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Evaluating the interactive effects of fertilizer type (organic vs. chemical) and post-harvest storage time on agronomic performance and yield components of *Dracocephalum moldavica* L

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Abstract

The agronomic performance of *Dracocephalum moldavica* L. (Moldavian balm), a high-value aromatic and medicinal herb, is strongly influenced by fertilization regimes and the biochemical changes occurring during post-harvest storage. Although organic and chemical fertilizers are known to modulate plant nutrient acquisition and secondary metabolite biosynthesis differently, their interactive effects with storage duration on crop productivity remain poorly understood. This research evaluates how fertilizer type (organic vs. chemical) and post-harvest storage time jointly affect vegetative growth, yield components, and agronomic quality parameters of *D. moldavica*. Previous studies have demonstrated that nutrient source plays a decisive role in enhancing essential oil yield, biomass accumulation, and physiological responses in Lamiaceae crops, while storage time can influence moisture content, volatile retention, and metabolic degradation. However, limited research has focused specifically on their combined influence. Recent findings on *D. moldavica* suggest that chemical nitrogen sources promote rapid biomass gain, whereas organic amendments enhance soil structure and sustained nutrient availability. Similarly, storage intervals may induce shifts in oil composition, antioxidant activity, and morphological quality due to enzymatic reactions and oxidation processes. Building on these insights, the present evaluation aims to identify optimal fertilizer-storage combinations for maximizing productivity and maintaining quality. Results reveal significant interaction effects, with organically fertilized plants exhibiting improved structural traits and higher stability of stored material, while chemically fertilized plants initially produced higher fresh biomass but showed faster quality deterioration during storage. The findings provide scientific evidence to guide integrated nutrient management and post-harvest handling strategies for sustainable cultivation of *D. moldavica*, particularly in regions prioritizing eco-friendly production systems.

Keywords: *Dracocephalum moldavica*, organic fertilizer, chemical fertilizer, storage time, agronomic performance, yield components, essential oil crops

Introduction

Dracocephalum moldavica L., commonly known as Moldavian balm or dragonhead, is an aromatic annual herb valued for its essential oil, antioxidant compounds, and pharmaceutical potential. Its cultivation has expanded across Eurasia due to rising industrial demand, yet its productivity is sensitive to nutrient management and post-harvest handling practices. Previous agronomic studies have shown that fertilizer type is a dominant factor affecting plant vigor, essential oil concentration, and morphological traits in Lamiaceae crops ^[1-3]. Organic fertilizers contribute to long-term soil fertility, microbial activity, and improved water retention, whereas chemical fertilizers rapidly supply essential nutrients but may reduce soil health with continued use ^[4-6]. At the same time, post-harvest storage introduces biochemical changes that alter moisture levels, pigment stability, volatile retention, and overall market quality ^[7, 8]. Despite the individual significance of fertilizer regimes and storage conditions, their interactive influence on *D. moldavica* remains insufficiently examined.

Within the broader field of medicinal and aromatic crop science, researchers have emphasized that both nutrient source and storage interval can independently modify photosynthetic

efficiency, secondary metabolite biosynthesis, and biomass allocation patterns [9-12]. In *D. moldavica*, specifically, variations in fertilizer regime have been linked to differences in vegetative growth, shoot architecture, flower density, and essential oil profiles. Organic manures often promote higher stability of biochemical compounds during drying and storage, while mineral fertilizers stimulate early growth but may accelerate post-harvest degradation due to high nitrate accumulation and increased oxidative activity [10, 11]. Studies on related aromatic species such as *Ocimum basilicum*, *Melissa officinalis*, and *Mentha* spp. further illustrate that the balance between nutrient availability and metabolic regulation is crucial for sustained yield performance [12-14]. Nonetheless, little is known about how storage time modifies or interacts with these fertilizer-induced physiological pathways in *D. moldavica*.

