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# Sustainable nutrient bioformulations derived from floral waste for improving growth performance of *Trigonella foenum-graecum* L.

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Floral residues are generated in large quantities but are commonly discarded, despite their richness in macro- and micro-nutrients. In this study, we explored the conversion of floral waste into nutrient-rich liquid (MNM- multi-nutrient mixture) using a low-cost fermentation approach. Two formulations were prepared: one produced by fermenting flower waste with cow urine (MNM1) and another using flower waste combined with jaggery solution (MNM2). Comprehensive nutrient profiling showed that both formulations contained substantial levels of essential elements, including nitrogen, phosphorus, potassium, calcium, magnesium, sodium, zinc, iron, manganese, copper, and nickel. The growth-promoting efficiency of these formulations was evaluated on *Trigonella foenum-graecum* L. (fenugreek) under controlled experimental conditions. Both formulations significantly enhanced morphological, physiological, and yield-related traits compared with the untreated control plants. Application of the bioformulations enhanced fresh biomass by up to 40%, highlighting their effectiveness. Overall, the findings demonstrate that floral waste can be sustainably transformed into nutrient-rich bioinputs that enhance crop performance, contribute to the valorisation of organic waste, and promote environmental sustainability.

KEYWORDS
**floral waste, nutrient management, nutrient solution, plant growth, *Trigonella foenum-graecum***

## 1 Introduction

India's floriculture sector has expanded rapidly over the past decade, with national production reaching approximately 2,910 thousand metric tonnes, including 2,263 thousand metric tonnes of loose flowers and 647 thousand metric tonnes of cut flowers (Vahoniya et al., 2018). Tamil Nadu remains the leading producer, followed by Karnataka, Madhya Pradesh, and West Bengal. Market projections indicate that the industry, valued at INR 292.0 billion in 2024, is expected to grow to INR 744.0 billion by 2033 at a compound annual growth rate of 10.9% (Vahoniya et al., 2018). Despite substantial growth in the floriculture sector, the management of floral waste remains inadequate, with more than 8 million metric tonnes discarded each year (Sowmya, 2024). These residues hold cultural and religious importance but are often dumped in landfills or water bodies (Atal, 2022), where they degrade water quality, disrupt aquatic

habitats, and contribute to methane emissions during anaerobic decomposition (Sahu et al., 2024). Yet, floral biomass contains abundant secondary metabolites, including flavonoids, phenolics, and alkaloids, that can enhance plant tolerance to stress (Tang et al., 2024), suggesting an untapped resource for agricultural use.

Cow urine, another commonly underutilised bioresource, has gained attention for its agronomic value. It is naturally enriched with essential macro- and micro-nutrients and has been widely applied to improve soil fertility, prepare botanical pesticides, and formulate plant growth enhancers (Ambigalakshmi et al., 2023). Its increasing use in organic production systems reflects its capacity to stimulate soil biological activity and enrich nutrient availability (Devasena and Sangeetha, 2022; Pradhan et al., 2018). Cow urine contains key nutrients such as nitrogen, phosphorus, and potassium (Ledgard et al., 1982), and its incorporation into biofertilizers enhances crop vigour while supporting eco-friendly cultivation practices. Farmers have reported several benefits, including enhanced pest resistance (Patel et al., 2019), reduced input costs, and improved yields, attributed in part to its function as a bio-enhancer that stimulates microbial activity in the soil (Ambigalakshmi et al., 2023).

Combining cow urine with floral residues offers a promising strategy to create nutrient-rich inputs capable of improving plant growth and soil health (Miah et al., 2017). These natural components supply essential nutrients and bioactive compounds that participate in key metabolic pathways, including photosynthesis, protein synthesis, and carbohydrate metabolism, thereby supporting plant development and enhancing physiological performance (Sharma et al., 2016). Studies have also indicated improvements in crop quality attributes such as protein content and total soluble solids (Kuai et al., 2016). Integrating flower waste into agricultural formulations additionally supports bioremediation efforts, reduces the environmental burden of organic waste disposal, and restores ecosystem functions (Gawade et al., 2020; Sharma et al., 2018). Such bioresources are cost-effective, require minimal chemical supplementation, and are widely accepted among farmers (Kensa, 2011).

Conventional chemical fertilisers were instrumental in enhancing crop productivity during the Green Revolution by correcting soil nutrient limitations (Eliazer Nelson et al., 2019). However, their continued and excessive use has raised serious environmental and health concerns. These products depend heavily on fossil fuels for manufacturing and contribute significantly to greenhouse gas emissions (Smil, 2004). Moreover, long-term application has resulted in nutrient leaching, groundwater contamination, and declining soil structure, adversely affecting both ecological integrity and human well-being (Ghosh, 2004). Overreliance on chemical inputs has also reduced soil microbial diversity and organic matter content, progressively diminishing soil fertility (Lal, 2004). These challenges have intensified global interest in organic amendments and integrated nutrient management to restore soil sustainability (Tilman et al., 2002).

