	548
Albizia green leaf manuring	335	585	666	528
Dalbergia green leaf manuring	347	529	653	510
Mean	323	551	642	505
Alley cropping				
No green leaf manuring	348	672	745	588
Leucaena green leaf manuring	500	760	851	704
Albizia green leaf manuring	428	753	833	671
Dalbergia green leaf manuring	425	756	831	671
Mean	425	735	815	659
LSD (0.05)	8.2			
Cropping systems				
Nutrient	8.78			
Interaction	12.57			

Source: Ghost et al. (2007) cited by Kebede (2021)

Similarly, growing some legume species as monocultures continuously continuously may result in nitrate leaching (Vasconcelos et al., 2020), while others may result in high N_2O emissions. Similarly, Ghost et al. (2007) cited by Kebede (2021) reported that the sustained practice of alley cropping with nitrogen-fixing

leguminous trees serves as an effective approach to harness biological nitrogen fixation (BNF). The effects of sole cropping, alley cropping systems, application of green leaf manures, and varying nitrogen levels on castor seed yield are presented in Table 2. Senbayram et al. (2016) found that when legumes were grown in monocultures, they produced higher cumulative N₂O emissions than fertilized wheat. Due to the numerous constraints of employing legumes as monocultures, farmers are urged to grow legumes as intercrops, rotational crops, or mixed crops.

Contribution of legume to soil health

Legumes in soil quality

Legumes improve soil quality by fixing nitrogen, adding organic matter, improving soil structure, controlling erosion, suppressing weeds, increasing microbial activity, cycling nutrients, and managing soil moisture. Legumes have several advantages, including increasing soil natural matter, enhancing soil porosity, recycling nutrients, improving soil structure, decreasing soil pH, diversifying microscopic lives in the soil, and reducing disease buildup and weed problems in grass-type crops (Stagnari et al., 2017). Integrating legumes into agricultural systems, whether through crop rotations, cover cropping, or intercropping, can result in more sustainable and productive soils, enhancing the overall health of agricultural ecosystems.

Soil natural rely

Since legumes can fix atmospheric nitrogen, improve soil fertility, limit erosion, sequester carbon, manage weeds and pests, and effectively manage water, they are essential for natural soil replenishment. Because they contain a lot of protein, legumes are rich in nitrogen. Legume-derived nitrogen accelerates residue decomposition by balancing the soil C:N ratio (Stagnari et al., 2017). Table 3 presents the nutrient composition and carbon-to-nitrogen (C:N) ratios of the above-ground biomass of key legume green manure crops. These measurements highlight each species' capacity to enrich soil fertility and influence organic matter turnover. Variations in nutrient levels demonstrate differences in nitrogen fixation, biomass production, and nutrient recycling potential, while the C:N ratios indicate how quickly residues decompose and release nutrients. This knowledge is essential for choosing suitable legume species that can improve soil quality, benefit succeeding crops, and strengthen sustainable agricultural systems. According to Ghosh et al. (2007) cited in Kebede, (2021), intercropping with *Leucaena leucocephala* led to yield reductions of approximately 38% in maize, 34% in black gram, and 29% in cluster bean compared to their respective sole cropping systems. As a result, the decomposition of leftover legumes enriches the soil with organic materials. Improved soil structure, water-holding ability, and cation exchange capacity, all essential for nutrient availability and retention come from higher levels of organic matter content. Therefore, increasing the productivity and sustainability of farming systems may result from including legumes into agricultural methods through crop rotation, cover crops, and green manuring. Farmers can increase their production and long-term health while lowering their need for chemical fertilizers by taking advantage of the natural advantages of legumes.

Soil porosity

As a result, the soil becomes richer in organic matter as leftovers from legumes break down. A higher level of organic matter enhances the soil's ability to store water, exchange cations, and maintain nutrients, all of which are critical for nutrient availability and retention. Cover cropping, green manuring, and crop rotation are ways to include legumes in agricultural methods that may result in more productive and sustainable farming systems. Farmers may increase their productivity and long-term health by utilizing the natural benefits of

legumes and lowering their need for chemical fertilizers. Therefore, improving the structure and health of the soil through the use of legumes as cover crops, intercropping systems, or crop rotations can promote a more fruitful and sustainable agricultural system.

Table 3. Nutrient concentrations and carbon-to-nitrogen (C:N) ratios in the above-ground biomass of selected green manure crops (Source: Ghosh et al., 2007 cited in Kebede, 2021)

Green manure crops	Total Nutrient concentration (% dry weight)						
	N	P	K	S	Ca	Mg	C: N ratio
Sesbania (<i>Sesbania aculeata</i>)	2.62	0.32	1.48	0.19	1.40	1.62	16.4
Sunnhemp (<i>Crotalaria juncea</i>)	2.86	0.34	–	–	–	–	16.1
Cowpea (<i>Vigna unguiculata</i>)	2.69	0.28	2.26	0.28	1.50	1.73	17.1
Cluster bean (<i>C. tetragonoloba</i>)	2.80	–	–	–	–	–	17.3
Mung bean (<i>Vigna radiata</i>)	2.21	–	–	–	–	–	16.1
Subabul (<i>L. leucocephala</i>)	3.15	0.20	1.73	–	1.88	0.41	12.7
Gliricidia (<i>Gliricidia maculata</i>)	3.49	0.22	2.44	–	1.89	0.43	10.42

Recycle nutrients

The recycling of nutrients are facilitated by legumes in both natural and farmed environments. Legumes indirectly contribute to overall nutrient cycling mechanisms that can improve vitamin and other micronutrient availability and recycling, even if direct vitamin recycling in the soil-plant system is not as important as it is for minerals like phosphorus or nitrogen. Although legumes do not directly recycle vitamins in the same manner as they fix nitrogen, they do play a major role in enhancing the entire nutrient cycling process by improving soil health, structure, and fertility. Legumes improve soil structure, add organic matter, encourage microbial activity, and increase nutrient availability, all of which help recycle and make vitamins and other vital nutrients more available to plants in the soil. Deeply rooted crops can recycle nutrients from the soil profile because perennial and biennial legumes have deep roots. As a result, fertilizer is used more sustainably, and less nutrients, especially nitrate nitrogen are lost as a result of leaching beneath the roots of crops with shorter roots later in the cycle (Figure 1). Increasing soil sustainability is one of the advantages of legume crops (Stagnari et al., 2017). Therefore, incorporating legumes into crop rotations, cover crops, and green manuring can help to create an environment that is more nutrient-rich and sustainable.

Improve soil structure

Typically, legumes have large, deep root systems that aid in improving the structure and porosity of the soil by breaking up compacted soil. In succeeding crops, this improved water infiltration and root penetration. The rise in more stable soil aggregates was blamed for these advancements. The protein called glomalin functions as a "glue" to hold soil particles together into stable aggregates. It does this symbiotically along the roots of legumes and other plants. According to Stagirari et al. (2017), this aggregate stability decreases crusting and soil erodibility by increasing pore space and tilth. Because of their deep, fibrous root systems, organic matter addition, improved soil porosity and aeration, improved water infiltration and retention, erosion control, microbial activity stimulation, and decreased soil compaction, they thus play a crucial role in improving the

soil structure. Legumes can therefore be incorporated into crop rotations, cover crops, and green manuring techniques to improve soil health, boost production, and guarantee the sustainability of agricultural systems.

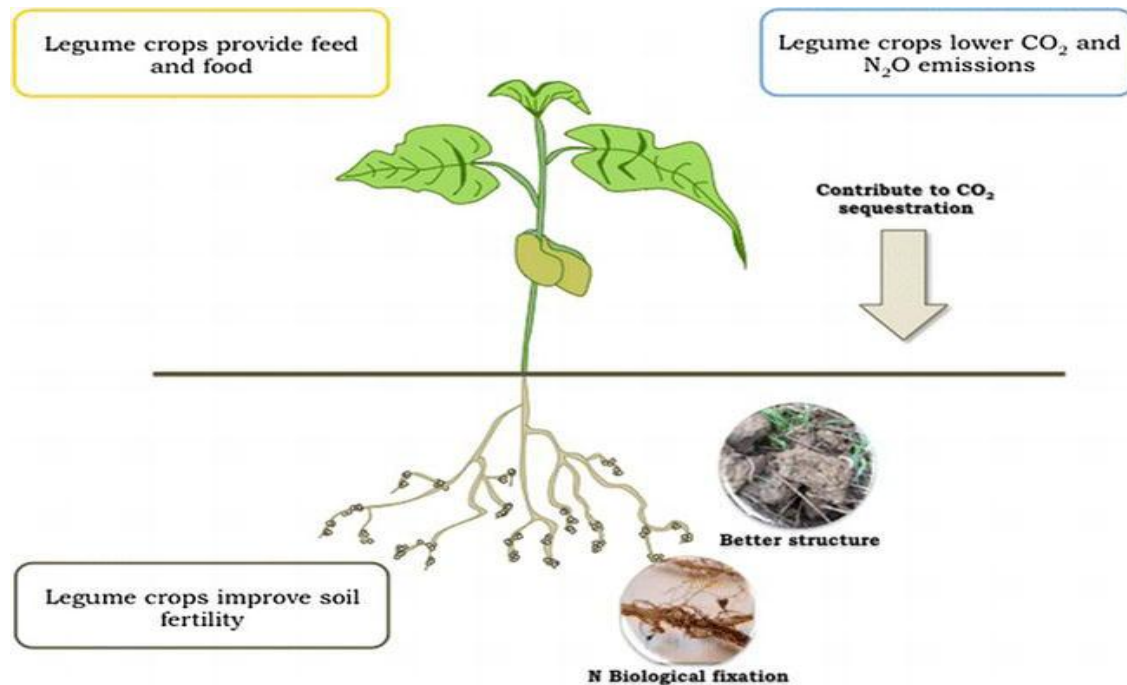


Figure 1: Role of legumes crops in improving soil fertility (Source: Stagnari et al., 2017 cited by Yuvaraj et al., 2020)

Lower soil pH

Though they usually do not significantly lower soil pH on their own, legumes can affect soil pH through a number of methods. Their interactions with soil processes and microbial activity are often linked to their impacts on soil pH. Legumes do not directly lower soil pH, but their biological activities and interactions with soil microbes can create environments that do. This involves the generation of organic acids from root exudates and the breakdown of organic matter, the release of H⁺ ions during nitrogen fixation and nutrient intake, and increased microbial activity that results in the synthesis of CO₂ and carbonic acid. Soil pH is lowered by inoculated, nodulated legumes because they obtain nitrogen from the air as diatomic N instead of the soil as nitrate. Alfalfa and soybeans decreased the pH of clay loam soil in greenhouse experiments by one unit. In soils with a pH above the limit for the best crop growth and development, legumes can lower pH and improve plant-soil-microbial activity (Stagnari et al., 2017). Legumes can gradually affect soil pH through crop rotation and soil management techniques, improving overall soil health and nutrient availability.

Soil fertility improvement

Grain legumes are vital crops in various cropping systems because they fix atmospheric nitrogen in the soil and increase phosphorus turnover by biological processes. Legumes aid in the cycle of other vital elements including potassium and phosphorus. Additionally, by nutrient recycling that is, through releasing organic acids that help solubilize phosphorus so that plants may access it more readily they increase soil fertility. Grain legumes cover over 190 million hectares worldwide, and they add 5–7 million tons of nitrogen to soils annually (Vidigal et al., 2019). Because of their ability to fix nitrogen, legumes can save up to 60% of the

fertilizer needed for cereals the following season. Intercropping and rotating between legumes and cereals might help preserve soil health and minimize the need for fertilizer, as the cultivation of cereals leads to a greater depletion of soil nutrients (Yirga et al., 2010). Additionally, they increase soil fertility by promoting microbial activity, which is made possible by the presence of legumes in the soil. Thus, the breakdown of organic matter, the cycling of nutrients, and the overall fertility of the soil are all improved by active soil microbial communities.

Contribution of legume residues to soil sustainability

Due to their relatively high nitrogen content, legume residues can provide a source of mineral nitrogen for crops that come after them (Kebede, 2020). According to Louarn et al. (2015), nutrients obtained from broken-down sections of legume plants make up a substantial portion of the nutrients transferred below ground. According to Moura et al. (2015), both live and dead soil surface cover legumes increase soil root capacity and decrease soil moisture loss and evapotranspiration rate. Sangare et al. (2016) state that using residues from legume crops is an alternate strategy for raising soil fertility. Legume residues do, however, contribute to a soil N pool that releases nitrogen over time rather than acting as a quick source of nitrogen for plants (Formowitz et al., 2009). Research has indicated that the incorporation of organic wastes into soil leads to higher crop yields (Shafi et al., 2014). The impacts of legume trees on soil improvement were investigated by Moura et al. (2015). Treatments with high biomass had increased carbon stocks in the litter and total organic carbon. Moura et al. (2015) state that to keep the balance between carbon inputs and rapid decomposition rates, leftovers must be added continuously. To boost their effectiveness, mineral fertilizers and organic residues can be combined, and a more prudent strategy that combines mineral fertilizers with soil organic additions such legumes is being advocated (Moura et al., 2015). More cover crops made of legumes have so been encouraged to be used as green manures. However, the benefits of legumes for soil fertility are contingent upon their legume-cereal ratio, the length of time that legume biomass is produced, and the management of residues. To reduce the amount of nutrients added to the soil, edible legumes, for example, are typically collected and their leaves eaten as vegetables or fodder. According to estimates, the nitrogen benefit of adding a grain legume to a rotation is between 0 and 90 kg N ha⁻¹ for soybeans with a short or medium growth period and usually higher for legumes with a longer growth period, like pigeon peas, which grow for about 180 days (Kerr et al., 2007).

Soil protection from erosion and water conservation

Grain leguminous crops offer ground cover that shields the soil from wind and water erosion, particularly when utilized as cover crops. Among the many ways legumes help conserve soil and water are by covering the soil both during and after cropping seasons. Crop leftovers spread out as mulch or active crops could be the source of soil cover. Reduced water evaporation results from high soil cover, which blocks the sun's heat from heating the soil directly (Vidigal et al., 2019). On the same plot of land, residues from grain and legume farming can also reduce soil erosion, retain soil moisture, and boost production (Vidigal et al., 2019).

Legumes regulate soil erosion in an intercropping system by shielding bare soil from raindrop impact. This allows the soil to retain water on the surface, accelerate surface runoff, and hide surface pores. Cowpea is the best cover crop for reducing soil erosion in the maize-cowpea intercropping system. In a similar vein, runoff was decreased by 20–30% when sorghum was grown alone and by 45–55% when cowpeas were grown monoculture. Particularly in intercrops of taller cereals with short legume crops, higher legume crops serve as wind barriers to short crops and reduce soil erosion (Nweke, 2018). Leguminous crops create a canopy that lowers nutrient runoff, preserves soil structure, and helps stop soil erosion.

Economic benefits to the farmers

Grain legumes have a significant impact on smallholder lives in Ethiopia and play a variety of roles at different levels, from farm households to national economies. A report by Ferede et al. (2014) states that the cultivation of grains and legumes provides a livelihood for over 8.5 million smallholder farmers. This is because most legumes often referred to as multipurpose produce multiple products and have multiple uses, either during growth or after harvest (Muoni et al., 2019). These benefits include improving food and nutrition security, supplying income, improving soil fertility, providing livestock feed, improving soil fertility, controlling soil erosion, water conservation, acting as a fuel source, and a range of other benefits. Contributions of various legume types and species to human food (kg ha^{-1}), livestock feed (kg ha^{-1}), and soil fertility (BNF ha^{-1}). To sum up, legume crops provide two basic benefits to farmers, (1) it is used as a source of income, legumes crops can be a lucrative crop for farmers due to their market demand and lower input costs for fertilizers and pesticides, (2) it is used for maintaining food security, it is a reliable source of protein and other nutrients, legumes play a key role in food security, particularly in developing countries where access to animal protein may be limited.

Empirical evidence from Ethiopia further demonstrates the ecological and economic value of legumes in mixed cropping systems: Maize-faba bean intercropping increases land productivity, boosts household income, and improves soil fertility relative to sole maize systems (Gidey et al., 2024). Maize-cowpea associations generate higher net revenues than monocultures, largely due to more efficient utilization of nutrients, space, and sunlight (Kussie et al., 2024). Sorghum-haricot bean intercrops enhance soil microbial activity, stabilize yields, and strengthen system fertility (Ashenafi et al., 2025). Despite these advantages, large yield gaps persist across Ethiopia's major cereal and grain legume crops. Current farmer yields remain far below their water-limited potential, with wheat, maize, sorghum, and common bean producing only about 26.8%, 19.7%, 29.3%, and 35.5% of potential yields, respectively (Belachew et al., 2022). Adoption of improved cultivars alongside better nutrient management and inoculation practices has been shown to raise yields by 24–160%, often doubling or tripling productivity (Belachew et al., 2022). Moreover, cereal-legume intercropping and rotation systems further increase yields, suppress pests, and reduce reliance on synthetic fertilizers.