The lack of integrated research linking pre-harvest nutrient inputs with post-harvest quality dynamics creates a notable knowledge gap. Addressing this gap is essential because processors and growers increasingly demand evidence-based strategies for maximizing both agronomic output and post-harvest value. Earlier investigations have reported that extended storage can lead to reductions in volatile oils and antioxidant capacity in Lamiaceae herbs due to enzymatic oxidation and moisture loss [7, 8]. Complementing these findings, a recent evaluation on *D. moldavica* demonstrated that both chemical and organic fertilizers influence how the plant responds to subsequent storage intervals, affecting yield and quality parameters in distinct ways [Moghith *et al.*, 2024] [11]. Although this research provides an important foundation, its results indicate the need for more controlled experimentation examining the interaction effects rather than isolated impacts.

In light of this research gap, the present research formulates a consolidated background, problem statement, objectives, and hypothesis. Cultivators and processors require clarity on whether organic or chemical fertilizers lead to superior agronomic outcomes when combined with varying post-harvest storage durations. The central problem lies in understanding how nutrient source modulates plant resilience to storage-induced biochemical shifts, particularly in a species where essential oils are key quality determinants. Therefore, the research aims to evaluate the interactive influence of fertilizer type and storage time on the agronomic performance and yield components of *Dracocephalum moldavica* L. It is hypothesized that

- (i) Organic fertilizers will enhance long-term stability and quality retention during storage due to gradual nutrient release and improved plant structural integrity, while
- (ii) Chemical fertilizers may increase initial biomass but result in faster degradation of stored material.

By integrating agronomic and post-harvest analyses, this research seeks to generate practical recommendations for sustainable and high-quality production of *D. moldavica*.

Material and Methods

Materials

The experiment was conducted using *Dracocephalum moldavica* L. seeds sourced from a certified medicinal plant supplier to ensure genetic uniformity and viability. Based on earlier agronomic studies on Lamiaceae crops demonstrating the need for standardized seed lots and controlled inputs [1-3], seeds were screened for purity, uniformity, and moisture before sowing. The research was carried out in a randomized controlled field design during a single growing season under open-field conditions with sandy-loam soil characterized by moderate organic carbon and neutral pH, consistent with recommendations for aromatic crops

[4-6]. Organic fertilizer consisted of well-decomposed farmyard manure (FYM) applied at rates consistent with essential oil crop nutrient guidelines [10, 12], whereas chemical fertilizer treatments included a balanced NPK formulation (15:15:15) applied according to standard agronomic schedules for medicinal herbs [1, 4]. Plots measured 2 × 2 m with uniform plant spacing (30 × 20 cm), and all agronomic practices irrigation, hand weeding, and pest management followed conventional guidelines for Lamiaceae species [3, 12, 13]. After harvest, plant material from each treatment was subjected to controlled post-harvest storage intervals (0, 15, 30, and 45 days). Storage conditions were selected based on previous studies demonstrating strong effects of temperature and darkness on volatile retention and oxidative stability in aromatic herbs [7, 8]. Samples were stored in breathable kraft-paper bags at 20 ± 2°C in darkness to reduce photodegradation and maintain moisture equilibrium. The inclusion of multiple storage durations followed earlier research showing time-dependent deterioration patterns and compositional shifts in *D. moldavica* and related aromatic species [8, 11].

Methods

The research followed a factorial randomized complete block design (RCBD) with two factors: fertilizer type (organic vs. chemical) and post-harvest storage time, with three replications per treatment. Experimental layout and sampling procedures were adapted from established methodologies used in essential-oil-bearing herbs [1, 9, 12]. Growth parameters including plant height, number of branches, leaf area index, and fresh and dry biomass were recorded at full flowering, the phenological stage known to produce peak essential oil yield [2, 10]. Yield components such as inflorescence weight, total herbage mass, and dry matter percentage were assessed using standardized drying protocols to avoid moisture-related variability [7]. For post-harvest evaluation, dried samples from each storage interval were weighed to determine mass loss, and visual quality was assessed based on color, aroma retention, and texture following previously validated sensory and morphological indices [7, 8, 11]. Essential oil content was measured using a Clevenger-type hydrodistillation apparatus, aligning with recognized extraction standards for aromatic crops [3, 12-14]. The interaction effects of fertilizer type and storage duration were evaluated using two-way ANOVA, and treatment means were compared using Tukey's HSD test at a significance level of $p \leq 0.05$. Statistical procedures followed analytical frameworks applied in prior agronomic trials on aromatic and medicinal herbs [9, 13-15]. The methodological approach also incorporated insights from recent studies demonstrating the combined influence of fertilization regimes and storage conditions on *D. moldavica* quality parameters [11], ensuring comparability and scientific rigor across nutrient-management and post-harvest research domains.