Fenugreek (*Trigonella foenum-graecum* L.) was selected as a model crop due to its short growth cycle, enabling rapid evaluation of treatment effects. It is highly responsive to nutrient inputs, making it suitable for assessing nutrient-enriched bioformulations. Additionally, its economic and nutritional importance as a widely cultivated leafy vegetable and medicinal plant supports its selection for studying sustainable nutrient management strategies (Acharya et al., 2008). In this context, (MNMs) containing both macro- and micro-nutrients have emerged as a promising approach for improving soil fertility and crop productivity (Marschner, 2011). Unlike single-nutrient fertilisers, MNMs offer a more balanced nutrient supply, thereby enhancing plant growth and nutrient-use efficiency (Adolwa et al., 2023). The utilisation of discarded flowers for the preparation of MNMs provides an innovative strategy that simultaneously promotes organic waste recycling and supports agricultural enhancement (Miah et al., 2017). Through bioconversion processes, floral residues can be converted into nutrient-rich bioformulations that contribute to sustainable agriculture and align with circular economy principles (Srivastav and Kumar, 2021).

Building on these concepts, the present study developed two multi-nutrient mixtures (MNMs) derived from floral waste and evaluated their effects on the growth and physiological performance of *Trigonella foenum-graecum* L. under controlled conditions. While floral waste recycling and cow urine-based bio inputs have been previously reported, the formulation of standardised, nutrient-profiled liquid preparations from mixed floral residues has received limited attention. Earlier investigations primarily focused on composting methods or traditional fermented products without comprehensive mineral characterisation or detailed physiological assessment. In this study, floral waste valorisation was integrated with quantitative nutrient profiling, including macro- and micro-nutrients, pH, and electrical conductivity and systematic evaluation of early vegetative-stage physiological and nutrient responses, thereby providing a structured assessment of fermentation-derived bioformulations.

# 2 Methodology

## 2.1 Preparation of MNMs

Floral waste was procured from a local flower vendor in Vellore, Tamil Nadu, India (Latitude: 12.919708, Longitude: 79.13314). To maintain the organic purity of the biomass, non-biodegradable components such as plastic wrappers, synthetic threads, and other foreign materials were meticulously removed. The cleaned flower waste was rinsed thoroughly with tap water and air-dried under ambient conditions. Fermentation was conducted in two sanitised 25 L plastic containers. Fresh cow urine was obtained from Gir cattle maintained at the Livestock Unit of the VIT School of Agricultural Innovation and Advanced Learning (VAIAL), Vellore. For the first formulation (multi-nutrient mixture MNM1), 250 grams each of flower petals from five species: *Chrysanthemum indicum*, *Polianthes tuberosa*, *Gomphrena globosa*, *Rosa* spp., and *Chrysanthemum morifolium* were added to a mixture of 10 litres of cow urine and 5 litres of potable water.

In the second container (MNM2), an equal quantity and composition of floral biomass were mixed with a jaggery solution prepared by dissolving 5 kilograms of jaggery in 10 litres of potable water. Both containers were covered with sterile cotton cloth to facilitate aerobic fermentation to facilitate aerobic fermentation while minimising contamination. The containers were placed in a shaded environment, protected from direct sunlight, and allowed to ferment undisturbed for 10 days to encourage natural microbial activity. Following the incubation period, the fermented mixtures were filtered through muslin cloth to remove residual solids. The resulting nutrient-rich liquids were transferred aseptically into sterilised, airtight containers and stored in a cool, dry place to maintain stability and shelf life. The analysed mineral nutrient composition of the two formulations (MNM1 and MNM2) is detailed in Table 1. The preparation technique

TABLE 1 Nutrient composition of multi-nutrient mixtures (MNM1 and MNM2).

| Nutrients | MNM1 (mg $L^{-1}$) | MNM2 (mg $L^{-1}$) |
|---|---|---|
| Total Nitrogen | 2,300 | 300 |
| Phosphorus | <1 | <1 |
| Potassium | 806 | 4,942 |
| Calcium | 380 | 245 |
| Magnesium | 192 | 93 |
| Sodium | 4,810 | 580 |
| Zinc | 2.48 | 1.83 |
| Iron | 8.93 | 7.16 |
| Manganese | <1 | <1 |
| Copper | 0.78 | 0.28 |
| Nickel | <1 | <1 |
| pH | 8.12 | 6.42 |
| Electrical Conductivity (dS $m^{-1}$) | 2.6 | 3.4 |

T1 – Control (no amendment); T2 – MNM1 (flower waste fermented with cow urine); T3 – MNM2 (flower waste fermented with jaggery solution); and T4 – Commercial control (Panchagavya).

for the nutrient bioformulations is protected under an Indian patent filed by the authors (Indian Patent application no. 202541094314) and was carried out in accordance with the procedures described in the patent documentation.

The substrates used for formulation preparation possess documented nutrient and biochemical characteristics. Cow urine contains nitrogen (primarily as urea), along with phosphorus, potassium, calcium, magnesium, sulfur, and trace elements (Ledgard et al., 1982; Miah et al., 2017). Jaggery solution provides fermentable sugars, mainly sucrose, and minor mineral constituents that support microbial proliferation during fermentation (Sharifi-Rad et al., 2023; Hussain et al., 2012). Panchagavya, composed of cow dung, urine, milk, curd, and ghee, contains macro- and micro-nutrients, organic acids, and beneficial microbial populations reported to promote plant growth (Sathiyaraj et al., 2022; Chakraborty and Sarkar, 2019).