Conclusion

Food legumes are the perfect crops to cultivate in order to achieve the developmental goals of decreasing poverty and hunger, improving human health and nutrition, and strengthening ecosystem resilience because of their varied and significant functions in farming systems and the diets of the disadvantaged. Incorporating legumes into production systems is necessary to guarantee the resilience and sustainability of agricultural livelihoods. Given this, it is imperative to comprehend the unique traits of each legume and how they function in an agricultural system, as this is a potential means of resolving the problems associated with low crop yields and raising sustainable output. Therefore, improving soil health and guaranteeing sustainable crop production in Ethiopia require the incorporation of grain leguminous crops into agricultural systems. By improving soil fertility, structure, and organic matter content, these crops support more resilient and productive farming systems, benefiting both the environment and the farmers. Promoting the cultivation of leguminous crops, along with continued research and extension services, can further advance sustainable agricultural practices in Ethiopia, contributing to the country's food security and environmental sustainability goals. Regarding the sustainable crop production, breeding programs focused on developing climate-resilient legume varieties can help mitigate the impacts of climate change on crop production. Besides these, varieties

with improved drought tolerance, disease resistance, and adaptation to changing environmental conditions can ensure more stable yields and sustainable crop production.

Implications for research and policy

i). Advancing the development of legume varieties that are tolerant to drought, heat, and emerging pests and diseases is critical for Ethiopia's smallholder farming systems. Research should focus on breeding climate-smart cultivars adapted to diverse agroecologies, ensuring stable yields under variable environmental conditions, and addressing both nutritional quality and market preferences, ii). Maximizing biological nitrogen fixation through the effective use of rhizobium inoculants is essential for improving soil fertility and reducing dependency on synthetic fertilizers. Systematic evaluation of inoculant strains under local soil and climatic conditions is needed to identify the most effective combinations for different legume crops, ensuring consistent agronomic and economic benefits, iii). Understanding the economic value of legumes within integrated crop-livestock systems is crucial for informing policy and investment decisions. Research should quantify the contributions of legumes to household income, livestock feed, soil fertility, and overall farm resilience, providing evidence to guide farmers, development agencies, and policymakers in promoting legume-based production systems, iv). Despite their benefits, legume adoption remains limited due to weak extension services, inadequate access to quality seeds and inoculants, and insufficient farmer knowledge. Strengthening farmer education programs, participatory demonstrations, and extension delivery mechanisms is essential to improve adoption rates, support informed decision-making, and enhance the sustainability of legume-based systems.

Acknowledgment: N/A.

Funding: N/A.

Conflict of interest: The authors declared that there is no conflict of interests.

Ethics approval/declaration: N/A.

Consent to participate: N/A.

Consent for publication: N/A.

Data availability: All Authors' contribution: All authors are equally contributed.

Conflict of Interest: The authors declared that there is no conflict of interest existing.

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RESEARCH ARTICLE

Ecological Risk and Bioaccumulation of Heavy Metals in Soil–Vegetable Systems under Wastewater Irrigation

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Received: 10 October, 2025, Accepted: 24 November, 2025, Published: 27 November, 2025

Abstract

This study investigates the implications of wastewater irrigation on soil and vegetable safety in Tamburawa, Kano State, Nigeria, amid challenges of limited freshwater resources. It highlights the ecological risks and bioaccumulation of heavy metals; copper (Cu), chromium (Cr), iron (Fe), lead (Pb), and zinc (Zn) in the rhizosphere soil and edible parts of vegetables (cabbage, carrot, lettuce, onion, and spinach) multiple samples of which were analyzed using Atomic Absorption Spectrophotometry (AAS). Key physicochemical soil parameters were assessed to determine their effects on metal mobility. Pollution indices, including the contamination factor (CF), pollution load index (PLI), and geo-accumulation index (Igeo), were employed to gauge pollution severity. The findings indicated that lead (Pb) and iron (Fe) levels surpassed FAO/WHO permissible limits, with Pb concentrations reaching 23.0 mg/kg in carrot shoots and Fe at 1046.5 mg/kg in onion leaves, whereas Cu and Zn remained within safe limits. The soils were slightly alkaline with pH 7.76 and a sandy-loam texture which, combined with low organic carbon and cation exchange capacity, facilitated metal mobility. The high CF values for Pb and Fe suggest severe contamination, particularly in carrot and spinach rhizosphere soils. PLI values exceeding 1 corroborated the presence of cumulative pollution at several sites. Overall, the results underscore the significant ecological risks and heavy metal bioaccumulation associated with wastewater irrigation, necessitating immediate action in wastewater treatment, soil remediation, and ongoing monitoring to safeguard urban food systems.

Keywords: Soil contamination; urban agriculture; rhizosphere soil; wastewater irrigation

Introduction

Irrigation using wastewater has become an increasingly important strategy for managing water scarcity and sustaining agricultural production in many developing countries (Singh 2021; Nowwar et al., 2023). In arid and semi-arid regions, particularly in urban and peri-urban areas where freshwater is scarce or costly, the use of untreated or partially treated wastewater is now a common practice because of its continuous availability and nutrient-rich composition (Qadir et al., 2022; Chen et al., 2023). Wastewater is known to contain essential plant

nutrients such as nitrogen, phosphorus, and potassium, which can enhance soil fertility and crop productivity, thereby supporting food security and income generation for smallholder farmers in peri-urban regions (Hasheem et al., 2021; Woldetsadik et al., 2023). Despite these agronomic benefits, wastewater often contains substances that are highly toxic to both the environment and human health, including heavy metals that can accumulate in soils and pose long-term ecological and health risks (Abbas et al., 2023). Metals such as lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), and chromium (Cr) are commonly detected in industrial and municipal wastewater sources (Abdullahi et al., 2025; Ugya et al., 2019). These metals are non-biodegradable and can persist in the soil for extended periods, with concentrations increasing over time through repeated irrigation and cultivation (Bellanthudawa et al., 2023; Zhou et al., 2020).

The mobility and bioavailability of heavy metals in soil depend on several physicochemical properties, including pH, soil texture, organic matter content, redox potential, and irrigation practices (Wu et al., 2022). In many urban farming areas, soils often exhibit low cation exchange capacity (CEC), which enhances metal mobility and facilitates their uptake by plants (Golia, 2023; Lucija et al., 2025). Consequently, high concentrations of metals can accumulate in the edible parts of vegetables, exposing consumers to chronic health risks such as kidney damage, neurological disorders, and cancer (Boahen et al., 2024; Mawari et al., 2022). In Africa, wastewater irrigation is widespread in major cities such as Lagos, Kano, Ibadan, and Port Harcourt, where domestic, commercial, and industrial wastewaters are used for year-round vegetable production (Tayo, 2021). In Kano State, for instance, industrial zones such as Challawa and Sharada discharge untreated effluents directly into natural water channels, creating serious environmental hazards for downstream farms that rely on these waters for irrigation (Abdulsalam et al., 2023). In such regions, monitoring programs are often absent or poorly managed, and farmers are generally unaware of the contamination risks associated with their irrigation water (Bellanthudawa et al., 2023; Oladipo et al., 2022). Heavy metal pollution not only threatens human health but also disrupts soil–plant interactions. Elevated concentrations of Cr, Pb, and Cd can suppress soil microbial biomass, enzyme activity, and the functioning of symbiotic bacteria such as *Rhizobium*, thereby reducing nitrogen fixation and nutrient cycling (Rashid et al., 2023). These ecological disruptions impair soil fertility, threaten sustainable agriculture, and increase the risk of bioaccumulation in crops.

Tamburawa, located on the outskirts of Kano metropolis, is one of the most productive vegetable-growing regions in northern Nigeria. The area relies heavily on irrigation water from the River Kano, which is frequently contaminated with industrial effluents (Abdullahi et al., 2025; Shawai et al., 2019). Crops such as lettuce, spinach, carrot, onion, and cabbage are cultivated on a commercial scale; however, there is limited empirical evidence on the extent of heavy metal contamination in the soils and vegetables grown in this area (Abdullahi et al., 2025; Shawai et al., 2019). Previous studies have reported elevated levels of lead and cadmium in vegetable tissues from Tamburawa, but comprehensive assessments of contamination depth and associated ecological risks remain scarce (Zhang et al., 2023). The long-term accumulation of heavy metals in soil can degrade soil quality by affecting microbial activity and nutrient cycling, while also posing significant food safety risks—undermining efforts to promote sustainable urban agriculture (Bellanthudawa et al., 2023; Zhou et al., 2020).

While direct measurements of metal concentrations provide essential baseline information, interpreting ecological and food-safety risks requires standardized pollution indices. The Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI) are widely used to assess both the magnitude and severity of contamination relative to background levels (Hakanson, 1980; Müller, 1969; Tomlinson et al., 1980). These indices enable classification of soil pollution levels, inter-regional comparison, and identification of the most ecologically hazardous metals.

Therefore, this study aimed to determine the concentrations of selected heavy metals (Cu, Cr, Fe, Pb, and Zn) in the edible parts of five commonly cultivated vegetables and their rhizosphere soils from wastewater-irrigated farms in Tamburawa, Kano State. Furthermore, the study evaluated ecological contamination using CF, Igeo, and PLI indices and provided evidence-based recommendations for monitoring and remediation to promote safe and sustainable urban agriculture.

Materials and methods

Study area

The research was conducted in Tamburawa, located approximately 25 km southeast of Kano metropolis, Nigeria (Figure 1). The area lies within the Sudan savanna ecological zone, characterized by distinct wet and dry seasons. Tamburawa has developed into a major commercial hub for vegetable cultivation, supported primarily by wastewater irrigation sourced from the Kano River, which receives effluents from the Challawa industrial estate. The soils of the study area are predominantly sandy loam, well-drained, and moderately fertile. Local farmers engage in year-round cultivation of various vegetables, including lettuce, spinach, cabbage, onion, and carrot, among others. The intensive use of wastewater for irrigation has made Tamburawa an ideal site for assessing soil contamination and ecological risks associated with heavy metal accumulation in wastewater-irrigated farmlands.

Sampling procedure

Sampling of vegetables

Five commonly consumed vegetable species were selected for this study: cabbage (*Brassica oleracea*), carrot (*Daucus carota*), lettuce (*Lactuca sativa*), onion (*Allium cepa*), and spinach (*Spinacia oleracea*). The selection was based on their nutritional importance, regional cultivation prevalence, and potential for heavy metal accumulation. Mature and healthy plants were randomly harvested using clean stainless-steel tools, following standard protocols for trace metal studies in crops (Anirban et al., 2023; Ene et al., 2024). At each sampling plot, three composite replicate samples were collected per vegetable species. Each composite comprised five randomly selected healthy plants, pooled to form one replicate ($n = 3$ per species). This sampling design ensured statistical robustness and followed established procedures in heavy metal assessment studies in vegetables (Sultana et al., 2022).

The harvested vegetables were separated into distinct anatomical parts for analysis: cabbage (leaves and shoots), carrot (taproot and shoot), lettuce (leaves and shoots), onion (bulb and leaves), and spinach (leaves and shoots). This partitioning enabled evaluation of metal distribution within different plant tissues.

Immediately after collection, samples were thoroughly washed with tap water to remove visible soil and dust particles, followed by rinsing with deionized water to eliminate surface contaminants. This cleaning procedure ensured that subsequent analyses reflected internal metal accumulation rather than external deposition (Li et al., 2023). The cleaned plant materials were then cut into small pieces, air-dried under shade for 5–7 days, and stored in labeled paper envelopes pending laboratory digestion and heavy metal analysis.

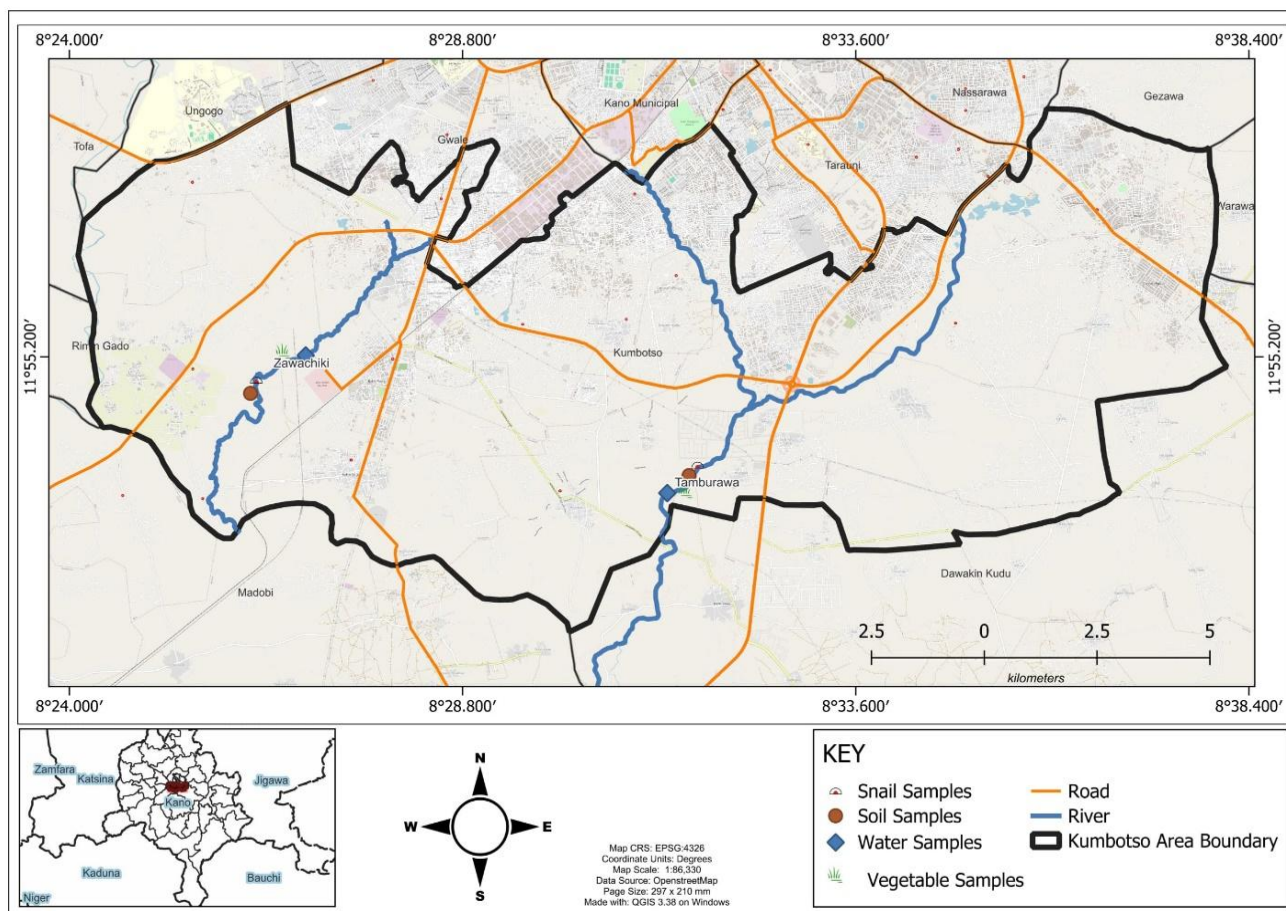


Figure 1. Study Area; Tamburawa, Kumbotso Local Government Area, Kano State, Nigeria

Sampling of rhizosphere soil

Rhizosphere soil samples were collected simultaneously with the vegetable samples. The rhizosphere was defined as the soil loosely adhering to the roots after gently shaking off bulk soil. For each composite replicate, approximately 200 g of root-adhered soil was collected from a 0–20 cm depth at three points per plant, pooled, air-dried, and sieved through a 2 mm mesh (Asamoah et al., 2025; Carrera et al, 2025). Thus, each vegetable species had three rhizosphere composite replicates ($n = 3$).

Sampling was conducted on the same vegetable plots used for plant collection. For each species, three sub-samples were taken across the root zone and combined to form one representative sample. The rhizosphere soils were coded as follows:

- RSPC – rhizosphere soil from cabbage
- RSPCR – rhizosphere soil from carrot
- RSPL – rhizosphere soil from lettuce
- RSPO – rhizosphere soil from onion
- RSPS – rhizosphere soil from spinach

Following standard soil preparation procedures, samples were air-dried at ambient temperature, crushed to disaggregate clods, and sieved through a 2 mm mesh to remove stones and coarse debris (Asamoah et al., 2025; Carrera et al., 2025). The processed samples were stored in clean polyethylene zip-lock bags and kept in a desiccator until further analysis. This procedure ensured uniformity and comparability between plant tissues and corresponding rhizosphere soils for assessing heavy metal distribution.

Sample digestion and heavy metal analysis

Heavy metals in soil and plant samples were extracted using the wet digestion method following APHA (2012) and USEPA (1996) protocols. Approximately 1.0 g of the sieved sample was weighed into a digestion flask, followed by the addition of 10 mL nitric acid (HNO_3) and 2 mL perchloric acid (HClO_4). The mixture was heated on a hot plate at 120°C until the volume was reduced to approximately 2 mL, and a clear solution indicated complete digestion. After cooling, each digest was filtered through Whatman No. 42 filter paper into a 50 mL volumetric flask, and the volume was made up to the mark with deionized water. The resulting solution served as the stock digest for heavy metal determination. Samples with concentrations exceeding the calibration range of the Atomic Absorption Spectrophotometer (AAS) were appropriately diluted (1:2, 1:5, or 1:10) with deionized water, and the corresponding dilution factors were applied to obtain accurate concentrations.

