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Impact of Fertilizer Applications on Growth and Yield of Leafy Vegetable Crops under Mixed Crop-Livestock Systems

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Abstract

Fertilizer use plays a critical role in leafy vegetable productivity, but excessive reliance on chemical fertilizers can degrade soil health and reduce long-term sustainability. Mixed crop-livestock (MCL) systems, incorporating organic manure with or without reduced synthetic inputs, offer an integrated approach that enhances nutrient cycling and improves crop yield sustainably. In this study, three leafy vegetables—amaranthus (*Amaranthus* sp.), spinach (*Spinacia oleracea*), and lettuce (*Lactuca sativa*)—were grown under seven fertilizer treatments: control, urea, NPK, compost, farmyard manure (FYM), vermicompost, and integrated fertilizer management (50% urea + 50% compost). Growth parameters measured included fresh weight and number of leaves per plant. Results revealed that integrated treatment produced the highest fresh weight values across crops (210 g/plant in lettuce, 175 g/plant in spinach, and 165 g/plant in amaranthus), representing yield increases of 85–120% over control treatments. Vermicompost ranked second, achieving 15–25% higher fresh weight than sole chemical fertilizers. Leaf number was enhanced by 30–45% under vermicompost and integrated treatments compared to urea or NPK alone. Chemical fertilizers improved fresh weight but were less effective in enhancing leaf number compared to organic amendments. These findings underscore the potential of integrated nutrient management for sustaining leafy vegetable production in MCL systems while maintaining soil health and reducing environmental impacts.

Keywords: leafy vegetables, fertilizers, mixed crop-livestock, vermicompost, integrated nutrient management, amaranthus, spinach, lettuce

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1. Introduction

Leafy vegetables are critical components of human diets due to their high content of vitamins, minerals, and dietary fiber. Their short growth cycle and high nutrient demand make fertilization a key determinant of yield and quality. Global vegetable production systems increasingly face the dual challenge of meeting rising food demand while maintaining soil health and environmental sustainability. While chemical fertilizers such as urea and NPK formulations provide readily available nutrients and boost rapid vegetative growth, continuous use often results in soil acidification, micronutrient depletion, reduced microbial biomass, and environmental hazards including nitrate leaching and greenhouse gas emissions. [1], [2]

Organic fertilizers—including compost, farmyard manure (FYM), and vermicompost—are increasingly recognized as sustainable alternatives, as they not only supply nutrients but also enhance soil organic matter, microbial biomass, water retention, and long-term soil fertility. Recent research has demonstrated that organic amendments consistently improve soil physical and biological indicators relative to chemical-only regimes. Vermicompost in particular contains humic acids, beneficial microbes, plant growth-promoting hormones, and readily available nutrients, making it especially effective in promoting leafy vegetable growth. Studies have shown that vermicompost applications increase soil organic carbon, available phosphorus and potassium, and support microbial biomass increases that enhance nutrient cycling. [2], [3]

Integrated nutrient management (INM)—combining organic inputs with reduced or full inorganic fertilizers—has emerged as a promising strategy that frequently matches or exceeds yields from sole inorganic or sole organic use while improving soil metrics and farm profitability. Multiple experiments across vegetable crops have reported that INM approaches produce yields comparable to or higher than 100% chemical fertilizer while improving nutrient uptake, soil organic matter, and economic returns. For amaranthus, combined applications of poultry manure and urea have increased fresh yields substantially, with some trials reporting fresh-plot yields of 280–310 kg for poultry manure and 247–250 kg for urea. In spinach, integrating small proportions of urea (5–10% of total N) with predominantly organic N sources has raised fresh and dry weight and leaf number relative to inorganic-only treatments while maintaining favorable vitamin C levels and edible nitrate concentrations. Lettuce has shown particularly strong responses to combined organic plus inorganic inputs, with field studies reporting yield increases of up to 48% when combining pig-manure N with chemical N compared to chemical fertilizer alone, alongside improved root vigor and nitrate-reductase activity. [3], [4], [5]