## 2.2 Greenhouse experiment

A controlled pot experiment was conducted during February–March 2024 in the Net House facility of the VIT School of Agricultural Innovation and Advanced Learning (VAIAL), VIT Vellore, to evaluate the growth-promoting potential of two floral waste-based bioformulations on *Trigonella foenum-graecum* L. (fenugreek). The study consisted of four treatments:

T1: Control (no amendment)
T2: MNM1 (flower waste fermented with cow urine)
T3: MNM2 (flower waste fermented with jaggery solution)
T4: Commercial control (Panchagavya)

Fenugreek was grown in 9-inch plastic pots filled with a uniform potting mixture of red soil and vermicompost in a 2:1 ratio. A thin layer of coco peat was used as surface mulch to enhance moisture retention and maintain uniform pot conditions. The growth substrate was homogenised thoroughly and divided evenly among all pots.

The experiment was laid out in a Completely Randomised Design (CRD) with four replications per treatment. Fenugreek seeds were pre-soaked in water for 24 h to improve germination, and subsequently, 2 g of seeds was sown per pot. Plants were maintained under natural light (10–12 h photoperiod), an ambient temperature of 28 ± 2 °C, and a relative humidity of 60–70%. At 10 days after sowing (DAS), foliar applications were carried out using a handheld sprayer. MNM1 and MNM2 were applied as foliar sprays at a concentration of 2 mL $L^{-1}$, while Panchagavya was applied at 3% (v/v). Spraying was performed uniformly to ensure even coverage of the foliage. The application rates of MNM1 and MNM2 were determined based on preliminary optimisation experiments to identify an effective concentration that enhanced plant performance without inducing phytotoxic effects. Panchagavya was applied following established usage guidelines. These concentrations were selected to ensure treatment comparability and plant safety under controlled conditions. The crop was maintained under the same environmental conditions and destructively sampled at 20 DAS, representing the vegetative stage suitable for growth and physiological assessments.

All morphological, physiological, and biochemical parameters were evaluated at 20 days after sowing (DAS), corresponding to the early vegetative stage of *Trigonella foenum-graecum*. Physiological measurements, including chlorophyll content (SPAD index), net photosynthetic rate, stomatal conductance, and transpiration rate, were recorded *in vivo* prior to sampling using non-destructive methods. Following these measurements, plants were destructively sampled at 20 DAS for the assessment of morphological traits, biomass determination, and biochemical and nutrient analyses.

## 2.3 Measurement of growth and physiological parameters

The morphological and growth parameters measured included leaf length, leaf breadth, number of leaves, shoot length, root length, leaf area, fresh biomass, and dry biomass, following standard agronomic protocols.

Chlorophyll content was measured using a SPAD-502Plus Chlorophyll Meter (KONICA MINOLTA, Japan). Gas-exchange traits, net photosynthetic rate, stomatal conductance, and transpiration rate were quantified using a LI-COR 6800 Portable Photosynthesis System (LI-COR Biosciences, Lincoln, NE, United States).

Plant tissue samples were collected for nutrient analysis, and the results are summarised in Table 2. Data on morphological, physiological, and biochemical responses are illustrated in Figures 1–3.

## 2.4 Statistical analysis

All data were analysed using JMP Pro 18 statistical software. Differences among treatment means were evaluated using Tukey's (HSD) test, and statistical significance was considered at $p < 0.05$.

# 3 Result and discussion

To evaluate the agronomic potential of floral waste-derived bioformulations, discarded floral biomass was processed through controlled fermentation to produce two liquid multi-nutrient mixtures (MNM1 and MNM2), prepared using cow urine and a jaggery-based

TABLE 2 Nutrient analysis results of fenugreek (*Trigonella foenum-graecum*) plants.

| Treatment | N (%) | P (%) | K (%) | Ca (%) | Mg (%) | Su (%) | Zn (mg/kg) | Fe (mg/kg) | Mn (mg/kg) | Ca (mg/kg) | Ni (mg/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T1 | 2.13 ± 0.03 | 0.21 ± 0.01 | 3.75 ± 0.16 | 1.05 ± 0.01 | 0.36 ± 0.03 | 0.23 ± 0.02 | 58.58 ± 2.45 | 371.81 ± 10.15 | 36.65 ± 1.62 | 16.32 ± 0.53 | 4.94 ± 0.36 |
| T2 | 3.32 ± 0.06 | 0.38 ± 0.01 | 7.07 ± 0.03 | 2.60 ± 0.03 | 1.46 ± 0.05 | 0.50 ± 0.03 | 99.45 ± 6.34 | 589.81 ± 1.64 | 68.77 ± 4.84 | 19.93 ± 0.05 | 9.13 ± 0.94 |
| T3 | 3.10 ± 0.08 | 0.36 ± 0.03 | 6.65 ± 0.05 | 2.31 ± 0.01 | 0.85 ± 0.02 | 0.40 ± 0.01 | 84.14 ± 2.52 | 546.49 ± 3.22 | 49.29 ± 0.35 | 20.46 ± 0.10 | 9.79 ± 0.34 |
| T4 | 2.75 ± 0.06 | 0.30 ± 0.02 | 5.77 ± 0.18 | 2.14 ± 0.04 | 0.57 ± 0.06 | 0.36 ± 0.02 | 70.18 ± 4.01 | 484.31 ± 21.71 | 46.80 ± 1.13 | 18.13 ± 1.68 | 7.48 ± 0.47 |

T1 – Control (no amendment); T2 – MNM1 (flower waste fermented with cow urine); T3 – MNM2 (flower waste fermented with jaggery solution); and T4 – Commercial control (Panchagavya). Values are presented as mean ± SE. Bars with different letters indicate significant differences among treatments at $p < 0.05$ according to Tukey's HSD.