The concentrations of copper (Cu), chromium (Cr), iron (Fe), lead (Pb), and zinc (Zn) were determined using AAS following the APHA (2012) standard procedure. To ensure quality assurance and quality control (QA/QC), reagent blanks, duplicate samples, and certified reference materials were included throughout the analytical process.

Physicochemical properties of rhizosphere soil

The physicochemical properties of rhizosphere soil were analyzed because these parameters significantly influence heavy metal solubility, mobility, and bioavailability. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 soil-to-water suspension using a calibrated glass-electrode pH meter and a conductivity meter, respectively (Song et al., 2025). Organic matter (OM) content was estimated by the Walkley–Black dichromate oxidation method (Dong et al., 2021). The cation exchange capacity (CEC) was measured using the ammonium acetate extraction method at pH 7.0 (Purnamasari et al., 2021). These soil parameters are well-recognized regulators of heavy metal retention and release (Kumar et al., 2023), and their determination helps to interpret the potential bioavailability of metals in wastewater-irrigated soils.

Pollution indices for soil assessment

To evaluate the degree of heavy metal contamination in rhizosphere soils, the Contamination Factor (CF), Geo-accumulation Index (I_{geo}), and Pollution Load Index (PLI) were calculated following standard approaches (Müller, 1969; Hakanson, 1980; Tomlinson et al., 1980).

Contamination factor (CF)

The contamination factor expresses the extent of metal accumulation in the soil relative to a background concentration and is calculated by following equation 1.

$$CF = \frac{C_{metal}}{C_{background}} \dots \dots \dots \text{Equation (1)}$$

Where:

C_{metal} = measured concentration of heavy metal in the sample (mg/kg)

$C_{background}$ = reference value (mg/kg)

Classification of CF (Hakanson, 1980)

- $CF < 1$: Low contamination
- $1 \leq CF < 3$: Moderate contamination
- $3 \leq CF < 6$: Considerable contamination
- $CF \geq 6$: Very high contamination

Background values used (mg/kg)

In this study, the background values were adopted from Kabata-Pendias (2011), which provides global average concentrations trace elements in uncontaminated soils, which offers regional background data for Nigerian soils (Sulaiman et al., 2021). These sources are widely used in heavy metal contamination studies in Africa for comparable soil types. The background vales are as follows:

- Pb: 2.0 mg/kg
- Cd: 0.3 mg/kg
- Cu: 20.0 mg/kg
- Zn: 50.0 mg/kg
- Ni: 10.0 mg/kg

Geo-accumulation Index (Igeo)

The Geo-accumulation Index uses background levels of concentration of metals in soil, along with a correction factor, as a measure of the degree of concentration of a metal in the soil (Equation 2).

$$I_{geo} = \log_2 \left(\frac{C_n}{1.5 \times B_n} \right) \dots \dots \dots \text{Equation (2)}$$

Where:

- C_n = measured concentration of the metal
- B_n = geochemical background values
- 1.5 = constant for natural variability (Muller, 1969; Kabata-Pendias, 2011)

Classification of Igeo (Muller, 1969):

- $I_{geo} \leq 0$: Unpolluted
- $0 < I_{geo} \leq 1$: Unpolluted to moderately polluted
- $1 < I_{geo} \leq 2$: Moderately polluted
- $2 < I_{geo} \leq 3$: Moderately to strongly polluted

- $3 < I_{geo} \leq 4$: Strongly polluted
- $4 < I_{geo} \leq 5$: Strongly to extremely polluted
- $I_{geo} > 5$: Extremely polluted

Pollution Load Index (PLI)

The Pollution Load Index is a measure developed through combining all the other measures given in a sample into one index which reflects overall heavy metal pollution in the sample. It is computed as the n th root of the product of CF of the metals that are being analyzed (Equation 3). The method was adopted by Tomlinson et al., (1980) for marine and estuarine sediments and has since widely applied to terrestrial and agricultural soils (Nasir et al., 2023; Soleimani et al., 2023).

PLI was calculated using equation3:

$$PLI = (CF_1 \times CF_2 \times \dots CF_n)^{\frac{1}{n}} \dots \dots \dots \text{Equation (3)}$$

Where:

CF = contamination factor of each metal

n = number of metals considered

PLI Interpretation (Tomlinson et al., 1980):

PLI < 1: No pollution

PLI = 1: Baseline level

PLI > 1: Pollution present

Statistical analysis

All experimental data were expressed as mean $\pm$ standard error (SE) of triplicate determinations. Statistical analyses were performed using GENSTAT 17th Edition. One-way Analysis of Variance (ANOVA) was applied to test for significant differences among heavy metal concentrations across vegetable plots. Where significant differences were observed, means were separated using Duncan's Multiple Range Test (DMRT) at a 5% significance level ($p < 0.05$). Distinct letters (a–d) in the tables indicate statistically significant differences among means.

Results and discussion

Physicochemical properties of the rhizosphere soil

The physicochemical properties of the rhizosphere soil are presented in Table 1. These properties are fundamental in determining the solubility, retention, and bioavailability of heavy metals within the soil–plant system. The soil pH was 7.76, falling within the FAO/WHO (2007) safe agricultural range of 6.0–8.5. Soils with alkaline pH generally reduce the solubility of cationic metals such as Pb^{2+} , Zn^{2+} , and Cu^{2+} , owing to their precipitation as hydroxides, carbonates, or phosphates, and adsorption onto negatively charged soil colloids

(Muhammad et al., 2025). However, under low-buffering conditions, typical of sandy soils with minimal organic colloids, these metals can remain relatively mobile despite alkalinity (Burachevskaya et al., 2024). This suggests that the alkaline condition in the study area may not be sufficient to prevent metal mobility and bioavailability. The electrical conductivity ($EC = 1.79$ dS/m) indicated moderate salinity, below the critical threshold of 4 dS/m where salinity stress can significantly impair crop growth (FAO/WHO, 2007). Nonetheless, prolonged irrigation with wastewater could gradually increase sodium accumulation, altering soil structure and promoting metal desorption from exchange sites (Abdel-Malek et al., 2024; Qadir et al., 2022). Elevated Na^+ concentrations can disperse clay particles and release adsorbed heavy metals, enhancing their movement toward plant roots. The soil texture comprised 76.28% sand, 16.88% silt, and 6.79% clay, classifying it as sandy loam. This texture type is typical of arid and semi-arid regions and is known for low metal retention capacity due to its small surface area and reduced adsorption potential (El-Hemamy et al., 2025). The limited clay fraction and low organic matter content reduce the number of active binding sites for heavy metals, increasing leaching potential and metal mobility. In contrast, fine-textured soils (high in clay or organic colloids) tend to immobilize metals by surface complexation and cation exchange (Zhao et al., 2023).

Exchangeable base analysis revealed the dominance of Ca^{2+} (11.70 cmol/kg), followed by Mg^{2+} , Na^+ , and K^+ . High calcium levels are characteristic of semi-arid soils and may compete with heavy metals for adsorption sites, thereby reducing metal availability (Lee et al., 2025). However, the relatively elevated Na^+ (1.11 cmol/kg) poses a potential sodicity hazard, particularly under continuous wastewater irrigation, as Na^+ can displace Ca^{2+} and Mg^{2+} on exchange sites and promote dispersion of clay minerals—conditions that enhance metal migration and solubility. The cation exchange capacity ($CEC = 1.45$ cmol/kg) was very low, far below the benchmark of >10 cmol/kg for fertile soils (Ćirić et al., 2023). Such low CEC reflects a deficiency in negatively charged colloids (clays and humic substances), implying limited adsorption capacity for cationic heavy metals and, consequently, a greater tendency for metal leaching and bioavailability (Roulia, 2024). This low CEC condition helps explain the elevated contamination factors observed for Pb and Fe in later sections of this study.

The organic carbon content ($OC = 8.06$ g/kg or 0.81%) was also below the 2% minimum threshold for maintaining soil fertility and structural stability (FAO, 2015). Organic matter strongly influences metal behavior through complexation, adsorption, and redox reactions. Low OC implies reduced complexation potential, leading to weak immobilization of metals in the soil matrix (Su et al., 2024). Conversely, dissolved organic compounds from wastewater could form soluble metal–organic complexes, enhancing vertical and lateral mobility of metals in the soil profile. Macronutrient analysis showed total nitrogen (1.33 g/kg) and available phosphorus (77.66 mg/kg), values consistent with nutrient enrichment commonly associated with wastewater irrigation (Singh, 2021; Saleh et al., 2025). While this enrichment enhances soil fertility, excess phosphorus may form insoluble complexes with Fe and Zn, reducing their bioavailability to plants (Yang et al., 2024). Moreover, nutrient–metal interactions could influence competitive uptake dynamics, particularly where Fe–P and Zn–P antagonisms occur in the rhizosphere.

Comparative assessment against international soil quality standards indicates that the study soils were within the acceptable pH and salinity ranges but notably deficient in CEC and organic matter, both of which are critical for heavy metal retention and immobilization. The combination of sandy texture, low CEC, and low organic carbon implies high potential mobility and bioavailability of metals, thereby increasing the risk of transfer from soil to vegetables. These conditions offer a plausible explanation for the high Contamination Factor (CF), Geo-accumulation Index (Igeo), and Pollution Load Index (PLI) values observed for Pb and Fe in this study.

Although the alkaline pH tends to restrict solubility, the dominance of sandy particles, low exchange surfaces, and limited organic matter facilitate enhanced metal migration and uptake by plants.

Hence, the physicochemical characteristics of the soil not only promote heavy metal transfer to edible plant parts but also amplify cumulative ecological and food safety risks, as reflected in the pollution indices discussed in the subsequent sections.

Table 1. Physicochemical properties of the rhizosphere soil in the study area

Parameters	Values/class
pH	7.76
EC (dS\ cm)	1.79
Sand (%)	76.28
Silt (%)	16.88
Clay (%)	6.79
Textural class	Sandy-loam
Ca	11.70
Mg	2.85
K	0.79
Na	1.11
CEC	1.45
OC (g/kg)	8.06
TN (g/kg)	1.33
AP (mg/kg)	77.66

Note: EC–electrical conductivity; Ca–calcium; Mg– magnesium; K–potassium; Na–sodium; CEC–cation exchange capacity; OC–organic carbon; TN–total nitrogen; AP–available phosphorus.

Heavy metal concentrations in vegetable samples

Heavy metals including Copper (Cu), Chromium (Cr), Iron (Fe), Lead (Pb), and Zinc (Zn) were detected in the edible components of the five vegetables analyzed in this study (Table 2). The concentration of Cu ranged from 3.61 mg/kg in spinach shoots to 7.63 mg/kg in spinach leaves, with most values exceeding the FAO/WHO (2007) permissible limit of 3.0 mg/kg. Chromium was found at levels between 11.11 mg/kg in cabbage shoots and 24.45 mg/kg in onion bulbs, significantly higher than the safe threshold of 2.3 mg/kg. Iron concentrations varied widely, from 75.4 mg/kg in spinach shoots to 1046.5 mg/kg in onion leaves, all surpassing the FAO/WHO limit of 425 mg/kg. Lead was detected only in cabbage leaves (4.33 mg/kg) and carrot shoots (23.0 mg/kg), far above the maximum limit of 0.3 mg/kg. Zinc concentrations ranged from 5.88 mg/kg in spinach shoots to 32.66 mg/kg in carrot shoots, remaining below the FAO/WHO limit of 60 mg/kg. Statistically significant differences ($p < 0.05$) were observed for Cr, Fe, Pb, and Zn, reflecting crop-specific variations in heavy metal uptake. The elevated levels of these metals can be explained by several interacting mechanisms.

Wastewater used for irrigation often contains industrial and domestic effluents rich in heavy metals such as Cr and Pb, which are non-biodegradable and highly persistent (Abdullahi et al., 2025; Ugya et al., 2019).

Soil physicochemical properties, including sandy texture, low organic carbon, and low cation exchange capacity, reduce metal adsorption and retention, making them more mobile and bioavailable to plants (Alloway, 2013; Kabata-Pendias, 2011). Alkaline pH may partially limit solubility; however, in soils with low buffering capacity,

metals remain available for plant uptake. Additionally, differences in metal accumulation among crops can be attributed to plant-specific factors such as root morphology, transpiration rate, and leaf surface area, which influence both root absorption and foliar deposition of metals (Woldetsadik et al., 2023; Chen et al., 2023). For example, the high Pb content in carrot roots likely reflects the strong adsorption of Pb onto root surfaces and its limited translocation to shoots (Mthembu et al., 2024 4).

Table 2. Heavy metals concentrations (mg/kg) in wastewater irrigated vegetables.

Sample	Cu (3.0)	Cr (2.3)	Fe (425)	Pb (0.3)	Zn (60)
Cabbage Shoot	4.52 ± 0.11 ^a	11.11 ± 0.45 ^a	102.6 ± 5.2 ^a	N.D	8.46 ± 0.27 ^d
Cabbage Leaves	3.67 ± 0.10 ^b	18.33 ± 0.56 ^b	156.5 ± 7.4 ^c	4.33 ± 0.18 ^a	7.82 ± 0.33 ^d
Carrot Shoot	6.33 ± 0.13 ^a	18.33 ± 0.56 ^b	770.6 ± 34.2 ^c	23.00 ± 1.00 ^b	32.66 ± 1.20 ^a
Carrot Taproot	7.23 ± 0.14 ^a	13.89 ± 0.45 ^b	296.9 ± 14.6 ^d	N.D	11.22 ± 0.44 ^b
Lettuce Shoot	4.18 ± 0.11 ^b	23.89 ± 0.60 ^c	908.5 ± 41.3 ^c	N.D	11.80 ± 0.39 ^b
Lettuce Leaves	4.58 ± 0.12 ^b	22.22 ± 0.55 ^c	495.0 ± 20.5 ^d	N.D	12.49 ± 0.46 ^b
Onion Leaves	6.67 ± 0.18 ^a	23.89 ± 0.58 ^c	1046.5 ± 48.3 ^b	N.D	16.98 ± 0.55 ^a
Onion Bulb	5.93 ± 0.17 ^a	24.45 ± 0.60 ^c	788.7 ± 35.2 ^c	N.D	19.32 ± 0.63 ^a
Spinach Shoot	3.61 ± 0.10 ^b	19.44 ± 0.47 ^b	75.4 ± 3.3 ^a	N.D	5.88 ± 0.19 ^c
Spinach Leaves	7.63 ± 0.20 ^a	23.89 ± 0.59 ^c	369.1 ± 18.0 ^d	N.D	12.86 ± 0.45 ^b

Note: Values are expressed as mean ± SE (n = 3); WHO/FAO permissible limits in the parentheses. N.D = Not Detected. Superscript a-e indicate statistical differences ($P < 0.05$, DMRT)

Nutrient-metal interactions may further influence heavy metal dynamics. High phosphorus levels from wastewater irrigation can alter Fe and Zn solubility and uptake, whereas cationic metals such as Ca^{2+} and Mg^{2+} compete with Cu^{2+} , Pb^{2+} , and Zn^{2+} for binding sites in soil and plant tissues (Kabata-Pendias, 2011). Furthermore, industrial Fe and Cr discharged into irrigation water, combined with sediment transport, contribute to excessive metal accumulation in the rhizosphere and edible plant parts (Abbas et al., 2023).

Overall, vegetables grown under wastewater irrigation in Tamburawa exhibit elevated levels of toxic metals, especially Cr, Pb, and Cu, with statistically significant variations across crops. The combination of wastewater contamination, soil characteristics, and plant-specific uptake mechanisms underlies the observed accumulation patterns. These findings highlight the urgent need for wastewater treatment, regular monitoring of heavy metals in vegetables, and implementation of mitigation strategies to ensure food safety and sustainable urban agriculture.

Heavy metal concentrations in the rhizosphere soil of vegetables

Heavy metals including Cu, Cr, Fe, Pb, and Zn were detected in the rhizosphere soils of all five vegetables cultivated under wastewater irrigation in Tamburawa (Table 3). Cu concentrations ranged from 1.21 mg/kg in cabbage soil (RSPC) to 3.30 mg/kg in carrot soil (RSPCR), with the carrot rhizosphere slightly exceeding the FAO/WHO permissible limit of 3.0 mg/kg. Chromium levels varied from undetectable in cabbage and carrot

soils to 8.89 mg/kg in spinach rhizosphere (RSPS), exceeding the FAO/WHO limit of 2.3 mg/kg for all detected samples. Iron showed the highest accumulation, ranging from 1338.0 mg/kg in cabbage to 5106.5 mg/kg in carrot soil, while Pb concentrations varied between 13.83 mg/kg in onion rhizosphere (RSPO) and 76.83 mg/kg in carrot (RSPCR), all far above the safe threshold of 0.3 mg/kg. Zn ranged from 1.82 mg/kg in cabbage soil to 9.83 mg/kg in onion soil, remaining below the FAO/WHO limit of 60 mg/kg. Statistically significant differences ($p < 0.05$) were observed for Fe, Pb, and Zn, reflecting differential accumulation across vegetable types.