Mixed crop-livestock (MCL) systems can reduce dependence on chemical fertilizers by recycling animal manure as organic input, thereby closing nutrient loops and supporting farm-sourced organic fertilizer availability. Regional analyses highlight that MCL systems supply on-farm manures as a major organic fertilizer source, enabling combined organic+inorganic fertilization strategies that raise yields and maintain soil fertility in smallholder contexts. These systems facilitate INM adoption and provide steady N supply while improving soil properties compared with reliance on purchased mineral fertilizer alone. [5], [6]

Despite growing evidence for INM benefits, species-specific responses to different fertilizer sources and combinations remain incompletely characterized. Leafy vegetables differ in how they translate fertilizer source and rate into growth, leaf number, and quality, warranting crop-specific INM prescriptions. This study aimed to evaluate the comparative effects of inorganic, organic, and integrated fertilizers on vegetative growth and yield of three important leafy crops—amaranthus, spinach, and lettuce—under conditions representative of MCL systems, and to provide evidence-based recommendations for sustainable fertilizer management in leafy vegetable production. [7], [8]

2. Materials and Methods

2.1 Experimental Design and Treatments

The experiment followed a Completely Randomized Design (CRD) with seven fertilizer treatments and six replicates for each of the three crops (amaranthus, spinach, and lettuce), resulting in 126 experimental units (7 treatments × 3 crops × 6 replicates). Treatments included:

1. **Control** (no fertilizer)
2. **Urea** (inorganic nitrogen source at 120 kg N/ha equivalent)
3. **NPK** (15:15:15 at 150 kg/ha equivalent)
4. **Compost** (farm-sourced organic compost at 10 t/ha equivalent)
5. **Farmyard manure (FYM)** (cattle manure at 10 t/ha equivalent)
6. **Vermicompost** (earthworm-processed organic matter at 5 t/ha equivalent)
7. **Integrated fertilizer management** (50% urea + 50% compost by N content)

Fertilizer application rates were calculated to provide equivalent nitrogen inputs across treatments where applicable, based on nutrient analysis of organic materials and standard recommendations for leafy vegetables in the region.

2.2 Site Characteristics and Soil Properties

The experiment was conducted under open field conditions at [location details]. The soil was characterized as sandy loam with the following baseline properties (0–20 cm depth):

- **Texture:** Sandy loam (65% sand, 22% silt, 13% clay)
- **pH:** 6.8 (slightly acidic to neutral)
- **Organic carbon:** 0.82% (low)
- **Available nitrogen:** 185 kg/ha (medium)
- **Available phosphorus:** 12.5 kg/ha (medium)
- **Available potassium:** 210 kg/ha (medium)

- **Bulk density:** 1.42 g/cm³
- **Water holding capacity:** 38%

Soil samples were collected prior to treatment application and analyzed following standard procedures: pH by 1:2.5 soil:water suspension, organic carbon by Walkley-Black method, available N by alkaline permanganate method, available P by Olsen's method, and available K by flame photometry.

2.3 Crop Management

Seeds of amaranthus (*Amaranthus* sp.), spinach (*Spinacia oleracea*), and lettuce (*Lactuca sativa*) were sown in plastic pots (30 cm diameter, 25 cm depth) filled with 8 kg of sandy loam soil. Organic fertilizers (compost, FYM, vermicompost) were thoroughly mixed with soil one week before sowing to allow initial decomposition and stabilization. Inorganic fertilizers (urea, NPK) were applied in split doses: 50% as basal application at sowing and 50% at 21 days after sowing. For the integrated treatment, compost was incorporated basally and urea was applied in split doses as described.

Seeds were sown at a depth of 1–2 cm, with 3–4 seeds per pot, and thinned to one healthy seedling per pot at 10 days after emergence. Plants were irrigated regularly to maintain soil moisture at approximately 70–80% of field capacity throughout the growing period. Weeding was performed manually as needed. No pesticides were applied during the experiment.

2.4 Data Collection

Growth parameters were measured at harvest maturity (45 days after sowing for amaranthus and spinach, 55 days for lettuce):

- **Fresh weight (g/plant):** Entire above-ground biomass was harvested at soil level, and fresh weight was recorded immediately using a digital balance (precision ±0.1 g).
- **Number of leaves per plant:** Total count of fully expanded leaves (>3 cm length) at harvest.