solution, respectively. The nutrient composition of these formulations was first characterised to determine their macro- and micronutrient profiles. Subsequently, their effects were assessed under greenhouse conditions on *Trigonella foenum-graecum*, where key physiological (chlorophyll content and gas-exchange traits), morphological (shoot length, root length, and leaf area), yield-related (fresh and dry biomass), and plant nutrient uptake parameters were measured. This integrated evaluation enabled a comprehensive assessment of formulation efficiency in improving plant growth and soil nutrient status while promoting sustainable recycling of organic waste resources (Manna et al., 2018; Xu et al., 2012). Although floral residues can naturally decompose in soil, such uncontrolled degradation often results in nutrient losses and slower mineralisation. In contrast, controlled fermentation enhances nutrient solubilisation, stimulates microbial activity, and ensures immediate nutrient availability, thereby improving plant uptake efficiency.

Phosphorus concentrations were low in both MNM1 and MNM2 (<1 mg $L^{-1}$). Phosphorus is a key macronutrient involved in ATP synthesis, nucleic acid formation, and the maintenance of cellular membrane integrity. Recent studies demonstrate that adequate phosphorus availability enhances plant tolerance to abiotic stresses by modulating gene expression and influencing stomatal responses (Khan et al., 2023). Moreover, phosphorus plays a crucial role in regulating root development through the Target of Rapamycin (TOR) signalling pathway, which integrates nutrient status with cell growth and metabolic activity, underscoring its broader importance in plant development.

Potassium, which was found at high concentrations in MNM2 (4,942 mg $L^{-1}$) and at moderate levels in MNM1 (806 mg $L^{-1}$), plays a vital role in enzyme activation, stomatal regulation, and maintaining water-use efficiency. These physiological functions are strongly associated with improved tolerance to salinity and drought stress (Johnson et al., 2022), which aligns with the enhanced plant performance observed following MNM application.

Calcium (MNM1: 380 mg $L^{-1}$; MNM2: 245 mg $L^{-1}$) plays a key role in cell wall stabilisation, signal transduction, and stress response modulation (Feng et al., 2023). Previous studies have highlighted its contribution to enhancing crop resilience under adverse conditions (Jing et al., 2024). Magnesium, present at physiologically relevant levels in both formulations (MNM1: 192 mg $L^{-1}$; MNM2: 93 mg $L^{-1}$), is essential for chlorophyll biosynthesis (Ahmed et al., 2023), Rubisco activation, and efficient carbon assimilation, consistent with reports linking adequate magnesium supply to improved plant growth and quality (Chaudhry et al., 2021). Although sodium (MNM1: 4810 mg $L^{-1}$; MNM2: 580 mg $L^{-1}$) is not an essential nutrient, it may partially substitute for potassium under certain stress conditions. Nevertheless, excessive sodium levels must be carefully monitored to avoid potential toxicity and ion imbalance (Kronzucker et al., 2013).

Micronutrients, including zinc, iron, manganese, and copper, were also present in bioavailable concentrations in both formulations. Zinc (MNM1: 2.48 mg $L^{-1}$; MNM2: 1.83 mg $L^{-1}$) plays a pivotal role in auxin metabolism, gene regulation, and enzymatic functioning, while iron (MNM1: 8.93 mg $L^{-1}$; MNM2: 7.16 mg $L^{-1}$) is essential for chlorophyll synthesis, redox reactions, and photosynthetic electron transport (Jalal et al., 2024; Li et al., 2023). Manganese (MNM1: <1 mg $L^{-1}$; MNM2: <1 mg $L^{-1}$) and copper (MNM1: 0.78 mg $L^{-1}$; MNM2: 0.28 mg $L^{-1}$) contribute to reactive oxygen species (ROS) detoxification, photosynthetic efficiency, and enzymatic catalysis (Mir et al., 2021). Trace levels of nickel (<1 mg $L^{-1}$) detected in both MNM1 and MNM2 are consistent with its recognised function in nitrogen