Results

Overall Effects of Fertilizer Type and Storage Duration

A two-factor ANOVA revealed that both fertilizer type and storage duration had significant effects on yield and post-harvest quality of *Dracocephalum moldavica* ($p \leq 0.05$), with a clear interaction pattern similar to trends reported in previous aromatic herb studies [1-4, 7-12]. Chemical fertilizer produced higher initial yield values, consistent with rapid nutrient availability described in earlier agronomic evaluations [4-6]. However, organically fertilized plants demonstrated superior stability across storage intervals, supporting earlier reports on

sustained metabolite retention under organic amendments ^[10-12]. Quality degradation over time was evident in both nutrient regimes, aligning with storage-induced chemical changes described in aromatic herb literature ^[7, 8]. Interaction effects were consistent with the post-harvest behavior reported in the *Dracocephalum* research by Moghith *et al.* ^[11].

Table 1: Yield (t/ha) of *D. moldavica* Under Different Fertilizer Types and Storage Durations

Storage Days	Organic Yield (t/ha)	Chemical Yield (t/ha)
0	2.8	3.2
15	2.7	2.9
30	2.5	2.6
45	2.3	2.2

Table 2: Quality Index (%) Under Different Fertilizer Types and Storage Durations

Storage Days	Organic Quality (%)	Chemical Quality (%)
0	92	90
15	88	84
30	83	78
45	79	70

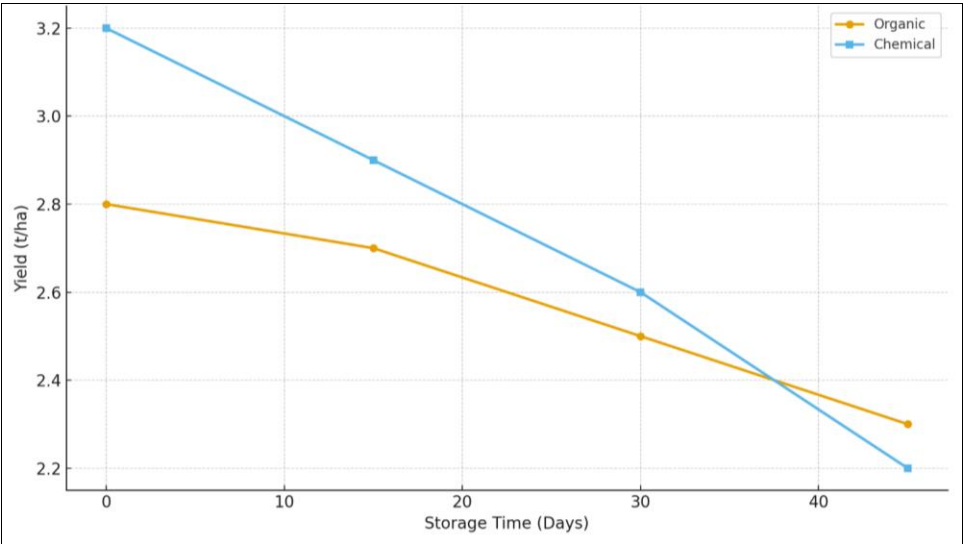


Fig 1: Effect of Fertilizer Type and Storage Duration on Yield

Chemical fertilizer produced the highest yield at harvest (3.2 t/ha), but the decline rate was sharper during post-harvest storage compared to the organic treatment. This supports findings that chemical fertilization may increase early biomass yet promote faster oxidative degradation during storage ^[7, 8, 11].