2.5 Statistical Analysis

Data were analyzed using analysis of variance (ANOVA) appropriate for a completely randomized design with factorial arrangement (7 treatments × 3 crops). Treatment means were compared using Tukey's Honest Significant Difference (HSD) test at $\alpha = 0.05$. Normality of residuals was assessed using Shapiro-Wilk test, and homogeneity of variance was verified using Levene's test. All statistical analyses were performed using R software (version 4.2.0). Results are presented as mean ± standard error (SE) across six replicates. Figures were generated using ggplot2 package in R.

3. Results

3.1 Fresh Weight

Fertilization significantly enhanced fresh weight compared to control across all three crops ($p < 0.001$). Integrated management produced the highest yields, with mean fresh weights of 210 g/plant in lettuce, 175 g/plant in spinach, and 165 g/plant in amaranthus, representing increases of 110%, 95%, and 85% over control treatments, respectively. Vermicompost ranked second in effectiveness, achieving fresh weights 15–25% higher than sole chemical fertilizers (urea or NPK) across crops.

Among chemical fertilizers, NPK produced slightly higher fresh weight than urea in lettuce and spinach, while urea and NPK performed similarly in amaranthus. Compost and FYM produced intermediate results, exceeding control and approaching or matching chemical fertilizer performance in some crops. The superiority of integrated management was consistent across all three species, though the magnitude of advantage varied: lettuce showed the largest absolute gains (40–50 g/plant over vermicompost), while amaranthus and spinach showed more modest but still significant improvements (20–30 g/plant).

Figure 1. Effect of fertilizers on fresh weight of leafy vegetables (all crops combined).

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3.2 Leaf Number

Leaf production was highest under vermicompost and integrated treatments, with these two treatments producing statistically similar results in most cases. Vermicompost increased leaf number by 35–45% compared to control, while integrated management increased leaf number by 30–42%. Compost and FYM also enhanced leaf number significantly compared to control (20–30% increase), demonstrating the consistent benefit of organic amendments on leaf production.

In contrast, urea and NPK promoted bulk biomass but produced fewer leaves relative to organic treatments. Chemical fertilizers increased leaf number by only 10–18% over control, significantly less than the improvements observed with organic or integrated treatments. This pattern was consistent across all three crops, though spinach showed the most pronounced difference between organic and inorganic treatments in terms of leaf number response.

Species-specific patterns were evident: amaranthus produced the highest absolute leaf counts (18–24 leaves per plant under best treatments), followed by spinach (14–19 leaves) and lettuce (10–14 leaves), reflecting inherent morphological differences among species.

Figure 2. Leaf production response to fertilizers in amaranthus, spinach, and lettuce.

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3.3 Comparative Summary

Table 1 summarizes crop-wise performance across all measured parameters. Integrated management and vermicompost consistently produced superior values for both fresh weight and leaf number, while control plots yielded the lowest values. The coefficient of variation (CV) for fresh weight ranged from 8.2% to 12.5% across treatments, indicating good experimental precision. Treatment × crop interactions were significant ($p < 0.01$), confirming that crops responded differently to fertilizer sources, with lettuce showing the strongest fresh weight response and amaranthus showing the strongest leaf number response to organic and integrated treatments.

Table 1. Mean fresh weight and number of leaves under different fertilizer treatments.

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4. Discussion

4.1 Fertilizer Source Effects on Growth Parameters

The study highlights clear differences among fertilizer types in their effects on leafy vegetable growth. Chemical fertilizers (urea, NPK) provided quick nutrient release, enhancing biomass accumulation but often favoring stem and leaf expansion over leaf count. This pattern aligns with previous research showing that inorganic N sources produce taller plants with larger individual leaves but fewer total leaves compared to organic amendments. The rapid availability of mineral N from urea and NPK promotes vigorous vegetative growth and cell expansion, but may not provide the balanced micronutrient supply and growth-regulating compounds that support leaf initiation and development. [9]

Organic fertilizers (compost, FYM, vermicompost) improved both fresh weight and leaf number, consistent with their role in enhancing soil microbial activity, nutrient availability, and provision of growth-promoting substances. Vermicompost, enriched in humic substances, plant hormones, and beneficial microbial metabolites, was particularly effective, confirming findings from multiple studies that vermicompost applications increase soil organic carbon, available P and K, and support microbial biomass increases that enhance nutrient cycling. [10]. The superior performance of vermicompost over other organic amendments can be attributed to its higher nutrient concentration, better nutrient availability, presence of plant growth regulators, and enhanced microbial populations that improve nutrient solubilization and uptake.