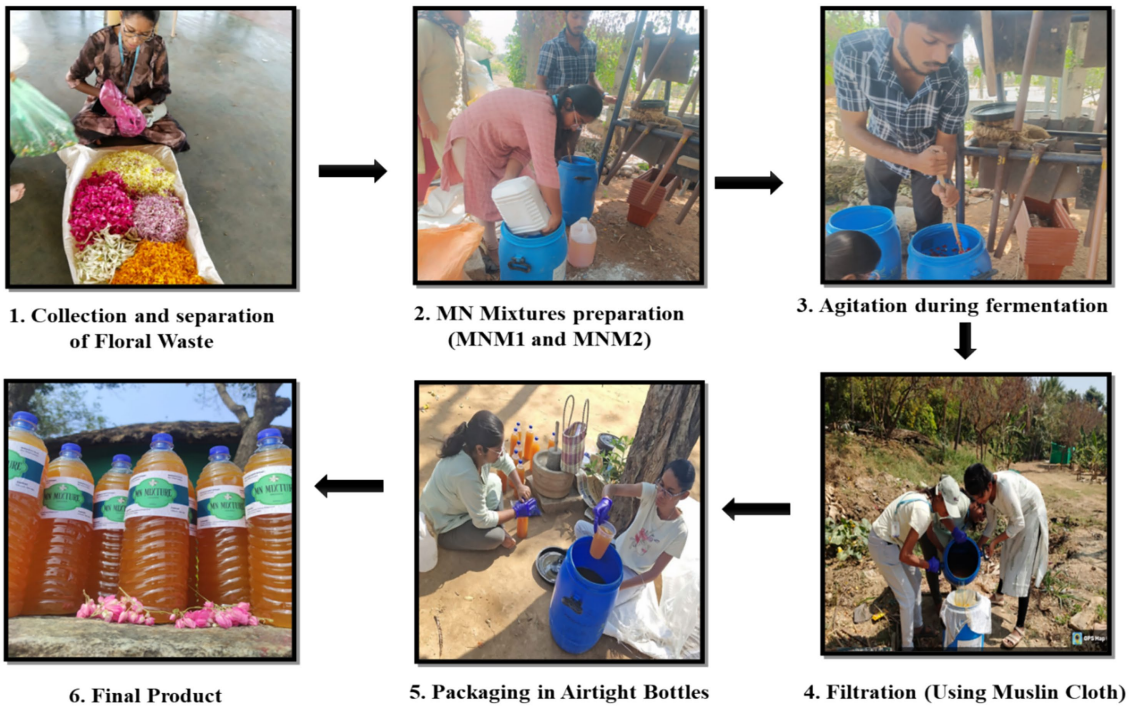



FIGURE 1
Workflow illustrating the preparation of multi-nutrient mixtures (MNMs) derived from floral waste.

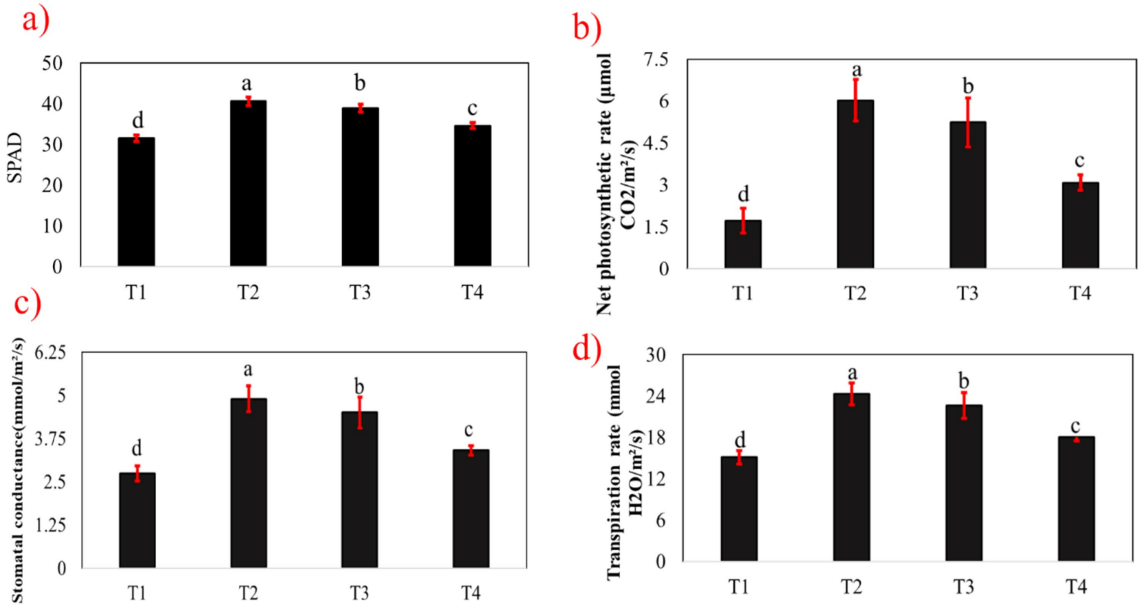



FIGURE 2
Enhancement of plant physiological parameters following the application of multi-nutrient mixtures: **(a)** SPAD index, **(b)** net photosynthetic rate, **(c)** stomatal conductance, and **(d)** transpiration rate. T1 – Control (no amendment); T2 – MNM1 (flower waste fermented with cow urine); T3 – MNM2 (flower waste fermented with jaggery solution); and T4 – Commercial control (Panchagavya). Values are presented as mean ± SE. Bars with different letters indicate significant differences among treatments at $p < 0.05$ according to Tukey's HSD test.

metabolism, urease activity, and antioxidant regulation, particularly in leguminous crops (Mendes et al., 2023). These nutrient characteristics are summarised in Table 1.

Application of MNM1 and MNM2 significantly enhanced the physiological and morphological performance of *Trigonella foenum-graecum* compared with the untreated control at 20 DAS. Chlorophyll content (SPAD index) increased by 28.9% under MNM1 and 23.2% under MNM2, indicating improved photosynthetic pigment accumulation. Comparable increases in chlorophyll concentration and leaf greenness have been reported in fenugreek and other leafy vegetables following vermicompost and vermiwash application (Machado et al., 2020; Tadayyon et al., 2018), suggesting that nutrient-rich organic