Table 3. Heavy Metals Concentrations (mg/kg) in the Rhizosphere of the soil employed for planting vegetables.

Sample	Cu (mg/kg)	Cr (mg/kg)	Fe (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
RSPC	12.1 ± 0.05 ^a	ND	1338.0 ± 65.1 ^a	29.67 ± 1.33a	1.82 ± 0.08a
RSPCR	3.30 ± 0.12 ^b	ND	5106.5 ± 221.7 ^b	76.83 ± 2.88b	8.46 ± 0.32 ^b
RSPL	2.88 ± 0.09 ^a	2.78 ± 0.08 ^a	4263.9 ± 192.0 ^b	21.00 ± 1.21a	8.15 ± 0.28 ^c
RSPO	2.88 ± 0.10 ^a	6.11 ± 0.21 ^b	3564.8 ± 170.2 ^b	13.83 ± 0.95c	9.83 ± 0.34 ^d
RSPS	3.05 ± 0.11 ^a	8.89 ± 0.31 ^b	3893.5 ± 178 ^b	16.83 ± 1.01c	6.99 ± 0.23 ^c

Note: Values are expressed as mean ± SE (n = 3); WHO/FAO permissible limits in the parentheses. N.D = Not Detected. Superscript a-e indicate statistical differences ($P < 0.05$, DMRT), RSPC= Rhizosphere of the soil employed for planting cabbage, RSPCR= Rhizosphere of the soil employed for planting, RSPL= Rhizosphere of the soil employed for planting lettuce, RSPO= Rhizosphere of the soil employed for planting onion RSPS= Rhizosphere of the soil employed for planting spinach

The elevated metal concentrations can be attributed to prolonged wastewater irrigation containing industrial and domestic effluents, which introduce heavy metals into the soil environment (Abdullahi et al., 2025; Ugya et al., 2019). Soil properties such as sandy loam texture, low cation exchange capacity, and low organic carbon reduce metal retention, enhancing mobility and bioavailability to plant roots (Alloway, 2013). The selective accumulation of Cr in certain rhizospheres may be influenced by crop-specific root exudates and localized inputs from nearby tanneries or paint industries (Kabata-Pendias, 2011). High Fe concentrations are likely driven by iron-rich sediments and industrial discharges, while elevated Pb reflects contamination from vehicular emissions, batteries, and metal wastes along irrigation channels (Mthembu et al., 2024). Zn accumulation patterns are consistent with long-term wastewater application and crop-specific uptake mechanisms (Woldetsadik et al., 2023). Thus these results indicated that the rhizosphere soils of wastewater-irrigated vegetables in Tamburawa exhibit persistent and crop-dependent heavy metal contamination, particularly for Fe and Pb. The interplay between wastewater composition, soil physicochemical characteristics, and plant-specific uptake drives metal accumulation, highlighting the critical need for regular monitoring, proper irrigation water treatment, and management interventions to mitigate ecological and food safety risks (Bellanthudawa et al., 2023).

Contamination factor and pollution load index

The Contamination Factor (CF) values for heavy metals in the rhizosphere soils of wastewater-irrigated vegetables are presented in Table 4, providing an assessment of contamination relative to baseline or background levels. According to Hakanson (1980), CF values are classified as: <1 (low contamination), 1–3 (moderate

contamination), 3–6 (considerable contamination), and ≥ 6 (very high contamination). In this study, Pb exhibited exceedingly high CF values, with 256.10 in carrot soil (RSPCR) and 98.90 in cabbage soil (RSPC), indicating extreme contamination. These values are substantially higher than reported in other industrially impacted agricultural areas in Nigeria (Sulaiman et al., 2021). Fe also showed high CF values across all rhizosphere soils, reflecting long-term accumulation from wastewater carrying sediment and iron-rich effluents (Soleimani et al., 2023; Tayo, 2021).

In contrast, Cu and Zn CFs in cabbage (RSPC) and spinach (RSPS) rhizospheres were below 1, indicating low contamination, consistent with observations in similar wastewater-irrigated farmlands (Abdullahi et al., 2025; Ugya et al., 2019). The carrot rhizosphere (RSPCR) showed moderate Cu contamination (CF = 1.10), likely due to its proximity to industrial drainage channels (Darma et al., 2024). Chromium, though undetected in RSPC and RSPCR, exhibited a high CF (3.87) in spinach rhizosphere (RSPS), suggesting localized contamination from tannery and metal-processing effluents (Tripathi et al., 2025). These patterns indicate that CF values are strongly influenced by wastewater composition, proximity to industrial sources, and crop-specific soil interactions.

The Pollution Load Index (PLI), which provides an overall measure of cumulative heavy metal pollution, further underscores these risks. PLI values for lettuce, onion, and spinach rhizospheres were 2.56, 2.76, and 2.98, respectively, exceeding the critical threshold of 1 and signaling poor soil quality and cumulative heavy metal stress (Elechi et al., 2023; Nasir et al., 2023). The rhizospheres of carrot and cabbage showed PLI values of zero, likely because undetectable Cr concentrations were excluded from the geometric mean calculation, a phenomenon reported in similar studies (Chen et al., 2023).

Overall, these results highlight that Pb and Fe are the primary contributors to soil contamination, while Cu, Zn, and Cr show variable, crop-specific accumulation patterns. The combination of CF and PLI data underscores the urgent need for monitoring, wastewater treatment, and remediation measures to mitigate heavy metal pollution in urban agricultural soils.

Table 4. Contamination Factor and Pollution Load Index for Rhizosphere of the soil employed for planting vegetables.

Sample	CF-Cu	CF-Cr	CF-Fe	CF-Pb	CF-Zn	PLI
RSPC	0.40	0.00	3.15	98.90	0.03	0.00
RSPCR	1.10	0.00	12.02	256.10	0.14	0.00
RSPL	0.96	1.21	10.03	70.00	0.14	2.56
RSPO	0.96	2.66	8.39	46.10	0.16	2.76
RSPS	1.02	3.87	9.16	56.10	0.12	2.98

Note: CF > 1 indicates contamination; PLI > 1 indicates soil deterioration; RSPC= Rhizosphere of the soil employed for planting cabbage; RSPCR= Rhizosphere of the soil employed for planting; RSPL= Rhizosphere of the soil employed for planting lettuce; RSPO= Rhizosphere of the soil employed for planting onion; RSPS= Rhizosphere of the soil employed for planting spinach.

Geo-accumulation index (I_{geo})

The results of Geo-accumulation Index (I_{geo}) which are depicted in Table 5 therein presenting another indicator of the intensive contamination of heavy metals in the rhizosphere of the soil employed in cultivating the studied

vegetables. Going by the classification of Muller (1969), Igeo 5 and above Implies that there is extreme pollution. The detection of Pb in the rhizosphere soil indicate serious pollution with maximum values of 7.42 in carrot, 6.04 in cabbage, which is congruent with the CF findings and a sign of the threat of Pb buildup in agricultural land (Onwuka et al., 2024).

Fe concentrations were at medium and fair pollution levels, with Igeo values ranging between 1.07 (RSPC) and 3.00 (RSPCR) in agreement with other researchers that indicated the enrichment of iron in raw sewage effluents (Abubakar et al., 2025). The Igeo values of Zn and Cu were mostly < 0 which is indicative of background or non-polluted conditions and this is supported by their low CFs (Hasheem et al., 2020). The fact that the highest Igeo Cr (1.37) obtained in RSPS contributes to moderate contamination to the fact that Cr is well known to persist in wastewater-affected sites (Elechi et al., 2023).

The results in this study highlight Pb and Fe to be crucial pollutants of concern in the-Tamburawa irrigation ecosystem. Therefore, proper and continuous monitoring coupled with long-term soil-remediation activity are required with a view to curbing bio-accumulation and human contact of heavy metals through food chains.

Table 5. Geo-accumulation Index for Heavy Metals in Rhizosphere Soil

Soil	Type	Igeo-Cu	Igeo-Cr	Igeo-Fe	Igeo-Pb	Igeo-Zn
RSPC		-1.89	$-\infty$	1.07	6.04	-5.63
RSPCR		-0.45	$-\infty$	3.00	7.42	-3.41
RSPL		-0.64	-0.31	2.74	5.54	-3.47
RSPO		-0.64	0.82	2.48	4.94	-3.19
RSPS		-0.56	1.37	2.61	5.22	-3.69

Note: Igeo > 1 indicates pollution. RSPC= Rhizosphere of the soil employed for planting cabbage; RSPCR= Rhizosphere of the soil employed for planting; RSPL= Rhizosphere of the soil employed for planting lettuce; RSPO= Rhizosphere of the soil employed for planting onion; RSPS= Rhizosphere of the soil employed for planting spinach.

Conclusion

This study demonstrated that wastewater-irrigated soils and vegetables in Tamburawa are heavily contaminated with Pb and Fe, with levels exceeding FAO/WHO limits and classified as extreme pollution by CF, PLI, and Igeo indices. The sandy texture, low organic matter, and low cation exchange capacity of the soils facilitated metal mobility and bioavailability, explaining the observed accumulation in edible crops. Crop-specific differences in metal uptake were evident, with carrot, lettuce, onion, and spinach showing the highest bioaccumulation of Pb and Fe.

These findings underscore the urgent need for monitoring and regulation of wastewater use in urban agriculture. Treatment of irrigation water before application, coupled with strategies such as phytoremediation or soil amendments, can mitigate heavy metal risks. Further research is recommended to evaluate human health hazards, bioaccumulation in crops, and seasonal variations, enhancing food safety and the sustainability of urban vegetable production.

Declaration

Acknowledgment: The first author acknowledges the support and unparalleled guidance of his MSc supervisors and others that contributed to the conduct of this study.

Funding: No funding was received for this work

Conflict of interest: The authors declare no conflict of interest.

Ethics Approval/Declaration: N/A

Consent to Participate: All the authors gave consent for participation.

Consent for Publication: All author(s) consent to the publication of this manuscript.

Data Availability: Data will be available on a formal request from the corresponding authors.

Authors' Contributions: Conceptualization: A.M.H.; H.A.S.; and A.A.O.; methodology, N.M.E.; B.G.B, and A.M.H.; software, A.A.O.; N.M.E.; and A.M.H.; formal analysis, N.M.E.; O.A and A.A.O.; writing—original draft preparation, A.M.H.; A.A.O.; O.A; and H.A.S.; writing—review and editing, A.A.O.; B.G.B and A.M.H; All authors have read and agreed to the published version of the manuscript.

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RESEARCH ARTICLE

Influence of Different Planting Dates on Growth of Blackberry Cutting Under the Agro-Climatic Condition

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Received: 23 October, 2025, Accepted: 29 November, 2025, Published: 12 December, 2025

Abstract

Blackberry (*Rubus fruticosus* L.) is an economically important small fruit crop valued for its nutritional, and medicinal attributes. Its successful propagation through stem cuttings is highly dependent on environmental conditions especially the time of planting. This study evaluated the effect of planting dates (15th July, 25th July, 4th August, and 14th August) on the growth of blackberry plant cuttings under the agro-climatic environmental condition of Swat, Pakistan. The experimental study were conducted in 2016 by using a Randomized Complete Block Design (RCBD) with three replications. The data on sprouting percentage, survival percentage, number of leaves, shoot length, number of roots, and root length were collected, and statistically analyzed. The results revealed that planting dates on some parameters significantly affected such as number of leaves ($P = 0.0145$), root number ($P = 0.0302$), and shoot length ($P = 0.0477$), while sprouting percentage, survival percentage, and root length were non-significant. Meanwhile, cuttings planted on 15th July consistently exhibited the greater performance, by achieving the highest sprouting percentage (73.33%) followed by survival percentage (66.67%), number of leaves (9.33), shoot length (27.17cm), number of roots (13.33), and root length (14.00cm). However, later planting dates relatively weaker growth responses. We conclude from the study that mid-July provides the favorable environmental conditions (for example; temperature, humidity, and soil moisture) for growth and development of blackberry cuttings in Swat. Therefore, 15th July is recommended as the most suitable planting date for enhancing propagation and successive plant vigor under the local agro-climatic condition. Furthermore, multi-location and multi-season studies are suggested to support region wide recommendations.

Keywords: Blackberry; Planting Date; Plant Morphology; Plant Growth; Agro-Climatic Condition

Introduction

Blackberry (*Rubus fruticosus* L.) is a perennial fruit crop belonging to the family Rosaceae (Hall, 1990; Meng et al., 2022). It is an economically significant small fruit species, extensively cultivated in temperate and subtropical regions worldwide (Gao et al., 2023; Paudel et al., 2025). Determining its exact center of origin is challenging, as different *Rubus* species are distributed across Asia, Europe, North America, and South America, making blackberry one of the fruit crops with the broadest geographical distribution (Hall, 1990; Meng et al., 2022). Historically, blackberries have been valued as wild fruits, with many species harvested both for household consumption, and for commercial purposes (Hall, 1990). Beyond their appealing flavor, blackberries are highly regarded for their exceptional nutritional and medicinal properties. They are rich sources of vitamins, phenolic compounds, and antioxidants that contribute to various health benefits, and disease prevention (Kaume et al., 2012; Milivojević et al., 2010). Due to their growing consumer demand, nutritional importance, and adaptability to diverse environmental conditions, blackberry cultivation is expanding steadily across the globe, including Pakistan. However, the successful propagation, and establishment of blackberry plants are strongly influenced by several environmental and management factors, among which the timing of planting plays a pivotal roles (Cao et al., 2018).

However, propagation through stem cuttings is one of the most reliable and cost-effective methods for blackberry production, as it ensures genetic uniformity and preserves desirable cultivar characteristics (Clark & Finn, 2014; Reed et al., 2017). The success of this propagation technique is largely influenced by environmental factors such as temperature, humidity, and soil moisture, all of which vary with planting time (Hartmann et al., 2011). The selection of appropriate planting date is therefore critical, as it provides favorable conditions for root initiation, shoot emergence, and subsequent plant development (Alam et al., 2016). In contrast, planting at an unsuitable time may expose cuttings to suboptimal climatic conditions, leading to poor rooting, low survival rates, and reduced plant vigor (Ahmad et al., 2015). The blackberry cultivars are generally classified into two main growth habits trailing and erect each occurring in both thorny and thorn-less forms. Trailing cultivars such as Marion, Logan, Baba berry, and Young berry typically lack cold hardiness, and may experience severe damage at temperatures between 0 and 5 °F (−17.8 to −15 °C). In contrast, erect cultivars including Chester, Darrow, and Illini exhibit greater cold tolerance and can with stand temperatures as low as −15 to −20 °F (−26.1 to −28.9 °C) with minimal injury (Barney & Himelrick, 1999).

Moreover, blackberry is regarded as a highly suitable crop for small-scale growers owing to its relatively low establishment cost, simple orchard management practices, and high nutritional value (Antunes et al., 2000). A global survey conducted in 2005 reported that blackberries were cultivated on approximately 20,035 hectares worldwide, representing a 45% increase since 1995 (Strik et al., 2007). Currently, *Rubus* spp. ranks among the most important berry crops globally, with more than 20,000 hectares under cultivation, primarily across Europe and North America (Wang & Lin, 2000; Kafkas et al., 2008; Milivojević et al., 2011). Mexico has emerged as the leading global producer, harvesting approximately 56,800 tons of fruit in 2011, primarily for export markets (FAOSTAT, 2013). Nutritionally, blackberries are an excellent source of dietary fiber, essential minerals, proteins, and vitamins, while being naturally low in calories, fat, and sodium (Jeyaraj et al., 2022). They also exhibit strong antioxidant activity due to their high phenolic and anthocyanin content, which enhances their value as a functional food crop (García-Mendoza et al., 2023). For optimal growth and productivity, blackberries require well-drained sandy loam soils with a pH of 6.2 - 6.8, and adequate organic matter to support root development and nutrient uptake. The propagation of blackberries can be achieved through several conventional methods, including layering, offsets, and root or stem cuttings (Botez et al., 1984).

In addition, tissue culture techniques have been successfully developed to facilitate the rapid multiplication of uniform, disease free planting material within a relatively short period (Jenks, 2011). The Swat valley in northern Pakistan possesses favorable agro-climatic conditions for the cultivation of small fruit crops. However, its pronounced seasonal variations in temperature and rainfall can substantially influence plant establishment, rooting, and overall growth performance. Identifying the optimal planting date is therefore essential for enhancing the survival and vigor of blackberry cuttings under these local environmental conditions. The previous research studies has demonstrated that even slight variations in planting time can significantly affect the growth dynamics, rooting success, and productivity of various fruit crops (Ali et al., 2017; Mehmood et al., 2019).