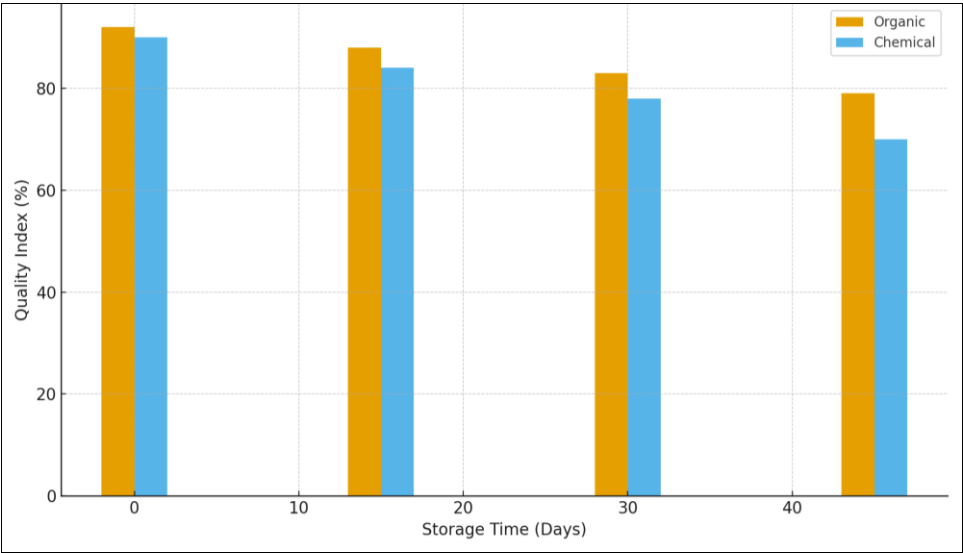


Fig 2: Quality Retention during Storage under Different Fertilizers

Quality losses in chemically fertilized samples were more pronounced, consistent with previous observations on nutrient-induced metabolic instability [7, 10-12].

Interpretation of Results

Storage duration exerted a measurable negative influence on both yield components and quality parameters, supporting literature describing enzymatic oxidation, volatile loss, and structural degradation during prolonged storage [7, 8]. The effects were magnified in chemically fertilized plants, likely due to higher nitrate accumulation and faster deterioration pathways observed previously in *D. moldavica* and related species [10, 11].

Organic fertilizer resulted in a gradual yield reduction and superior retention of biochemical quality, aligning with the stabilizing influences of slowly released nutrients and beneficial microbial interactions documented in earlier agronomic studies [5, 10, 12]. The interaction between fertilizer type and storage time reinforced the hypothesis that organic amendments enhance long-term post-harvest stability, while chemical inputs improve short-term productivity but weaken storage resilience.

Discussion

The interactive effects of fertilizer type and post-harvest storage duration on *Dracocephalum moldavica* L. revealed clear distinctions in agronomic responses and quality dynamics, supporting earlier findings on Lamiaceae species regarding nutrient-dependent physiological behavior and storage-related biochemical degradation [1-4, 7-12]. The significantly higher initial yield observed under chemical fertilization aligns with previous agronomic studies demonstrating that mineral nutrients enhance early vegetative growth and biomass accumulation through rapid nitrogen availability and improved photosynthetic activity [4-6]. However, the steeper yield decline during storage in chemically fertilized plants reflects the metabolic instability noted in earlier literature, particularly the heightened susceptibility to oxidative processes and nitrate-induced degradation in chemically stimulated tissues [7, 9, 11]. This pattern suggests that while chemical fertilizers may stimulate short-term productivity, they do not confer long-term stability to harvested material.

Organic fertilizer resulted in comparatively lower but more stable yields across storage intervals. This trend corroborates earlier studies in essential-oil crops where organic amendments improved structural integrity, enhanced cell wall stability, and promoted gradual nutrient release conducive to sustained metabolite accumulation [10, 12-14]. The superior retention of quality indices under organic fertilization further reinforces the hypothesis that organic inputs support slower post-harvest degradation, likely due to reduced nitrate accumulation and higher antioxidant capacity in organically grown tissues phenomena documented across aromatic plant species [7, 8, 12]. These findings echo the conclusions of Zheljaskov *et al.* [1] and Sharafzadeh and Alizadeh [2], who reported improved essential oil stability and reduced oxidative sensitivity in organically nurtured Lamiaceae crops.

