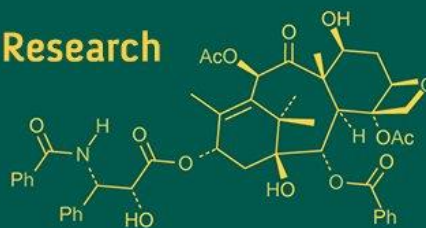
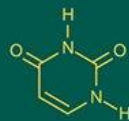


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Integrated fertilization with tropical orchard leaf extract biostimulants improves strawberry flowering and reproductive development

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Abstract

Strawberry (*Fragaria* × *ananassa*) is a valuable soft fruit crop whose yield depends on reproductive rather than purely vegetative growth, highlighting the need for sustainable nutrient management using botanical biostimulants. Comparative information on tropical orchard leaf extracts remains scarce, and no study has compared jamun, mango, guava, and jackfruit leaf extracts under contrasting RDF levels for strawberry flowering behaviour. This study evaluated these botanical leaf extracts, applied at two concentrations individually and in interaction with RDF, on flowering behaviour and reproductive potential in strawberry cv. Camarosa. A two-year experiment, using a factorial randomized block design with nine leaf extract treatments and two RDF levels, examined pooled data for days to first flowering, days to 50% flowering, and number of flowers per plant. RDF and botanical leaf extracts significantly improved all three flowering traits, with significant Leaf Extract × RDF interactions for every parameter. Jackfruit leaf extract 50% + RDF (A₂B₂) consistently produced the earliest first flowering, earliest 50% flowering, and highest flower number, with Jackfruit leaf extract 100% + RDF (A₂B₂) statistically comparable for several traits. Mango leaf extract 50% + RDF (A₂B₂) and Jamun leaf extract 50% + RDF (A₂B₂) also performed favourably, while the untreated Control without RDF (A₁B₁) consistently recorded the poorest flowering performance. Days to first and 50% flowering were strongly positively correlated ($r = 0.84$), whereas flowering time was negatively correlated with flower number. These findings support integrating botanical leaf extracts with RDF as a sustainable nutrient management strategy for improving strawberry flowering and reproductive efficiency.

Keywords: Botanical biostimulants, flowering earliness, integrated nutrient management, reproductive development, sustainable horticulture

1. Introduction

Strawberry (*Fragaria* × *ananassa* Duch.) is an important high-value soft fruit crop, valued for its distinctive flavour, appearance, and nutritional and antioxidant properties (Alvarez-Suarez *et al.*, 2014; FAOSTAT, 2024). Global production exceeds nine million tonnes annually, with cultivation expanding across subtropical regions, including India, where it has become an important commercial horticultural crop (NHB, 2024). As yield is fundamentally reproductive, flowering timing, synchrony, and flower number strongly influence fruit-set potential, harvest earliness, and productivity (Rana *et al.*, 2022; Zydlik *et al.*, 2024). Intensive production relies heavily on synthetic mineral fertilizers, contributing to declining nutrient-use efficiency, nitrate leaching, soil organic-carbon depletion, and environmental deterioration (Quddus *et al.*, 2025; Wang *et al.*, 2025). Moreover, strawberry's shallow root system makes it sensitive to nutrient imbalance; both nitrogen deficiency and excess can disrupt floral bud differentiation and delay reproductive transition (Jiang *et al.*, 2023; Choi *et al.*, 2024). Balanced N, P, and K nutrition is therefore essential for floral initiation, flowering synchrony, and reproductive efficiency, highlighting the need for sustainable nutrient-management strategies that maintain productivity while reducing reliance on synthetic inputs [2, 6, 12, 21, 23, 28, 32].

Botanical leaf extracts have emerged as promising biostimulant components of integrated nutrient management (du Jardin, 2015; Yakhin *et al.*, 2017) [7, 27]. Rich in phenolics, flavonoids, antioxidants, amino acids, vitamins, minerals, and hormone-like substances, they function primarily as physiological signalling and biostimulatory inputs rather than bulk nutrient

sources (Franzoni *et al.*, 2022; Cardarelli *et al.*, 2024). Their foliar application may modulate hormonal balance and meristematic activity, maintain chlorophyll and photosynthetic function, improve assimilate partitioning and nutrient uptake, and strengthen antioxidant defence, thereby supporting reproductive development (Soppelsa *et al.*, 2019; Mosa *et al.*, 2021). In strawberry, moringa leaf extract combined with potassium nitrate advanced flowering and improved yield attributes (Ismail and Ganzour, 2021), while seaweed biostimulants increased flower number, fruit set, and flowering duration (Al-Shatri *et al.*, 2020; Rana *et al.*, 2022; Bagh and Mishra, 2024; Zunic *et al.*, 2024). Integrated organic-inorganic nutrition has also reduced days to first flowering and increased flower production relative to recommended fertilizer alone (Raj and Prasad, 2023), while combined moringa, calcium, and potassium silicate enhanced flower number and fruit set (Mohammed and Majeed, 2023). Furthermore, guava, mango, jamun, and jackfruit leaves contain phenolics, flavonoids, and hormone-like bioactives with demonstrated physiological activity (Zhang *et al.*, 2022; Yuniarti *et al.*, 2025) [1, 4, 5, 9, 11, 13, 14, 22, 23, 25, 28, 29, 31].