Furthermore, the research on the influence of planting dates on blackberry propagation exists globally, but no localized studies have been conducted under the specific agro-climatic conditions of Swat, Pakistan. This lack of region-specific information limits the development of optimal planting schedules for improving the growth performance of blackberry cuttings in the area. The present study hypothesized that planting date significantly affects the growth and propagation of blackberry cuttings under the agro-climatic conditions of Swat, with mid-July providing the most suitable conditions for optimal growth of the plant. The study pursue to answer the following research questions; *Q1. How do different planting dates influence the sprouting and survival percentages of blackberry cuttings? Q2. To what extent does planting date affect critical growth parameters, including number of leaves, number of roots, shoot length, and root length?* However, the primary aim of the current research study was to determine the most suitable planting date for the successful growth and propagation of blackberry cuttings under the agro-climatic conditions of Swat. Moreover, the main objectives of the study were (1) to evaluate the effect of different planting dates on the sprouting and survival percentages of blackberry cuttings, (2) to assess the influence of suitable planting date on key growth parameters such as number of leaves, number of roots, shoot length and root length, and (3) to identify the optimal planting date that ensures the maximum growth, and propagation success rate under the agro-climatic conditions of Swat. Further, the findings of the study are planned to provide practical evidence base recommendations to local growers, young researchers, and horticulture practitioners to promote blackberry cultivation and propagation in the region.

Methodology

A research study entitled “Influence of different planting dates on the growth of blackberry cuttings under the agro-climatic condition” was conducted in 2016 at the Agriculture Research Institute, Mingora, and Swat, Pakistan. The softwood cuttings of blackberry were selected for propagation.

Experimental Materials and Design

The dormant pencil-sized cuttings, approximately 20cm in length, were prepared from healthy blackberry plants and planted in a growth medium under shade-house conditions. High humidity was maintained to minimize water loss through transpiration. A total of 120 cuttings were used, with ten cuttings per treatment, planted on four different propagation dates (D1: 15 July, D2: 25 July, D3: 4 August, and D4: 14 August). The experiment was arranged in a Randomized Complete Block Design (RCBD) with a single factor (propagation date) and three replications. Within each block ten cuttings were assigned to each propagation date, so a total to 30 cuttings per block and 120 cuttings overall.

Data Collection

Blackberry is an important medicinal and economic fruit plants of KP-Pakistan especially of district Swat. The survey was carried out during the year of 2016. The data were collected on various parameters of the berry such as sprouting period, survival period, number of leaves per plant, number of roots per plant, shoot length (cm), and root length (cm).

Parameters studied and method of recording data

During the experiment data was collected on the following parameters.

Sprouting percentage

Sprouting percentage was calculated by observing emergence in five randomly selected plants per replication and then the average was calculated by equation 1.

$$\text{Sprouting percentage (\%)} = \frac{\text{Number of cuttings sprouted}}{\text{Total number of cuttings planted}} \times 100 \quad \text{Equation...1}$$

Survival percentage

After complete sprouting and successful growth of these cuttings at the end of growing season for each treatment in each replication plant survival percentage was calculated by equation 2.

$$\text{Survival percentage (\%)} = \frac{\text{Number of plants survived}}{\text{Total number of plants Planted}} \times 100 \quad \text{Equation...2}$$

Number of roots per plant: Roots were counted in all plants, and average were calculated for each treatment and replication

Root length (cm): The length of roots from five randomly selected plants per replication was measured and averaged.

Shoot length (cm): The length of newly sprouted shoots from five randomly selected plants per replication was recorded using a measuring tape and averaged.

Number of leaves per plant: Leaves were counted on five randomly selected plants per replication, and the mean was calculated.

Statistical Analysis

All recorded data were subjected to analysis of variance (ANOVA) using the RCBD model. Mean separation was performed using the Least Significant Difference (LSD) test at the 5% probability level, where differences were statistically significant. Statistical analyses were performed by using STATISTIX software version 8.1 (Jan et al., 2022).

Results and Discussion

The results of the study entitled “Influence of different planting dates on growth of blackberry cutting under the agro-climatic condition” are presented and discussed below.

Sprouting percentage

The results revealed that planting dates had a non-significant effect on sprouting percentage. The mean value comparison highlight that the maximum sprouting (73.33%) was observed in cuttings planted on 15th July, followed by (70.00%) cuttings planted on 4th August. The lowest sprouting (50.00%) was recorded in cuttings planted on 25th July. However, the differences were statistically non-significant ($P = 0.4449$) (Table. 1 & 2; Figure. 1). The research findings are supported by Irshad et al. (2014), who studied the effect of planting dates and media on the growth of kiwi plant cuttings, and Ahmad et al. (2012), who observed the effect of different budding time of peach plant.

Table 1. Sprouting percentage and mean value of plant replication under different planting dates.

Planting Dates	R1	R2	R3	Mean
15 th July	70%	80%	60%	73.333
25 th July	30%	70%	50%	50.000
04 th Aug	70%	70%	80%	70.000
14 th Aug	90%	70%	40%	66.667

Table 2. Analysis of variance for sprouting percentage of replication under various planting dates.

Source	DF	SS	MS	F	P
R	2	450.00	225.000		
PD	3	966.67	322.222	1.03	0.4449
Error	6	1883.33	313.889		
Total	11	3300.00	CV	27.26	

Note: Abbreviations; DF = Degree of freedom, SS = Sum of square, MS = Mean Square, F = Ratio of variance, P = probability value

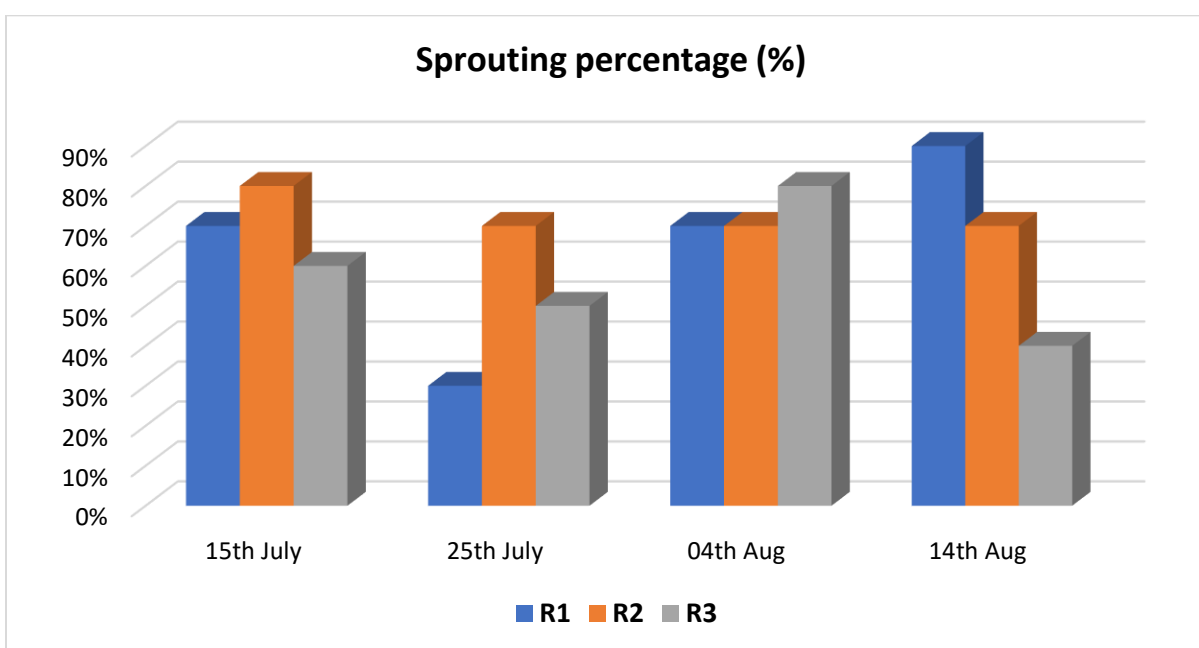


Figure. 1 Comparison of sprouting percentage among various planting dates and replications.

Survival Percentage

The planting dates did not significantly influence survival percentage. The mean values highlight that the highest survival percentage (66.67%) was observed in cuttings planted on 15th July, followed by (63.33%) in cuttings planted on 4th August. The lowest percentage (46.67%) was recorded in cuttings planted on 25th July. Although, differences were evident, they were statistically non-significant ($P = 0.4547$) (Table. 3 & 4; Figure. 2). The study findings are supported by Irshad et al. (2014), who observed the effect of planting dates on the growth of kiwi plant cuttings.

Table. 3 Survival percentage and mean value of plant replication under different planting dates.

PLANTIND DATES	R1	R2	R3	Mean
15 th July	60%	60%	80%	66.667
25 th July	30%	60%	50%	46.667
04 th Aug	70%	70%	50%	63.333
14 th Aug	70%	70%	40%	60.000

Table. 4 Analysis of variance for survival percentage under various planting dates.

Source	DF	SS	MS	F	P
R	2	216.67	108.333		
PD	3	691.67	230.556	1.00	0.4547
Error	6	1383.33	230.556		
Total	11	2291.67	CV	25.66	

Note: Abbreviations: DF = Degree of freedom, SS = Sum of square, MS = Mean Square, F = Ratio of variance, P = probability value

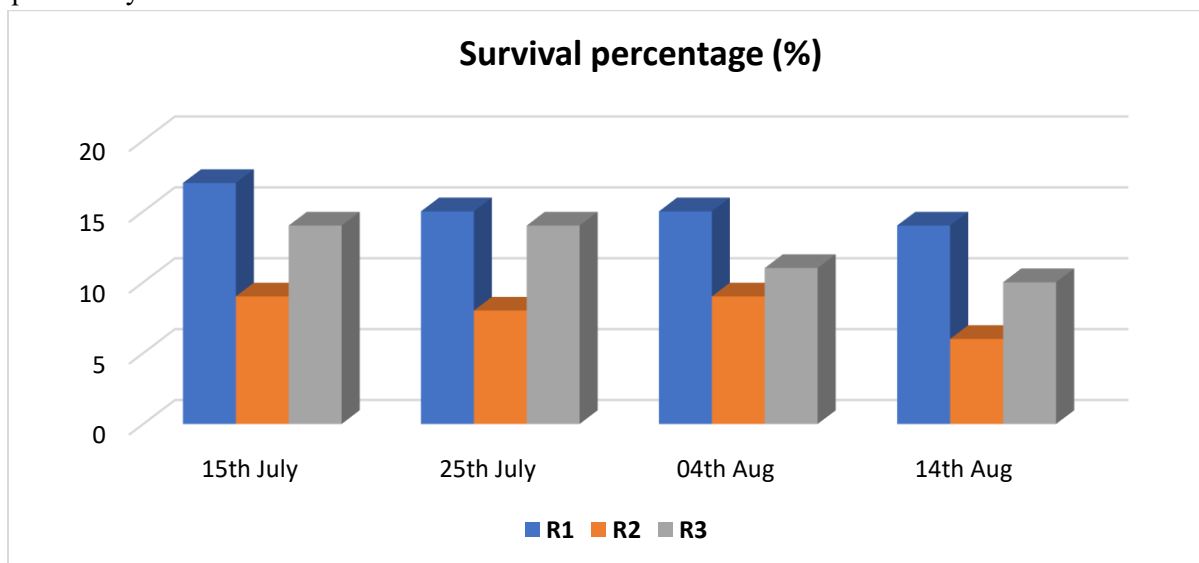


Figure 2. Comparison of survival percentage among various planting dates and replications

Number of Leaves per Plant

The planting dates significantly influenced the number of leaves per plant. The highest mean value of leaf number (9.33) was recorded in cuttings planted on 15th July, followed by 6.33 in cuttings planted on 4th August. The lowest value (0.00) was recorded in cuttings planted on 14th August. The higher leaf production in mid-July plantings may be due to early sprouting, which resulted in greater shoot elongation and consequently higher leaf numbers ($P = 0.0145$) (Table. 5 & 6; Figure. 3). However, similar results were reported by Yong and Kisum (1996), who observed maximum leaf numbers in plants with enhanced underground and aerial growth.

Table 5. Number of leaves and mean value of plant replication under different planting dates

PLANTIND DATES	R1	R2	R3	Mean
15 th July	9	13	6	9.333a
25 th July	6	6	4	5.333a
04 th Aug	7	4	8	6.333a
14 th Aug	0	0	0	0.000ab
LSD	-	-	-	1.9003

Table 6. Analysis of variance for number of leaves under various planting dates.

Source	DF	SS	MS	F	P
Row	2	3.500	1.7500		
Planting	3	136.250	45.4167	8.38	0.0145
Error	6	32.500	5.4167		
Total	11	172.250	CV	44.3	

Note: Abbreviations: DF = Degree of freedom, SS = Sum of square, MS = Mean Square, F = Ratio of variance, P = probability value

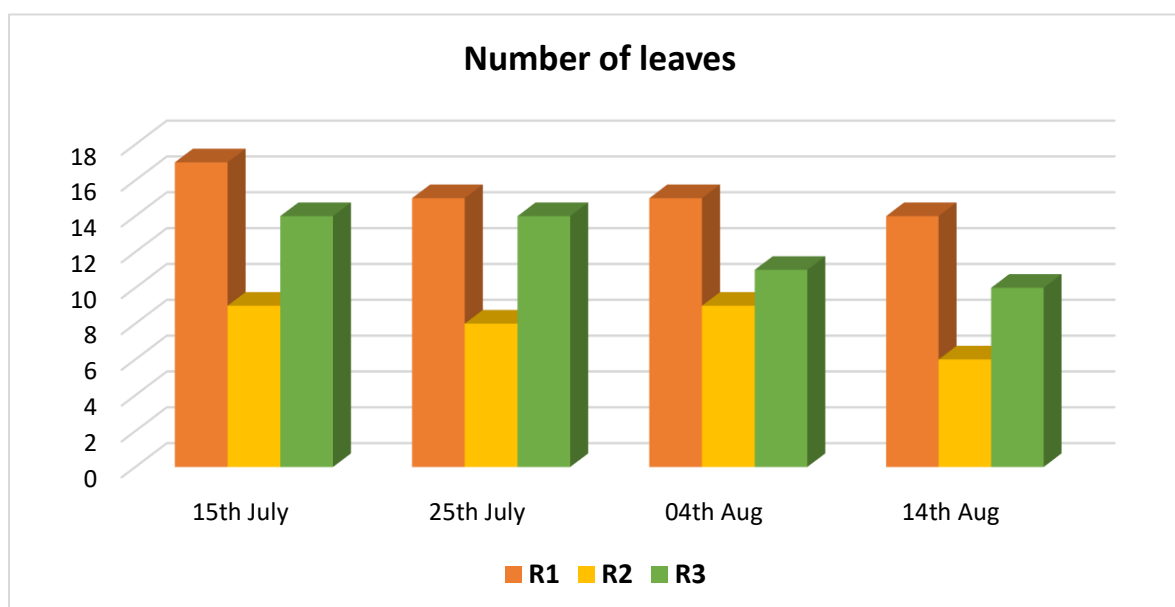


Figure. 3 Comparison of the number of leaves among replication across different planting dates

Number of Roots per Plant

The planting dates significantly affected number of roots per plant. The maximum number of roots (13.33) was recorded in cuttings planted on 15th July, followed by 12.33 in cuttings planted on 25th July. The lowest root number (10.00) was observed in cuttings planted on 14th August. The greater root number in July plantings may be attributed to early sprouting, which provided more time for root development ($P = 0.0302$) (Table. 7 & 8; Figure. 4). However, similar findings were reported by Sajid et al. (2012), who observed higher root numbers in *Platanus orientalis* with early sprouting and enhanced vegetative growth.

Table 7. Number of roots and mean value of plant replication under different planting dates.

PLANTIND DATES	R1	R2	R3	Mean
15 th July	17	9	14	13.333a
25 th July	15	8	14	12.333 a
04 th Aug	15	9	11	11.667ab
14 th Aug	14	6	10	10.000b
LSD	-	-	-	0.80501

Table 8. Analysis of variance for number of roots under various planting dates.

Source	DF	SS	MS	F	P
Row	2	106.167	53.0833		
Planting	3	17.667	5.8889	6.06	0.0302
Error	6	5.833	0.9722		
Total	11	129.667	CV	8.33	

Note: Abbreviations: DF = Degree of freedom, SS = Sum of square, MS = Mean Square, F = Ratio of variance, P = probability value

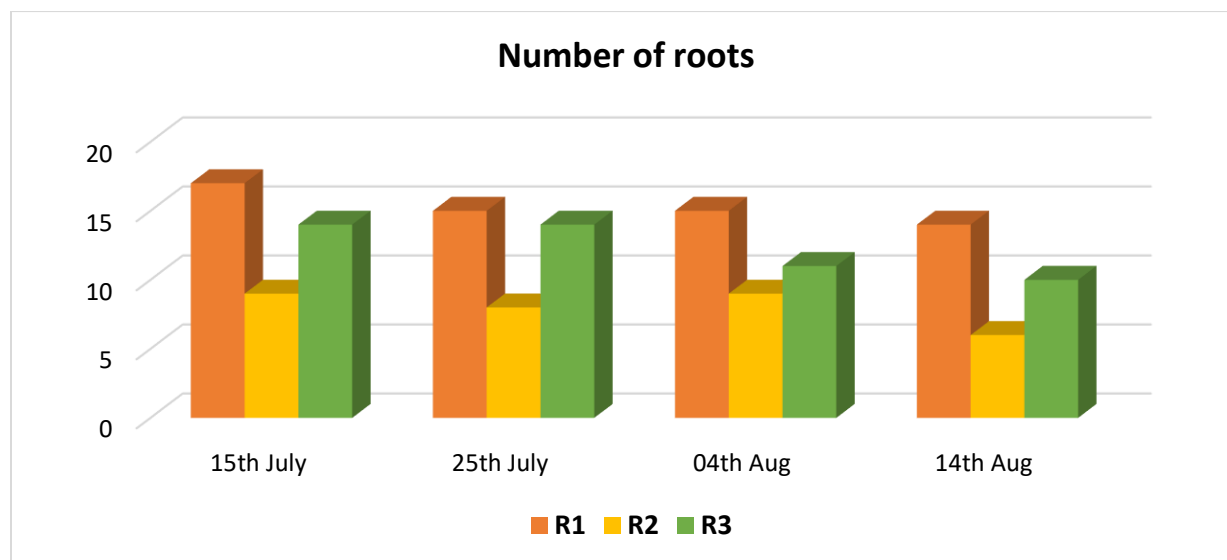


Figure. 4 Comparison of the number of roots among replication across different planting dates.