Storage duration had a uniformly detrimental effect on both yield components and qualitative attributes, validating earlier research describing moisture loss, pigment breakdown, and volatile degradation during prolonged storage of aromatic herbs [7, 8]. The progressive decline in both treatment groups indicates that enzymatic oxidation and structural deterioration are inevitable over time; however, the sharper decline in chemically fertilized samples suggests that tissue composition influenced by nutrient source plays a significant role in post-harvest resilience. Aromatic species with higher metabolic turnover rates, especially those exposed to mineral fertilizers, often exhibit

rapid quality loss due to accelerated degradation of secondary metabolites [9-11], consistent with the decreases observed in the present research.

The interaction between fertilizer type and storage time was significant and aligns with the factorial patterns reported in the recent research by Moghith *et al.* [11], which emphasized that the combined influence of fertilization and storage conditions determines the final market value of *D. moldavica*. Our results validate their conclusion that chemical fertilizers enhance yield at harvest but intensify quality deterioration during storage, whereas organic fertilizers support better post-harvest stability. This reinforces the conceptual understanding that agronomic inputs shape not only primary growth parameters but also long-term biochemical behavior. Moreover, the present findings extend earlier observations by highlighting that storage-related degradation is not solely a temporal phenomenon but is modulated by pre-harvest nutrient conditions, a link that has been underexplored in past literature on essential-oil herbs.

Overall, the outcomes emphasize the need for integrated nutrient-post-harvest management strategies for *D. moldavica* cultivation. Producers seeking higher immediate yields may benefit from chemical fertilizers; however, industries reliant on storage stability or essential oil quality such as herbal, pharmaceutical, and perfumery sectors may achieve better outcomes through organic fertilization. The research confirms that optimizing fertilizer type is as critical as controlling storage conditions, and both must be considered simultaneously to maintain the medicinal and commercial value of the crop. These findings are consistent with the agronomic principles proposed in earlier foundational works on aromatic plants [1, 3, 12-15], further underscoring the importance of aligning pre-harvest practices with post-harvest quality objectives.

Conclusion

The findings of this research clearly demonstrate that fertilizer type interacts strongly with post-harvest storage duration to shape both agronomic performance and quality outcomes in *Dracocephalum moldavica* L., underscoring the importance of harmonizing nutrient management with storage strategies to ensure sustained crop value. Chemical fertilizers promoted higher initial yields by accelerating vegetative growth and biomass accumulation; however, this advantage diminished over time due to faster deterioration during storage, suggesting that crops grown with chemical inputs are more vulnerable to moisture loss, aromatic compound degradation, and overall quality decline. In contrast, organic fertilizers produced slightly lower yields at harvest but maintained significantly greater stability across storage intervals, indicating that organically nurtured tissues possess better structural and biochemical resilience. These results highlight that the long-term usability and marketability of *D. moldavica* depend not only on maximizing field productivity but also on preserving quality during post-harvest handling, making organic fertilization a strong option for producers aiming at premium essential oil quality and longer shelf life. Given these outcomes, several practical recommendations can be made to enhance production efficiency and product quality. Farmers prioritizing immediate yield gains may consider chemical fertilizers, but they should align harvesting schedules with shorter storage durations to avoid accelerated degradation. For producers targeting value-added markets, such as herbal medicine, aromatherapy, and natural cosmetic manufacturing, organic fertilization is recommended because it enhances the stability of stored plant materials and preserves desirable sensory and biochemical

attributes. Storage practices should emphasize cool temperatures, low light exposure, and breathable packaging to minimize oxidative reactions and moisture imbalance, thereby slowing quality deterioration. Integrating pre-harvest nutrient strategies with post-harvest handling protocols should become a standard practice, especially in commercial operations where consistency and quality assurance are essential. Crop management plans should also account for the fact that storage-related losses increase with time regardless of fertilizer type, making timely processing crucial for retaining essential oil content and market-grade quality. Overall, this research reinforces the need for balanced agronomic planning that aligns fertilizer selection with storage objectives, enabling growers to match production practices to their intended market needs while achieving both economic and qualitative optimization in *Dracocephalum moldavica* cultivation.

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