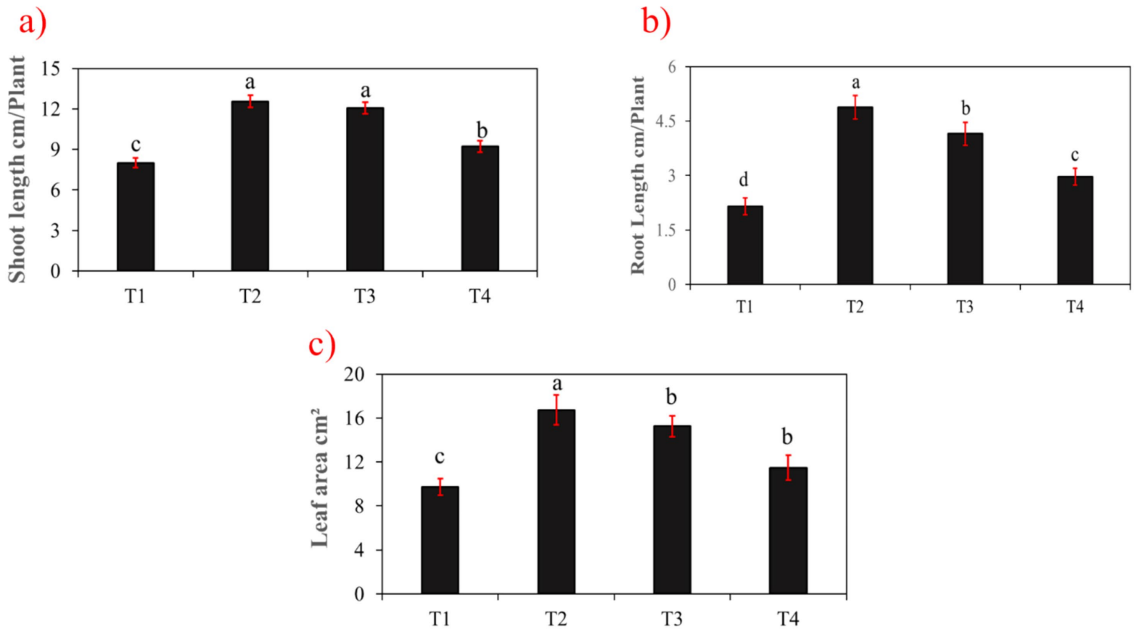



FIGURE 3
Enhancement of plant morphological parameters following application of multi-nutrient mixtures: **(a)** Shoot length, **(b)** root length, and **(c)** leaf area. T1 – Control (no amendment); T2 – MNM1 (flower waste fermented with cow urine); T3 – MNM2 (flower waste fermented with jaggery solution); and T4 – commercial control (Panchagavya). Values are presented as mean ± SE. Bars with different letters indicate significant differences among treatments at $p < 0.05$ according to Tukey's HSD.

amendments can stimulate photosynthetic capacity through improved nitrogen and magnesium availability (Supplementary Table S1; Supplementary Figure S1).

Notably, MNM2 induced a 252.9% increase in net photosynthetic rate, while stomatal conductance and transpiration also rose substantially under both formulations (MNM1: 77.7 and 62%; MNM2: 62.9 and 50.6%, respectively). Similar improvements in gas-exchange parameters have been documented with fermentation-based biofertilizers such as Panchagavya and compost extracts, where enhanced microbial metabolites and balanced nutrient supply promoted stomatal regulation and carbon assimilation. The responses observed in the present study indicate that floral waste-derived formulations perform comparably to established organic inputs, reinforcing their potential as effective organic fertiliser alternatives during crop growth.

Marked enhancements in vegetative growth were recorded following application of the MNM formulations at 20 DAS. Leaf area expanded by 72.1% under MNM1 and 56.7% under MNM2, while root length increased by 128.5 and 95.2%, respectively. Shoot length also showed substantial gains, rising by 58.2% with MNM1 and 51.8% with MNM2. Similar stimulation of shoot and root development has been reported in fenugreek and other leafy vegetables treated with vermicompost, compost extracts, and related organic amendments, where improved nutrient availability and enhanced microbial activity supported early vegetative growth (Xu and Mou, 2016; Jabborova et al., 2021).

Fresh biomass accumulation followed the same trend, increasing by 40% under MNM1 and 33.3% under MNM2 relative to the control. Improvements of comparable magnitude have been documented in studies employing integrated compost-based nutrient management and biofertilizer strategies (Shaaban et al., 2024), indicating that fermentation-derived organic inputs can effectively enhance early-stage biomass production. Collectively, these findings position the floral waste-derived MNMs within the broader framework of established organic nutrient technologies while highlighting their potential as efficient alternatives.

Tissue nutrient analysis demonstrated that MNM-treated plants exhibited greater accumulation of both macro- and micro-nutrients at 20 DAS compared with the control. Concentrations of nitrogen, potassium, calcium, magnesium, sulfur, and trace elements (Zn, Fe, Mn, Cu, and Ni) were consistently higher, reflecting improved nutrient acquisition and internal utilisation. Similar enhancements in nutrient uptake have been reported in fenugreek and other leafy crops supplied with compost-based and biologically active organic amendments, where improved soil nutrient availability and microbial interactions facilitated greater assimilation efficiency (Richardson and Simpson, 2011; Saadatian et al., 2017).