Shoot Length (cm)

The maximum shoot length (27.17 cm) was observed in cuttings planted on 15th July, followed by 18.07cm in cuttings planted on 4th August. The lowest shoot length (0.00cm) was recorded in cuttings planted on 14th August. The enhanced shoot elongation in mid-July plantings can be attributed to early sprouting and longer vegetative growth duration. Planting dates significantly influenced shoot length with ($P = 0.0477$) (Table. 9 & 10). Though, similar results were reported by Khan et al. (2016), who studied maximum aerial growth in plants established earlier in the season.

Table 9. Shoot length (cm) and mean value of plant replication under different planting dates.

PLANTIND DATES	R1	R2	R3	Mean
15 th July	16.7cm	34.8cm	30cm	27.167a
25 th July	8cm	15cm	5.7cm	9.5667ab
04 th Aug	23.2cm	4cm	27cm	18.067ab
14 th Aug	0.00cm	0.00cm	0.00cm	0.000 b
LSD	-	-	-	7.4464

Table 10. Analysis of variance for shoot length (cm) under various planting dates.

Source	DF	SS	MS	F	P
Row	2	27.76	13.878		
Planting	3	1215.58	405.193	4.87	0.0477
Error	6	499.04	83.174		
Total	11	1742.38	CV	66.57	

Note: Abbreviations: DF = Degree of freedom, SS = Sum of square, MS = Mean Square, F = Ratio of variance, P = probability value

Root Length (cm)

The statistical analysis revealed that planting dates had a non-significant effect on root length. The maximum root length (14.00cm) was recorded in cuttings planted on 15th July, followed by 12.50cm in cuttings planted on 25th July. The lowest root length (3.91cm) was recorded in cuttings planted on 14th August. Despite these variations, the results were statistically non-significant ($P = 0.0477$) (Table. 11 & 12). However, similar findings were reported by Khan et al. (2016), who studied the effect of timing and bud numbers on growth of dwarf umbrella tree cuttings.

Table 11. Root length (cm) and mean value of plant replication under different planting dates

PLANTIND DATES	R1	R2	R3	Mean
15 th July	28.5cm	4.5cm	9cm	14.0
15 th July	24cm	11cm	2.5cm	12.5
04 th Aug	8.5cm	3cm	6.5cm	6.0
14 th Aug	2.93	6.1cm	2.7cm	3.9
LSD	-	-	-	NS

Table. 12 Analysis of variance for root length (cm) under various planting dates

Source	DF	SS	MS	F	P
R	2	285.908	142.954		
PD	3	216.348	72.116	1.46	0.3170
Error	6	296.813	49.469		
Total	11	799.069	CV	77.27	

Note: Abbreviations: DF = Degree of freedom, SS = Sum of square, MS = Mean Square, F = Ratio of variance, P = probability value

Conclusion

In the light of findings of the present study, the following conclusion were drawn. We conclude that planting date plays a critical role in the successful growth and propagation of blackberry cuttings under the agro-climatic conditions of Swat. Although, cutting planted on 15th July highlight the highest overall numerical performance, the improvement was not uniform across all the traits. The statistical analysis revealed that number of leaves ($P = 0.0145$), number of roots ($P = 0.0302$), and shoot length ($P = 0.0477$) were significantly affected by planting date. While, parameters such as sprouting percentage ($P = 0.4449$), survival percentage ($P = 0.4547$), and root length ($P = 0.3170$) were non-significantly affected. The mid-July climatic conditions, characterized by moderate temperatures and adequate humidity provided an optimal environment for root initiation and shoot development, whereas delayed planting particularly after early August, resulted in poor growth and establishment. Therefore, it can be concluded that 15th July is the most suitable planting date for blackberry cuttings in Swat. These findings provide valuable guidance for farmers and horticulturists aiming to improve blackberry cultivation and highlight the importance of timely planting in maximizing propagation success. We recommend that further studies on the impact of multi-location and multi-season are needed to support the current research work under the agro-climatic conditions.

Declaration

Acknowledgment: The author is grateful to the Agriculture Research Institute, Mingora Swat for providing field and water facilities for experimental process. Also, the author is thankful to the GDC Barang Bajaur for providing support, and facilities in the preparation of manuscript.

Funding: This study received no external funding.

Conflict of interest: The authors declare no conflict of interest.

Ethics approval/declaration: Not Applicable

Consent to participate: All the authors gave consent for participation.

Consent for publication: All authors consent to the publication of this manuscript.

Data availability Statement: Data sharing is not applicable to this article, as the available data mentioned in main tables.

Author's contribution: Misbah Uddin¹ and Farman Ullah² conceived the main idea; Sammiya Jabeen⁵, Farman Ullah³, Muhammad Amjad⁶ and Asad Ullah³ designed the methodology; Misbah Uddin¹, Muhammad Usama³, and Farman Ullah³ helps in data collection; Tariq Jamal⁵, and Sammiya Jabeen⁵ design references; Misbah Uddin¹, Farman Ullah², Waqar Ahmad³ and Sunbal Jehan⁴ helps in scientific writing, critical review and final approval of the draft.

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RESEARCH ARTICLE

Effect of Post-Harvest Calcium Chloride Concentrations on Physio-Chemical Quality and Shelf Life of Mango (*Mangifera indica* L. cv. Calcuttia)

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Received: 05 May, 2025, Accepted: 08 December, 2025, Published: 14 December, 2025

Abstract

Mango experiences substantial post-harvest losses in South Asia due to rapid ripening, which shortens shelf life and reduces fruit quality. Post-harvest calcium chloride (CaCl_2) treatment is a low-cost approach known to enhance cell wall stability, delay softening, and reduce decay; however, the optimum concentration for 'Calcuttia' mango has not been well established. A laboratory experiment was conducted at the Horticulture Laboratory, College of Natural Resource Management, from 20 June to 3 July 2024 to evaluate the effect of different CaCl_2 concentrations on post-harvest quality and shelf life of mango (*Mangifera indica* L. cv. Calcuttia). Mature-green fruits were immersed for 10 min in CaCl_2 solutions at 0, 200, 400, 600, 800, 1000, and 1200 ppm, arranged in a completely randomized design with three replications. During ambient storage, physiological weight loss, pulp colour development, decay incidence, firmness, titratable acidity, total soluble solids, and shelf life were assessed. Mangoes treated with 800 ppm CaCl_2 exhibited the lowest physiological weight loss, reduced decay, higher firmness, and extended shelf life of up to 13 days, compared with 9 days in untreated fruits. Higher concentrations did not provide additional benefits, while lower concentrations were less effective. Total soluble solids were not significantly affected by CaCl_2 treatments. The results indicate that a 10-min post-harvest dip in 800 ppm CaCl_2 effectively delays ripening and enhances storage life of 'Calcuttia' mango without adversely affecting sweetness. Further evaluation under commercial handling and distribution conditions is recommended to confirm its practical applicability and compatibility with other non-chemical post-harvest treatments.

Keywords: CaCl_2 ; Post-harvest treatment; Physio-chemical properties; Quality, Shelf life

Introduction

Mango (*Mangifera indica* L.), popularly known as the "King of fruits," is one of the most important tropical fruits cultivated and consumed worldwide due to its unique flavor, attractive appearance, high nutritional value, and medicinal properties (Prasad et al., 2019; Jabbar et al., 2011). It belongs to the family Anacardiaceae and is considered one of the most widely grown fruit crops after banana and papaya (Kumah & Appiah, 2011). Mango fruits are rich in carbohydrates, vitamins A and C, minerals, antioxidants, and dietary fiber, making them highly valued for fresh consumption as well as for processing into products such as juice, pulp, nectar, pickles, jams, and dried slices. Owing to its wide adaptability, diversity in taste, color, and cultivar types, mango has gained global acceptance and economic importance.

In Nepal, mango is one of the most commercially important fruit crops, particularly dominant in the Terai and inner Terai regions. According to MoALD (2022), mango occupies the largest fruit-growing area in the country with an area of 43,688 ha and a production of 466,266 tons, with an average productivity of 10.67 t/ha (Pandey et al., 2023). In Madhesh Province, mango cultivation contributes significantly to farmers' income and local markets. Among the locally grown varieties, 'Calcuttia' is a late-season cultivar widely available in the region. It is characterized by medium-sized trees and fruits, oblong shape, green peel, yellow pulp, relatively firm texture, high yield potential, and comparatively better storage capacity. Despite these favorable traits, the commercial potential of 'Calcuttia' mango remains constrained by post-harvest losses under ambient storage conditions.

Mango is a climacteric fruit that continues to respire actively after harvest, exhibiting a sharp rise in respiration rate and ethylene production during ripening (Nacional et al., 2024). These physiological processes accelerate softening, color development, sugar accumulation, organic acid degradation, and ultimately senescence. Under the warm ambient conditions prevalent in Nepal, mango fruits ripen rapidly, resulting in a very short shelf life, high susceptibility to mechanical injury, microbial infection, and substantial post-harvest decay (Agric, 2021; Prasad et al., 2019). Post-harvest losses are considered one of the major challenges limiting mango commercialization, market expansion, and profitability, particularly in developing countries like Nepal where cold-chain infrastructure and advanced storage technologies are limited (Pandey et al., 2023).

The primary causes of post-harvest deterioration in mango include high metabolic activity, moisture loss through transpiration, enzymatic breakdown of cell wall components, and increased vulnerability to pathogens (Shirzadeh et al., 2011). Post-harvest decay is widely recognized as the major factor restricting storage life in many fresh horticultural commodities (Irtwange, 2006). Therefore, delaying ripening, reducing respiration and ethylene production, maintaining membrane integrity, and minimizing oxidative metabolism are essential strategies for extending shelf life and preserving fruit quality under ambient storage conditions (Shahin et al., 2020). Various post-harvest treatments such as hot water dips, fungicides, growth regulators, edible coatings, and chemical retardants have been explored to slow ripening and reduce losses in mango (Jabbar et al., 2011; Kumah & Appiah, 2011). However, many chemical treatments raise concerns related to food safety, consumer acceptance, environmental impact, and cost. In this context, calcium-based treatments have emerged as a safer, cost-effective, and eco-friendly alternative for post-harvest management of fruits.

Calcium is an essential plant nutrient known for its vital role in maintaining cell wall structure, membrane stability, and overall tissue integrity. Calcium ions (Ca^{2+}) form cross-links with pectic substances in the cell wall, thereby strengthening cell walls, delaying softening, and reducing membrane permeability (Shirzadeh et al., 2011). Numerous studies have demonstrated that calcium application reduces respiration rate and ethylene production, thereby slowing ripening and senescence in fruits such as mango, tomato, apple, peach, strawberry, and guava (Daundasekera, 2016; Rajkumar et al., 2019; Eroğul et al., 2024). Among different calcium salts, calcium chloride (CaCl_2) is the most commonly used due to its high solubility, effectiveness, low cost, and ease of application. Post-harvest calcium chloride treatments have been reported to improve firmness, reduce physiological weight loss, delay skin and pulp color development, maintain titratable acidity, suppress decay incidence, and extend shelf life without adversely affecting sweetness or consumer acceptability (Joyce et al., 2001; Karemera & Habimana, 2014; Chepngeno et al., 2016). Calcium chloride has also been shown to reduce post-harvest diseases and control microbial spoilage by maintaining fruit structural integrity and delaying tissue breakdown (Rajkumar et al., 2019). However, excessive concentrations of CaCl_2 may cause surface injury, shriveling, or quality deterioration, indicating the importance of optimizing concentration levels for specific fruit cultivars (Shirzadeh et al., 2011).

Although several studies have documented the beneficial effects of calcium chloride on mango and other fruits, information regarding the optimum concentration of CaCl_2 for post-harvest treatment of the locally important 'Calcuttia' mango under ambient Nepalese conditions remains limited. Most previous studies have focused on other mango cultivars or different agro-climatic regions, and the response of fruit quality parameters to varying CaCl_2 concentrations can differ significantly depending on cultivar, maturity stage, and storage environment. Therefore, a clear research gap exists in identifying an effective, safe, and economically feasible calcium chloride concentration for extending shelf life and maintaining the post-harvest quality of 'Calcuttia' mango in Madhesh Province. Addressing this gap is crucial for reducing post-harvest losses, improving fruit marketability, and enhancing farmers' income through improved post-harvest management practices.

Therefore, the present study was undertaken to evaluate the effect of different concentrations of calcium chloride as a post-harvest dip treatment on the physio-chemical characteristics and shelf life of mango (*Mangifera indica* L. cv. Calcuttia) under ambient storage conditions. The specific objectives of the study were to assess the influence of CaCl_2 concentrations on physiological weight loss, firmness, titratable acidity, total soluble solids, TSS:TA ratio, pulp color development, rotting percentage, organoleptic quality, and overall shelf life of mango fruits. We hypothesized that post-harvest application of calcium chloride would significantly delay ripening, reduce post-harvest losses, and extend shelf life of 'Calcuttia' mango, with an optimum concentration providing maximum benefit without negatively affecting fruit quality. The findings of this research are expected to provide practical recommendations for farmers, traders, and stakeholders for adopting an efficient and low-cost post-harvest treatment to improve mango quality and reduce losses in Nepal.

Materials And Methods

The investigation entitled Effect of different concentration of Calcium chloride (CaCl_2) as Postharvest treatment on quality and shelf-life of Mango (*Mangifera indica* L.)" was conducted from 2081/03/07 to 2081/03/21. The following were the details of the experimental materials, techniques and procedures employed during the study.

Experiment site (Location)

This research experiment was carried out in the Laboratory of College of Natural Resource Management, AFU, Bardibas(Mahottari). Mahottari district is one of the eight districts of province -2, which falls in the Terai region of Madhesh province in Nepal at latitude $26^\circ 52' 22.08''$ North, longitude $85^\circ 49' 42.96''$ East.

Selection of cultivar

The locally available variety of mango (Calcuttia) was selected for the experiment.

Design of experiment

The experiment was laid out in CRD (Completely Randomized Design) with 7 treatments and each were replicated thrice (3 times). Total there were 21 experimental units. Figure 1 shows the map of mahottari district. Figure 2 shows the map of Nepal showing the study area.



Figure 1: Map of Mahottari District

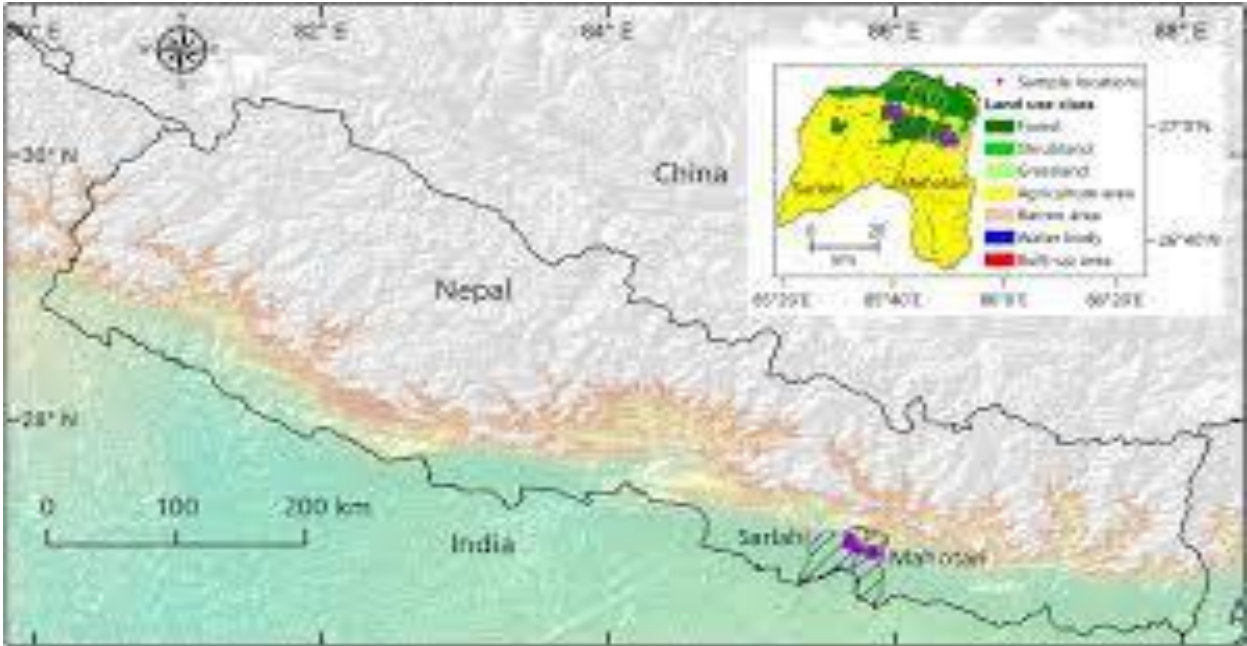


Figure 2: Map of Nepal showing the study area

Experimental (Treatment) details

Required concentration of Calcium chloride were weighed using a digital scale. Then it was dissolved in desired volume of distilled water to produce solutions containing 200 ppm, 400 ppm, 600ppm, 800ppm, 1000ppm and 1200 ppm of CaCl_2 , respectively. After treatment imposition, the physiological and chemical parameters of fruits were observed in 2 days interval until their shelf life ended in order to determine the different physio-chemical changes in the fruits during storage. A total of 21 experimental units were made.