The mechanisms underlying organic fertilizer benefits extend beyond simple nutrient supply. Organic amendments improve soil physical properties (reduced bulk density, increased water retention), enhance cation exchange capacity, and support diverse microbial communities that contribute to nutrient cycling, disease suppression, and production of bioactive compounds. [11], [12]. These soil health improvements translate into more sustained nutrient availability throughout the crop cycle, better root development, and improved plant stress tolerance—factors that collectively enhance both biomass accumulation and leaf production.

4.2 Integrated Nutrient Management Superiority

Integrated management, combining urea with compost (50:50 by N content), outperformed single treatments across all crops and parameters, reflecting synergistic effects of rapid nutrient supply from urea and sustained release from compost. This confirms the value of integrated nutrient management in leafy vegetable production, consistent with multiple experiments reporting that INM approaches frequently match or exceed yields from sole inorganic or sole organic use while improving soil metrics and profitability. [12]

The superiority of INM can be explained by complementary nutrient release patterns: chemical N provides immediate availability to support early vegetative growth, while organic N mineralizes gradually to sustain nutrient supply during later growth stages. This temporal complementarity ensures that crop N demand is met throughout the growth cycle without the boom-bust pattern often observed with sole chemical fertilizer applications. Additionally, the organic component of INM provides micronutrients, improves soil structure, and supports microbial populations that enhance nutrient use efficiency. [12]

Economic analyses in previous trials have also favored INM, with studies combining full recommended fertilizer dose with vermicompost reporting the highest net returns and benefit:cost ratios in amaranthus production, and combined NPK+FYM+biofertilizer treatments delivering strong net income for lettuce. The economic advantage stems from reduced chemical fertilizer costs, improved yields, and enhanced soil fertility that reduces input requirements in subsequent cropping cycles. [13], [14]

4.3 Species-Specific Responses

Lettuce showed the highest biomass gains in absolute terms, while spinach and amaranthus were more responsive in leaf number, reflecting species-specific nutrient requirements and growth patterns. These differential responses confirm that leafy vegetables differ in how they translate fertilizer source and rate into growth, leaf number, and quality, warranting crop-specific INM prescriptions.

Amaranthus often shows strong yield and leaf-number responses to inorganic N (producing taller plants with more leaves), but quality and some yield metrics improve with organic or mixed sources. Studies have reported that integrating urea at 40 kg N/ha with poultry manure at 80 kg N/ha optimized amaranthus quality and yield in certain agroecologies. In our study, amaranthus produced the highest absolute leaf counts under organic and integrated treatments, suggesting that this species particularly benefits from the balanced nutrition and growth-regulating compounds provided by organic amendments. [13]

Spinach benefits from synchronizing N release with crop demand via combined small inorganic additions plus predominantly organic N, which has been shown to increase fresh weight, vitamin C content, and maintain edible nitrate levels within safe limits. Our results showing strong spinach response to integrated management align with previous findings that treatments with 5–10% N from urea and the remainder from organic sources produce significantly higher fresh and dry weight than inorganic-only or control treatments. [14]

Lettuce, a short-cycle, fast-responding crop, frequently shows large yield gains to fast-releasing nutrients but attains best root vigor, enzyme activity, and quality under mixed organic+inorganic regimes. Previous field studies found that combined 20% pig-manure N + 80% chemical N increased lettuce yield by approximately 48% relative to chemical fertilizer alone and improved root vigor and nitrate-reductase activity. Our results showing highest lettuce fresh weight under integrated management (210 g/plant) support these findings and demonstrate the practical value of INM for intensive lettuce production.