Among the two formulations, the cow urine–based MNM (MNM-1) produced the highest tissue nutrient concentrations, including N (3.43–3.21%), P (~0.38%), K (~7.1%), Ca (~2.6%), and Mg (~1.5%), along with elevated levels of Zn (up to 110 mg $kg^{-1}$) and Fe (up to 593 mg $kg^{-1}$). Comparable increases in NPK uptake have been documented under vermicompost and vermiwash treatments in fenugreek (Tadayyon et al., 2018), supporting the role of nutrient-rich organic inputs in enhancing mineral assimilation. The jaggery-based formulation (MNM-2) also promoted nutrient enrichment, in agreement with findings from compost–biostimulant systems (Lunagariya et al., 2019). Increased Fe and Zn accumulation further aligns with evidence that microbially mediated organic amendments improve micronutrient solubilization and plant availability. Together, these results position floral waste-derived MNMs, particularly MNM-1, as effective organic nutrient sources capable of strengthening growth-stage nutrient assimilation and physiological performance (Table 2; Figures 2–4).

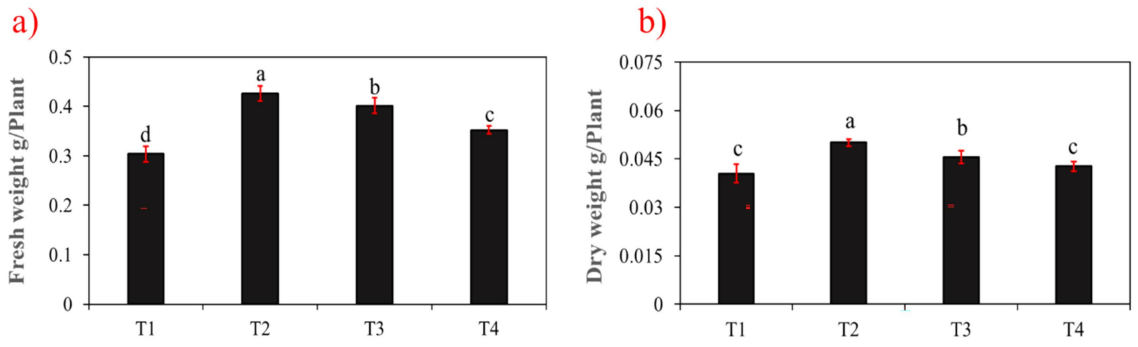



FIGURE 4
Improvement in plant yield parameters following application of multi-nutrient mixtures: **(a)** fresh weight and **(b)** dry weight. T1 – Control (no amendment); T2 – MNM1 (flower waste fermented with cow urine); T3 – MNM2 (flower waste fermented with jaggery solution); and T4 – Commercial control (Panchagavya). Values are presented as mean ± SE. Bars with different letters indicate significant differences among treatments at $p < 0.05$ according to Tukey's HSD.

The enhanced physiological performance and nutrient assimilation observed under MNM treatments are consistent with established findings on compost-based and biologically active organic amendments. Organic inputs are known to improve soil nutrient availability and stimulate plant physiological processes through enhanced microbial activity and mineral transformation (Richardson et al., 2009). Improvements in chlorophyll content and vegetative growth observed in the present study align with evidence that compost-derived amendments and organic fertilisers enhance photosynthetic efficiency and biomass production in leafy vegetables (Lazcano and Domínguez, 2011; Xu and Mou, 2016). Enhanced macro- and micro-nutrient uptake under MNM application also corresponds with reports demonstrating that organic nutrient sources increase nutrient use efficiency and plant mineral accumulation by improving rhizosphere interactions and nutrient solubilization (Adesemoye et al., 2009). Furthermore, biologically enriched organic systems have been shown to support root development and nutrient acquisition through improved soil biological activity and enzymatic processes. The magnitude of vegetative growth and nutrient responses observed at the early growth stage in this study places floral waste-derived MNMs within the broader framework of validated organic nutrient management strategies.

Comparison of the initial soil properties with post-harvest values demonstrated that MNM application influenced soil nutrient dynamics. The baseline soil contained 0.33% nitrogen, 0.05% phosphorus, and 0.17% potassium. Following harvest, MNM1-treated soil showed clear increases in nitrogen (0.40%), phosphorus (0.09%), and potassium (0.24%), whereas the control recorded lower values (0.32, 0.04, and 0.16%, respectively). Secondary nutrients also improved under MNM1 application, with calcium increasing from 0.50 to 0.82% and magnesium from 0.21 to 0.28%, while sulphur rose from 0.22 to 0.26%. These enhancements indicate improved nutrient retention and cycling, consistent with reports that cow urine–based organic amendments stimulate soil biological activity and nutrient transformation processes (Sodani and Kumar, 2017).

Micronutrient concentrations exhibited a similar pattern. Initial levels of zinc (44.8 mg $kg^{-1}$), iron (15,380 mg $kg^{-1}$), manganese (238.5 mg $kg^{-1}$), and copper (22.9 mg $kg^{-1}$) increased to 49.5, 18,398, 297.7, and 27.4 mg $kg^{-1}$, respectively, under MNM1 treatment. These observations align with previous findings indicating that organic bioinputs derived from plant residues enhance micronutrient availability in soil (Saadatian et al., 2017). Although MNM2-treated soils showed comparatively moderate increases in most nutrients, they exhibited higher nickel accumulation (16.5 mg $kg^{-1}$) relative to the initial value (13.5 mg $kg^{-1}$), suggesting formulation-dependent differences in micronutrient release dynamics. Overall, the comparison of pre- and post-treatment soil analyses supports the role of floral waste-derived MNMs in improving soil fertility and sustaining nutrient availability for plant growth (Richardson and Simpson, 2011; Marschner, 2011) (Tables 3, 4).