The treatment details along with their concentration were as follows.

T₁ = Distilled water (Control)

T₂ = Calcium Chloride (CaCl_2) @ 200 ppm

T₃ = Calcium Chloride (CaCl_2) @ 400 ppm

T₄ = Calcium Chloride (CaCl_2) @ 600 ppm

T₅ = Calcium Chloride (CaCl_2) @ 800 ppm

T₆ = Calcium Chloride (CaCl_2) @ 1000 ppm

T₇ = Calcium Chloride (CaCl_2) @ 1200 ppm

Generally, in the Nepalese market CaCl_2 is found in powdered form with 95%purity.

So, for 95% pure CaCl_2 , the solution was prepared in the following ways. Table 1 shows treatment details showing CaCl_2 concentration required in 1-liter distilled water to make solution

Table 1: Treatment details showing CaCl_2 concentration required in 1-liter distilled water to make solution

Treatments	ppm	Amount of 95% pure powdered CaCl_2	Volume of distilled water
T1	Control	-	-
T2	200 ppm	210.53 mg	1 liter
T3	400 ppm	421.05 mg	1 liter
T4	600 ppm	631.58 mg	1 liter
T5	800 ppm	842.11mg	1 liter
T6	1000ppm	1052.63 mg	1 liter
T7	1200ppm	1263.16 mg	1 liter

Lab Experiment

Two parameters viz. physical and chemical were recorded for observation at an interval of 2 days from the starting day of research till the end of shelf life of the fruits.

Physical observation includes the record of Physiological loss in weight, colour change in mango pulp, rotting% and shelf life of Mango which were taken from the non-destructive sample of each treatment combination of

every replication. Chemical observation includes the record of TSS, TA, Firmness and TSS:TA ratio which were taken from the destructive sample of every replication of each treatment combination.

▪ **Physiological loss in weight (%)**

All treated fruits were weighed using electronic digital balance on alternate days and percentage weight loss calculated by using following formula

$$\text{Weight loss (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100$$

▪ **Total soluble solids (°Brix)**

Total soluble solids (°Brix) were be determined with the help of handheld Refractometer. The measurement was done by dripping the fruit juice on the prism of the refractometer with the help of clean pipette. The reading was recorded at room temperature. The instrument was cleaned with distilled water and muslin cloth after every use.

▪ **Titrateable acidity (%)**

Titrateable acidity was determined by titrating pulp juice against 0.1N NaOH using phenolphthalein as an indicator. Titrateable acidity was calculated by using the following formula (Saini et al., 2001)

$$\text{Titrateable acidity(\%)} = \frac{N_b \times V_b \times \text{Milliequivalent wt. of predominant acid}}{\text{Volume of the sample}} \times 100 \times d.f$$

Where, N_b = normality of base

V_b = Volume of the base

d.f. = dilution factor

Milliequivalent wt. of predominant acid i.e. Malic acid = 0.067

▪ **Percentage of Rotting**

Rotting was calculated as number of rotted fruits per total number of fruits. The fruits were observed visually for rotting and calculated using formula below while Table 2 shows ranking rotting percentage.

$$\text{Rotting (\%)} = \frac{\text{No. of rotted fruit}}{\text{Total no. of fruit}} \times 100$$

Table 2: Ranking rotting percentage

Rotting%	Rank
0-20%	1
20-40%	2
40-60%	3
60-80%	4
80-100%	5

▪ **TSS: TA ratio**

It was calculated by dividing TSS percentage with the percentage of titratable acidity.

TSS: TA=Total soluble solid/Titratable acidity

▪ **Pulp color**

Color of pulp was observed and then ranked as below table 3;

Table 3: Rank	
Color	Rank
Green	1
Light yellow	2
Yellow	3
Dark yellow	4

▪ **Shelf life**

The stage where in more than 50% of stored fruits became unfit for consumption was considered as end of shelf life in that particular treatment. It was calculated by counting the period between the first day of storage after treatment to the end of the edible life of fruits.

▪ **Organoleptic test**

The visual characteristics of mango appearance for pulp color, aroma, taste, texture, flavor, etc each marked 20 were scored in daylight by a panel of 5 trained judges and then final scoring were done as below table 4.

Table 4: Ranking pulp colour	
Quality	Rating(%)
Excellent	90-100
Good	80-89
Fair	70-79
Poor	<70

Statistical methods

All collected data were entered into MS-Excel for statistical analysis and subjected to Analysis of Variance (ANOVA) using the Gen-Stat 15th edition. Duncan's Multiple Range Test at a 5% level of Significance (DMRT) was used to separate the means of treatments that were significantly different.

Result and Discussion

Physiological Weight Loss

Physiological weight loss of mango fruits increased progressively during storage in all treatments; however, the magnitude of loss differed significantly among calcium chloride concentrations. The untreated control fruits exhibited the highest cumulative weight loss throughout the storage period, while mangoes treated with 800 ppm CaCl_2 consistently showed the lowest weight loss. Other calcium-treated fruits also showed reduced weight loss

compared to the control, though the effect was less pronounced than at 800 ppm. The reduction in weight loss in CaCl_2 -treated fruits can be attributed to the role of calcium ions in strengthening cell wall structure and stabilizing membrane integrity, which reduces moisture loss through transpiration and lowers respiration rate. Calcium-mediated suppression of ethylene production further slows metabolic activity, thereby minimizing water loss and CO_2 evolution during storage. The superior performance of the 800 ppm concentration suggests that this level supplied adequate calcium to reinforce cell wall pectates without impairing gas exchange through surface deposits. These findings are in close agreement with Ferreira (2004), who reported significantly lower weight loss in calcium chloride-treated mangoes stored under ambient conditions. Similar reductions in post-harvest weight loss following calcium treatment have also been reported in pears and other climacteric fruits, emphasizing the effectiveness of calcium dips in reducing post-harvest desiccation (Mahajan and Dhatt, 2004). Table 5 shows effect of different concentration of Calcium chloride on titratable acidity of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081.

Table 5: Effect of different concentration of Calcium chloride on titratable acidity of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081

Treatment	Titratable acidity					
	Initial	3DAT	6DAT	9DAT	12DAT	Avg.
Control	0.97	0.335 ^a	0.2479 ^a	0.188 ^a	0.1362 ^a	0.3753 ^a
200ppm CaCl_2	0.97	0.395 ^{ab}	0.2993 ^{ab}	0.261 ^{ab}	0.1787 ^{ab}	0.4209 ^{abc}
400ppm CaCl_2	0.97	0.581 ^c	0.3685 ^{bc}	0.27 ^{ab}	0.2032 ^b	0.4785 ^{cd}
600ppm CaCl_2	0.97	0.402 ^{ab}	0.2836 ^{ab}	0.255 ^{ab}	0.1653 ^{ab}	0.4151 ^{ab}
800ppm CaCl_2	0.97	0.632 ^c	0.4355 ^c	0.295 ^b	0.2546 ^c	0.5174 ^d
1000ppm CaCl_2	0.97	0.462 ^b	0.3395 ^b	0.295 ^b	0.1809 ^{ab}	0.4495 ^{bc}
1200ppm CaCl_2	0.97	0.431 ^{ab}	0.2903 ^{ab}	0.234 ^{ab}	0.1876 ^{ab}	0.4227 ^{abc}
Grand mean	0.97	0.463	0.3235	0.257	0.1866	0.4399
CV%	-	12.8	13.9	17.9	14.4	7.3
Sem ($\pm$)	-	0.0343	0.026	0.0265	0.0155	0.01852
LSD	-	0.104	0.07887	0.0804	0.047	0.05616
F-value	-	***	**	NS	**	**

Note: Mean in a column with same letters are not significantly different ($p=0.05$) according to DMRT, CV=Coefficient of Variation, LSD= Least Significant Difference, SEm($\pm$)=Standard Errors of Means, *=Significantly different at ($p<0.05$), **=highly significant different at ($p<0.01$), ***=very significantly different at ($p<0.001$), NS=Non-significant., DAT= Days after treatment.

Titratable Acidity

Titratable acidity of mango fruits declined steadily during storage across all treatments; however, calcium chloride-treated fruits retained significantly higher acidity compared to the untreated control. Among the treatments, mangoes treated with 800 ppm CaCl_2 maintained the highest titratable acidity throughout the storage period, whereas the control fruits showed the most rapid decline. The slower reduction in acidity in calcium-treated fruits indicates delayed ripening and reduced metabolic activity. Organic acids such as malic and citric acid are utilized as respiratory substrates during ripening, and calcium treatments are known to suppress respiration by stabilizing cellular membranes and slowing ethylene-mediated physiological processes. As a result, the rate of acid degradation is reduced, allowing calcium-treated fruits to retain higher acidity and better flavor balance. These results are consistent with the findings of Singh et al. (2017), who observed higher titratable acidity retention in calcium-treated peach fruits during both ambient and cold storage. Similar trends were also reported

by Shirzadeh et al. (2011) in apple fruits, where calcium chloride treatment delayed acid depletion by reducing respiratory metabolism. Table 6 shows the effect of different concentration of Calcium chloride on firmness of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081.

Table 6: Effect of different concentration of Calcium chloride on firmness of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081

Treatment	Firmness					
	Initial	3DAT	6DAT	9DAT	12DAT	Avg.
Control	9	5.433 ^a	4.067 ^a	3.27 ^a	2.5 ^a	4.853 ^a
200ppm CaCl ₂	9	5.433 ^a	4.067 ^a	3.67 ^{ab}	3.067 ^{ab}	5.047 ^{ab}
400ppm CaCl ₂	9	6.567 ^b	5.8 ^{bc}	4.63 ^{ab}	3.933 ^b	5.987 ^{cd}
600ppm CaCl ₂	9	5.933 ^{ab}	4.6 ^{ab}	3.83 ^{ab}	3.067 ^{ab}	5.287 ^{abc}
800ppm CaCl ₂	9	8.4 ^c	6.567 ^c	5 ^b	3.8 ^b	6.553 ^d
1000ppm CaCl ₂	9	6.667 ^b	5.7 ^{bc}	4.97 ^b	3.867 ^b	6.04 ^{cd}
1200ppm CaCl ₂	9	6.333 ^{ab}	5.5 ^{bc}	4.53 ^{ab}	3.067 ^{ab}	5.687 ^{bc}
Grand mean	9	6.395	5.186	4.27	3.329	5.636
CV%	-	4.8	8.6	12.3	11.5	4.8
Sem (±)	-	0.1759	0.2582	0.302	0.2211	0.1554
LSD	-	0.5336	0.7832	0.917	0.6707	0.4714
F-value	-	***	***	**	**	***

Note: Mean in a column with same letters are not significantly different ($p=0.05$) according to DMRT, CV=Coefficient of Variation, LSD= Least Significant Difference, SEM(±)=Standard Errors of Means, *=Significantly different at ($p<0.05$), **=highly significant different at ($p<0.01$), ***=very significantly different at ($p<0.001$), NS=Non-significant.

Total Soluble Solids

Total soluble solids (TSS) content increased gradually during storage in all treatments as ripening progressed; however, the differences among treatments were statistically non-significant. This indicates that calcium chloride treatment did not markedly influence sugar accumulation in mango fruits. The increase in TSS during storage is mainly associated with the enzymatic conversion of starch into soluble sugars, a process that continues during ripening irrespective of calcium treatment. Although CaCl₂ delays ripening by reducing respiration and ethylene production, it does not significantly interfere with carbohydrate metabolism pathways responsible for sugar formation. Consequently, calcium-treated fruits followed a ripening pattern similar to that of the control with respect to TSS accumulation, albeit at a slightly slower rate. These observations corroborate the findings of Shirzadeh et al. (2011), who reported no significant effect of calcium chloride treatment on TSS content in apples during storage. Similar results have also been documented in mango and other fruits, indicating that calcium treatments preserve sweetness while primarily influencing textural and physiological attributes.

Firmness

Fruit firmness decreased progressively during storage in all treatments, but calcium chloride-treated mangoes retained significantly higher firmness than untreated fruits. The highest firmness values throughout the storage period were recorded in mangoes treated with 800 ppm CaCl₂, while the control fruits exhibited the greatest softening. The retention of firmness in calcium-treated fruits is closely associated with calcium's role in

maintaining cell wall integrity. Calcium ions bind with pectic substances in the middle lamella to form calcium pectate, which strengthens intercellular adhesion and reduces the activity of cell wall-degrading enzymes such as polygalacturonase. This delays the breakdown of cell wall components, resulting in slower softening and extended textural quality during storage. The present findings are in agreement with Shirzadeh et al. (2011), who reported significantly higher firmness in apples treated with calcium chloride during extended storage. Similar firmness retention due to calcium application has also been reported in mango (Joyce et al., 2001) and strawberry fruits (Eroğul et al., 2024), confirming the role of calcium in delaying fruit softening.

TSS: TA Ratio

The TSS:TA ratio increased during storage in all treatments as ripening progressed; however, untreated fruits exhibited the highest ratio, while mangoes treated with 800 ppm CaCl_2 recorded the lowest values. The lower TSS:TA ratio in calcium-treated fruits reflects delayed ripening and improved retention of organic acids rather than changes in sugar content. Since TSS levels were not significantly affected by calcium chloride, the reduced ratio is primarily attributed to the higher titratable acidity maintained in treated fruits. A lower TSS:TA ratio is generally associated with better flavor balance and slower maturity progression. These results are consistent with the findings of Karemera and Habimana (2014), who observed delayed ripening and improved quality indices in CaCl_2 -treated mango fruits. Similar reductions in TSS:TA ratio following calcium treatments have been reported in other climacteric fruits, indicating prolonged shelf life and enhanced eating quality.

Rotting Percentage and Pulp Color

Significant differences were observed in rotting percentage and pulp color development among the treatments. Mangoes treated with calcium chloride, particularly at 800 ppm, exhibited the lowest rotting incidence, while the untreated control fruits showed the highest decay. Pulp color development was also significantly delayed in calcium-treated fruits, with the control fruits showing faster transition from greenish-yellow to deep yellow. The reduced decay in calcium-treated fruits can be attributed to enhanced firmness and delayed senescence, which limit tissue breakdown and reduce susceptibility to pathogen invasion. Calcium-mediated stabilization of cell walls and membranes also restricts enzymatic activity and microbial proliferation. Delayed pulp color development further reflects reduced metabolic activity and slower pigment synthesis associated with suppressed ethylene action. These findings are in agreement with Karemera and Habimana (2014), who reported improved pulp color and reduced decay in CaCl_2 -treated mango fruits. Similar reductions in post-harvest decay have also been observed in strawberry and other fruits following calcium treatments (Eroğul et al., 2024; Rajkumar et al., 2019).

Shelf Life

Shelf life of mango fruits varied significantly among treatments, ranging from 9 days in the untreated control to 13 days in mangoes treated with 800 ppm CaCl_2 . Calcium-treated fruits remained marketable for a longer period under ambient storage conditions. The extension of shelf life can be attributed to delayed ripening, reduced respiration rate, improved firmness retention, and lower decay incidence in calcium-treated fruits. By strengthening cell walls and stabilizing membranes, calcium chloride slows senescence and preserves overall fruit quality. These results are consistent with Ferreira (2004), who reported delayed ripening and extended shelf life of mangoes following post-harvest calcium chloride treatments. Similar shelf-life enhancement due to calcium application has been documented in mango and other fruits (Joyce et al., 2001; Shirzadeh et al., 2011).

Organoleptic Quality

Organoleptic evaluation revealed that calcium chloride–treated mangoes received higher sensory scores compared to untreated fruits. Among the treatments, mangoes treated with 800 ppm CaCl_2 achieved the highest overall acceptability scores, while the control fruits recorded the lowest scores. The improved sensory quality of calcium-treated fruits is associated with better firmness, delayed ripening, reduced decay, and a more balanced sugar–acid ratio. Calcium treatments preserve desirable textural and flavor attributes without negatively affecting sweetness, resulting in enhanced consumer acceptability. These findings are in line with previous studies reporting improved sensory quality in mango and other fruits following calcium chloride application (Karemera & Habimana, 2014). Table 7 and table 8 are presented below. Figure 3 shows the effect of different concentration of calcium chloride on physiological loss in weight of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081. Figure 4 shows the effect of different concentration of Calcium chloride on total soluble solid of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081. Figure 5 shows the effect of different concentration of Calcium chloride on shelf life of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081. Figure 6 shows the effect of different concentration of Calcium chloride on organoleptic test of taste of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081.