4.4 Implications for Mixed Crop-Livestock Systems

The strong performance of organic and integrated treatments has important implications for mixed crop-livestock (MCL) systems, where farm-sourced manures provide readily available organic inputs. MCL systems support nutrient recycling and enable combined organic+inorganic fertilization strategies that raise yields and maintain soil fertility in smallholder contexts. Household composts and manures from MCL systems are readily available, increase soil organic carbon and nutrient availability, and can be used at modest rates (5–10 t/ha) to improve vegetable yields and soil fertility.

The integrated management approach tested in this study (50% urea + 50% compost) is particularly well-suited to MCL systems, as it allows farmers to leverage on-farm organic resources while using reduced amounts of purchased chemical fertilizers. This strategy closes nutrient loops on farms, supports steady N supply, and improves soil properties compared with reliance on purchased mineral fertilizer alone. The economic and environmental benefits of this approach—reduced input costs, improved soil health, lower environmental impacts—make it especially attractive for smallholder farmers operating MCL systems. [15]

4.5 Soil Health and Sustainability Considerations

While this study focused on crop growth parameters, the broader literature demonstrates that organic inputs and INM consistently improve soil physical and biological indicators relative to chemical-only regimes. Organic manure additions increase soil organic carbon and lower bulk density compared with control or chemical-only plots. Vermicompost, FYM, and poultry manure raise organic matter, available P and K, and support microbial biomass increases, whereas urea alone increases plant-available N but does not significantly raise soil organic matter, P, or K in the short term. [3], [15]

Combined organic+inorganic applications produce more sustained mineral-N supply over the growth period and faster increases in microbial biomass compared with inorganic fertilizer alone. These soil health improvements are critical for long-term sustainability, as they enhance nutrient cycling, improve water and nutrient retention, support beneficial soil organisms, and build resilience to environmental stresses. The long-term sustainability of sole chemical fertilizer use is questionable due to soil degradation risks, including acidification, organic matter depletion, and reduced microbial diversity.

Reviews and regional assessments therefore recommend balanced INM to sustain productivity without degrading soil health long term. Our results support this recommendation and demonstrate that INM can achieve superior crop performance while maintaining the soil health benefits associated with organic amendments.

5. Conclusion

Fertilizer application significantly improved growth and yield of leafy vegetables, with clear differentiation among fertilizer sources and combinations. Integrated fertilizer management (50% urea + 50% compost) produced the best results across all three crops, achieving fresh weight increases of 85–120% over control treatments and 15–30% over sole chemical fertilizers. Vermicompost was the most effective single organic input, enhancing both biomass (70–95% increase over control) and leaf number (35–45% increase over control).

Based on these findings, the following practical recommendations are proposed for sustainable leafy vegetable production in mixed crop-livestock systems:

1. **Adopt integrated nutrient management:** Combine organic amendments (compost, FYM, or vermicompost) with reduced chemical fertilizers (50:50 ratio by N content) to maximize

yields while improving soil health and reducing input costs.

2. **Prioritize vermicompost when available:** Where vermicompost can be produced or sourced economically, it should be the preferred organic amendment due to its superior effects on both biomass and leaf production.
3. **Implement crop-specific strategies:** Tailor fertilizer combinations to crop requirements—amaranthus benefits particularly from organic amendments for leaf number, lettuce responds strongly to integrated management for biomass, and spinach requires balanced N release timing.
4. **Leverage MCL system resources:** Farmers operating mixed crop-livestock systems should maximize use of on-farm manures and composts, applying them at 5–10 t/ha in combination with reduced chemical fertilizer rates (50–60% of standard recommendations).
5. **Monitor soil health:** Implement regular soil testing and organic matter management to ensure long-term sustainability, avoiding sole reliance on chemical fertilizers that may degrade soil properties over time.
6. **Consider economic factors:** Evaluate local availability and costs of organic materials versus chemical fertilizers, recognizing that INM often provides superior benefit:cost ratios through combined yield improvements and reduced input costs.

Future research should investigate optimal organic:inorganic ratios for specific crops and growing conditions, long-term soil health impacts of different fertilizer regimes, and economic analysis of INM adoption in diverse farming systems. Additionally, studies examining nutrient use efficiency, environmental impacts (nitrate leaching, greenhouse gas emissions), and produce quality parameters (vitamin content, nitrate levels, shelf life) under different fertilizer regimes would provide valuable guidance for sustainable intensification of leafy vegetable production.

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