TABLE 3 Soil nutrient status after harvest of *Trigonella foenum-graecum*.

| S. no | Parameters | Initial soil value |
|---|---|---|
| 1. | Organic carbon (%) | 0.48 |
| 2. | Nitrogen (%) | 0.33 |
| 3. | Phosphorus (%) | 0.05 |
| 4. | Potassium (%) | 0.17 |
| 5. | Calcium (%) | 0.50 |
| 6. | Magnesium (%) | 0.21 |
| 7. | Sulphur (%) | 0.22 |
| 8. | Zinc (mg/kg) | 44.80 |
| 9. | Iron (mg/kg) | 15.380 |
| 10. | Manganese (mg/kg) | 238.50 |
| 11. | Copper (mg/kg) | 22.90 |
| 12. | Nickel (mg/kg) | 13.50 |
| 13. | Soil texture | Sandy loam |
| 14. | pH | 6.8 |
| 15. | EC (dS $m^{-1}$) | 0.42 |

T1 – Control (no amendment); T2 – MNM1 (flower waste fermented with cow urine); T3 – MNM2 (flower waste fermented with jaggery solution); and T4 – Commercial control (Panchagavya).

A limitation of this study is the absence of cow urine-only and jaggery-only treatments, which would have enabled clearer separation of the individual effects of fermentation substrates from the specific contribution of floral biomass. Although the combined formulations significantly enhanced growth and nutrient uptake in *Trigonella foenum-graecum*, the relative role of each component could not be independently quantified. Future research should include component-wise

TABLE 4 Soil nutrient status after harvest of *Trigonella foenum-graecum*.

| Treatments parameters (% and mg/kg) | T1 (C) | T2 (MNM-1) | T3 (MNM-2) | T4 (CC) |
|---|---|---|---|---|
| Nitrogen (%) | 0.37 | 0.40 | 0.35 | 0.32 |
| Phosphorus (%) | 0.04 | 0.09 | 0.06 | 0.06 |
| Potassium (%) | 0.16 | 0.24 | 0.22 | 0.19 |
| Calcium (%) | 0.46 | 0.82 | 0.64 | 0.54 |
| Magnesium (%) | 0.22 | 0.28 | 0.24 | 0.23 |
| Sulphur (%) | 0.24 | 0.26 | 0.25 | 0.25 |
| Zinc (mg/kg) | 45.59 | 49.52 | 48.83 | 46.69 |
| Iron (mg/kg) | 15424.0 | 18398.0 | 18350.0 | 16749.0 |
| Manganese (mg/kg) | 244.68 | 297.66 | 248.13 | 243.11 |
| Copper (mg/kg) | 23.56 | 27.36 | 26.59 | 25.31 |
| Nickel (mg/kg) | 13.97 | 14.09 | 16.54 | 14.58 |
| pH | 7.42 | 7.68 | 7.35 | 7.51 |
| Electrical conductivity (dS $m^{-1}$) | 0.82 | 1.24 | 1.08 | 0.95 |

T1 – Control (no amendment); T2 – MNM1 (flower waste fermented with cow urine); T3 – MNM2 (flower waste fermented with jaggery solution); and T4 – Commercial control (Panchagavya).

controls to clarify the mechanisms underlying nutrient release, plant responses and metabolic components. Validation through multi-location field trials is also necessary to assess performance under diverse soil and climatic conditions. Furthermore, soil microbiome analysis and functional studies would provide deeper insight into microbial community shifts and nutrient cycling processes associated with these bioformulations, thereby strengthening their development as sustainable nutrient inputs.

## 4 Conclusion

The present study demonstrates that multi-nutrient mixtures (MNM1 and MNM2) derived from floral waste, cow urine, and jaggery water demonstrate potential as eco-friendly biofertilizers for *Trigonella foenum-graecum*. Between the two formulations, MNM1 consistently produced superior responses compared with MNM2, the commercial control, and untreated plants. This enhanced performance may be attributed to the richer and more balanced macro- and micro-nutrients composition of MNM1, which facilitated greater nutrient uptake, improved chlorophyll formation, enhanced photosynthetic activity, and increased biomass accumulation. These physiological improvements were reflected in notable gains in plant growth parameters and overall yield.

The successful utilisation of floral waste for developing nutrient-rich inputs also provides an environmentally sound solution for managing organic waste streams. By converting discarded floral biomass into valuable agricultural inputs, the approach reduces waste burden while offering a cost-effective alternative to chemical fertilisers. Overall, the findings highlight the potential of MNM1 and MNM2 to be incorporated into sustainable farming strategies, particularly in organic and low-input production systems. Valorising floral waste through nutrient recycling not only supports environmental conservation but also contributes to improving crop productivity in an economically and ecologically sustainable manner.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any identifiable images or data included in this article.

## Author contributions

KL: Software, Writing – original draft, Conceptualization, Writing – review & editing, Methodology, Data curation. CP: Writing – original draft, Software, Writing – review & editing, Methodology, Conceptualization, Data curation. NM: Conceptualization, Methodology, Data curation, Writing – review & editing, Writing – original draft, Software. PP: Data curation, Software, Methodology, Writing – original draft, Conceptualization, Writing – review & editing. DR: Writing – review & editing, Software, Writing – original draft, Supervision, Investigation, Formal analysis. TP: Investigation, Supervision, Data curation, Writing – review & editing, Conceptualization, Resources, Visualization, Validation, Funding acquisition, Writing – original draft, Project administration.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1794603/full#supplementary-material

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