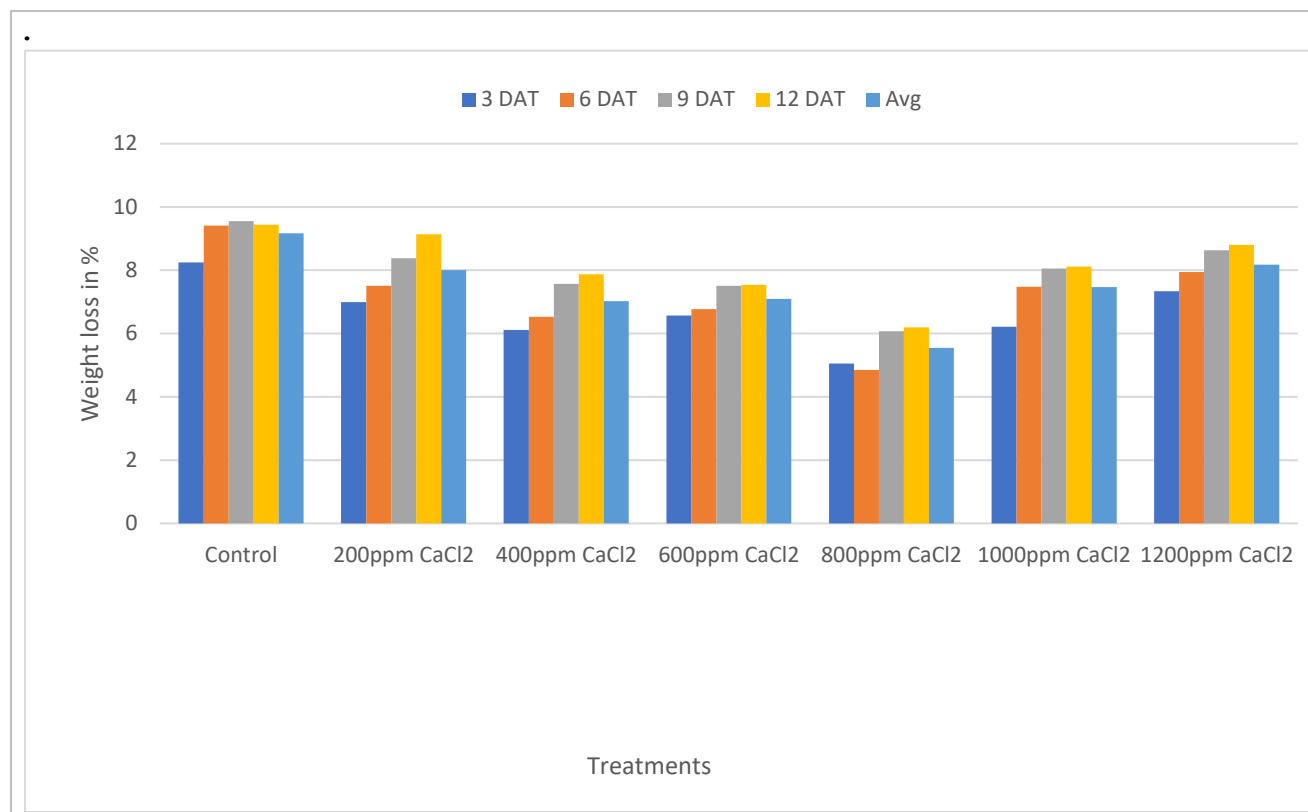


Figure 3: Effect of different concentration of calcium chloride on physiological loss in weight of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081

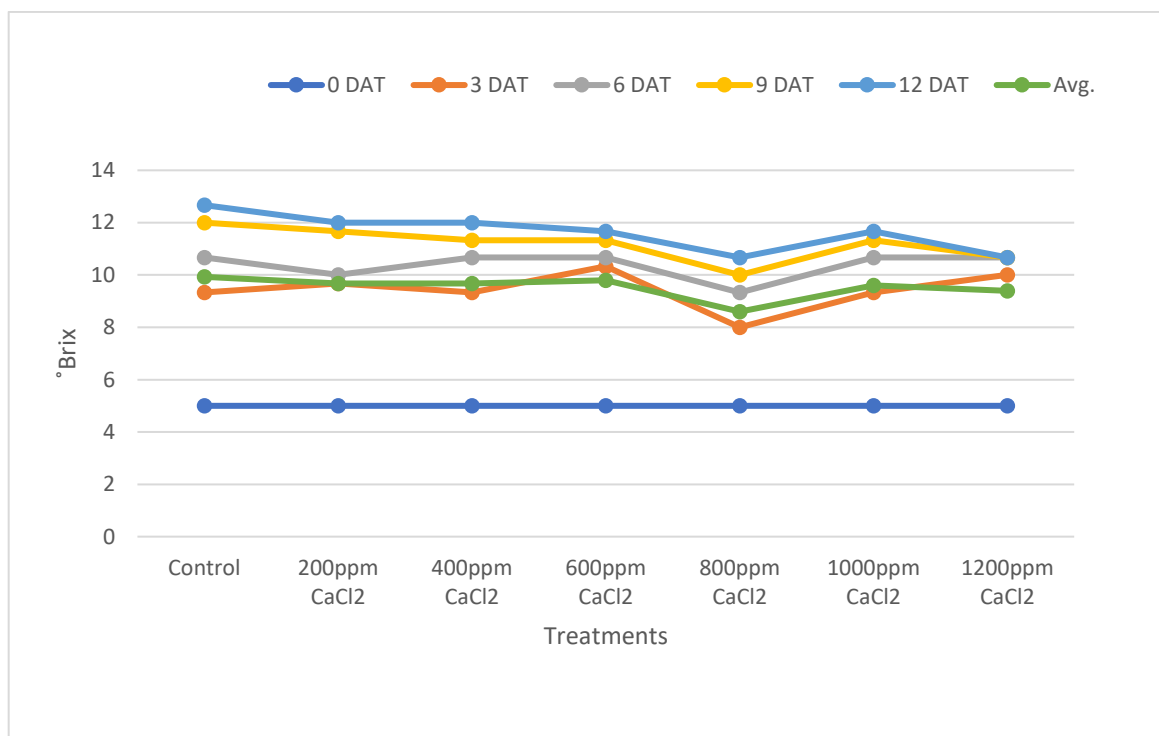


Figure 4: Effect of different concentration of Calcium chloride on total soluble solid of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081

Table 7: Effect of different concentration of Calcium chloride on TSS:TA ratio of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081

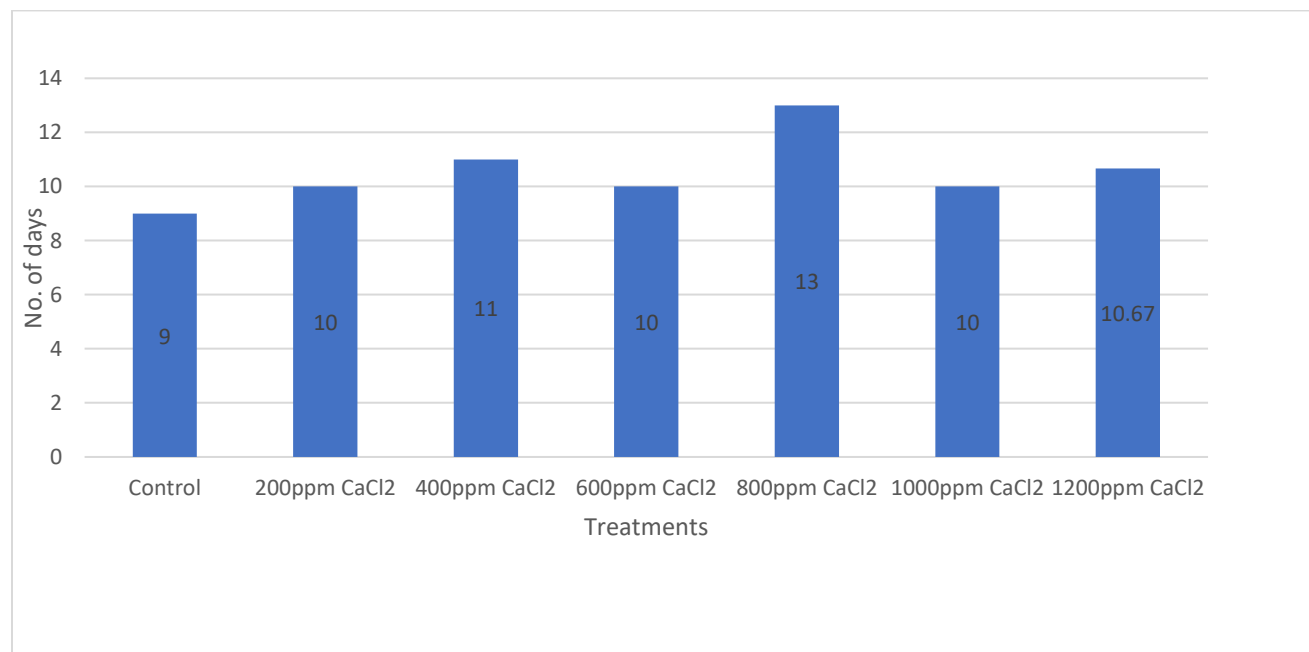
Treatment	TSS: TA Ratio					
	Initial	3DAT	6DAT	9DAT	12DAT	Avg.
Control	5.155	27.88 ^d	43 ^c	65 ^b	93 ^c	46.8 ^c
200ppm CaCl ₂	5.155	26.11 ^{cd}	35.7 ^{bc}	47.9 ^a	69.7 ^b	36.9 ^b
400ppm CaCl ₂	5.155	16.13 ^{ab}	28.9 ^{ab}	42 ^a	59.3 ^{ab}	30.3 ^{ab}
600ppm CaCl ₂	5.155	25.76 ^{cd}	37.7 ^{bc}	44.6 ^a	70.9 ^b	36.8 ^b
800ppm CaCl ₂	5.155	12.64 ^a	21.4 ^a	34.2 ^a	41.9 ^a	23.1 ^a
1000ppm CaCl ₂	5.155	20.18 ^{bc}	32.5 ^{bc}	39.4 ^a	66.5 ^b	32.8 ^b
1200ppm CaCl ₂	5.155	23.18 ^{cd}	36.8 ^{bc}	45.5 ^a	57.9 ^{ab}	33.7 ^b
Grand mean	5.155	21.7	33.7	45.5	65.6	34.3
CV%	-	17.1	16.9	16.9	15	14
SEm(±)	-	2.143	3.29	4.45	5.66	2.78
LSD	-	6.499	9.99	13.5	17.18	8.42
F-value	-	***	**	**	***	**

Mean in a column with same letters are not significantly different ($p=0.05$) according to DMRT, CV=Coefficient of Variation, LSD= Least Significant Difference, SEm($\pm$)=Standard Errors of Means, *=Significantly different at ($p<0.05$), **=highly significant different at ($p<0.01$), ***=very significantly different at ($p<0.001$), NS=Non-significant.

Table 8: Effect of different concentration of Calcium chloride on rotting % and pulp color of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081

Treatment	Rotting %	Pulp color
Control	2.4 ^c	2.33 ^{ab}
200ppm CaCl ₂	1.933 ^{bc}	2.2 ^a
400ppm CaCl ₂	1.667 ^{ab}	2.333 ^a
600ppm CaCl ₂	2.333 ^c	2.2 ^a
800ppm CaCl ₂	1.2 ^a	2.667 ^b
1000ppm CaCl ₂	1.933 ^{bc}	2.2 ^a
1200ppm CaCl ₂	2.133 ^{bc}	2.333 ^a
Grand mean	1.943	2.324
CV%	13.8	5.9
SEm(±)	0.1553	0.0797
LSD	0.4711	0.2417
F-value	***	**

Mean in a column with same letters are not significantly different ($p=0.05$) according to DMRT, CV=Coefficient of Variation, LSD= Least Significant Difference, Sem (±)=Standard Errors of Means, *=Significantly different at ($p<0.05$), **=highly significant different at ($p<0.01$), ***=very significantly different at ($p<0.001$), NS=Non-significant.

**Figure 5:** Effect of different concentration of Calcium chloride on shelf life of Mango (*Mangifera indica* L.cv. Calcuttia) in Bardibas, Mahottari, 2081

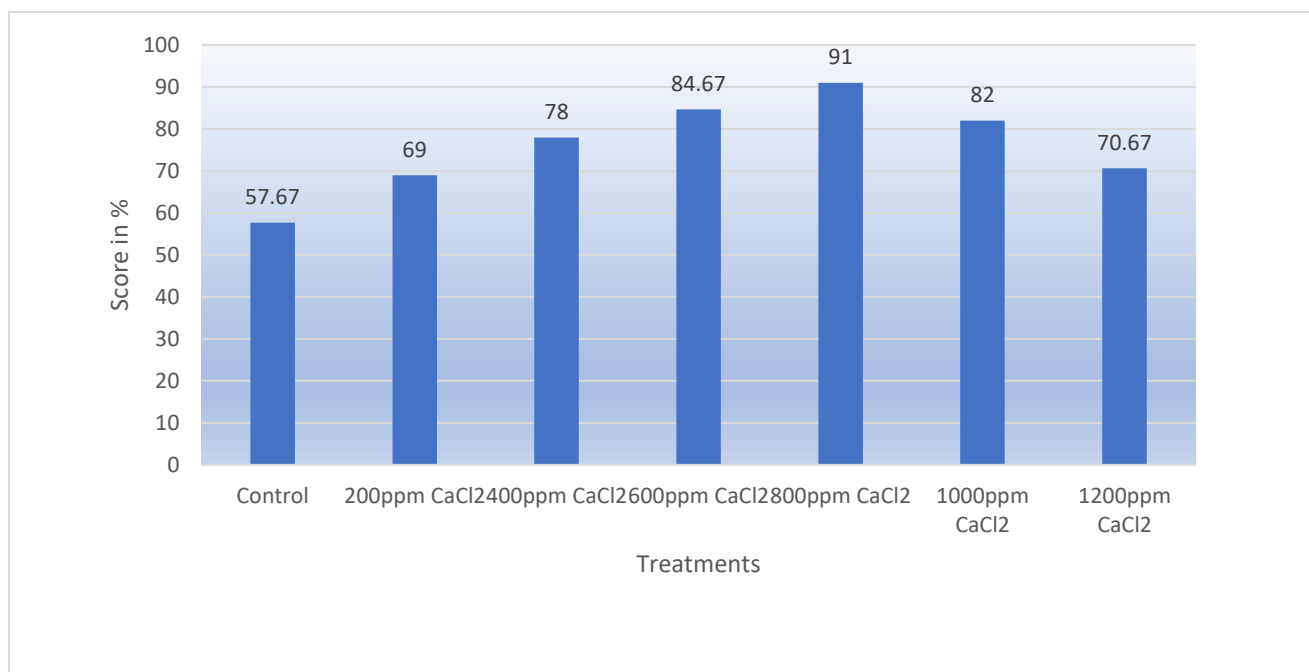


Figure 6: Effect of different concentration of Calcium chloride on organoleptic test of taste of Mango (*Mangifera indica* L. cv. Calcuttia) in Bardibas, Mahottari, 2081

Conclusion

This study demonstrates that post-harvest treatment with calcium chloride significantly affects the physio-chemical quality and storage behavior of mango (*Mangifera indica* L. cv. Calcuttia) under ambient conditions. Calcium chloride application reduced physiological weight loss, decay incidence, pulp color progression, and TSS:TA ratio, while maintaining higher firmness, titratable acidity, sensory acceptability, and extended shelf life. Total soluble solids were not significantly influenced, indicating that calcium treatment delayed ripening without adversely affecting sweetness. Among the tested concentrations, a 10-minute dip in 800 ppm CaCl₂ was the most effective, extending shelf life to 13 days compared with 9 days in untreated fruit. The beneficial effects are attributed to calcium-mediated stabilization of cell walls and membranes, suppression of respiration and ethylene production, and delayed enzymatic degradation associated with fruit softening and senescence. Higher concentrations did not result in additional quality improvements. These findings suggest that an optimized calcium chloride dip represents an effective post-harvest strategy for maintaining quality and extending shelf life of ‘Calcuttia’ mango. Further studies under commercial handling and distribution conditions are required to validate its broader applicability and to assess potential integration with other non-chemical post-harvest technologies.

Declaration

Acknowledgment: I owe much thanks to Our Principal Mr. Abhishek Shrestha, Asst. Prof. Umesh Timilsina, my mates and College of Natural Resource Management (CNRM), Bardibas for all facilities and help provided while conducting this research.

Funding: AFU

Conflict of interest: The authors declare they don't have potential conflict of interest

Ethics approval/declaration: not applicable

Consent to participate: not applicable

Consent for publication: Not required

Data availability: Data is available from the authors upon request

Authors' contribution: All authors equally contributed

AI Generative text statement: Yes (The authors have used AI for corrections)

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