Despite these findings, comparative information on jamun, mango, guava, and jackfruit leaf extracts within the same strawberry system remains scarce. Most studies have examined single extracts or concentrations, leaving their relative efficacy at different concentrations and in combination with the recommended dose of fertilizers (RDF) insufficiently explored, particularly for days to first flowering, days to 50% flowering, and number of flowers per plant. The integration of these locally available botanical extracts with conventional fertilization for sustainable improvement of strawberry reproductive performance has therefore not been systematically evaluated. The present study evaluated jamun, mango, guava, and jackfruit leaf extracts at 50% and 100% concentrations as foliar sprays, applied individually and in interaction with RDF, to determine their effects on flowering behaviour and reproductive potential in strawberry. The findings provide a basis for integrating botanical leaf extracts with recommended fertilization to support sustainable nutrient management and improved reproductive performance in strawberry cultivation.

2. Material and Methods

2.1 Experimental Site and Experimental Design

The experiment was conducted over two consecutive winter seasons (2024-25 and 2025-26) under open-field conditions at the New Nursery, Department of Horticulture, College of Agriculture, Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Adhartal, Jabalpur, Madhya Pradesh, India (23°12'09" N, 79°57'29" E; 300 m a.m.s.l.), a region with a subtropical climate and cool winters favorable for strawberry cultivation. A factorial randomized block design (FRBD) with three replications was used to assess the effects of botanical leaf extracts and the recommended dose of fertilizers (RDF) on strawberry (*Fragaria × ananassa* Duch.) cv. Camarosa. Factor A comprised nine levels: a water-sprayed control and foliar extracts of jamun (*Syzygium cumini*), mango (*Mangifera indica*), guava (*Psidium guajava*), and jackfruit (*Artocarpus heterophyllus*) leaves, each at 50% and 100% concentration. Factor B comprised two fertilizer levels (with and without RDF), yielding 18 treatment combinations replicated thrice, with six plants per experimental unit. Composite soil samples (0-30 cm depth)

collected before transplanting were clay in texture (19.6% sand, 30.4% silt, 50.0% clay), slightly acidic to neutral (pH 6.8), with normal electrical conductivity (0.47 dS m⁻¹), medium organic carbon (0.48%), low available nitrogen (256 kg ha⁻¹), high available phosphorus (24.4 kg ha⁻¹), and medium available potassium (248 kg ha⁻¹), indicating moderate fertility suitable for the crop.

2.2 Plant Material and Crop Establishment

Healthy, disease-free, tissue-cultured runners of cv. Camarosa, uniform in vigor with well-developed roots and 4-5 leaves, were procured from Jain Irrigation Systems Ltd., Jalgaon, Maharashtra, India. Damaged leaves and roots were trimmed, and plants were briefly field-acclimatized before transplanting on raised beds pre-laid with silver polyethylene mulch during the third week of October in both seasons, at 60 × 30 cm spacing. RDF (120:60:80 kg N:P₂O₅:K₂O ha⁻¹) was applied as a single basal dose through urea, single super phosphate, and muriate of potash before transplanting in the respective treatments. Irrigation, manual weeding, runner removal, and plant protection were applied uniformly across treatments to maintain healthy crop growth. Observations were recorded from six plants per unit and averaged for analysis.

2.3 Preparation and Application of Botanical Leaf Extracts:

Fresh, fully expanded, mid-canopy leaves of jamun, mango, guava, and jackfruit were harvested (≈100 g per species) from disease-free trees on the JNKVV campus during early morning under dry conditions, excluding young, senescent, or damaged foliage. Leaves were washed, rinsed, shade-dried to remove surface moisture, and processed separately by species to avoid cross-contamination. Extracts were prepared by the aqueous decoction method, with minor modifications following Mukherjee (2019), Nafiu *et al.* (2017), and Persic *et al.* (2019): chopped leaves were boiled in 1 L water for 15 min, reducing to ≈500 mL, cooled for 5 min, and filtered through muslin cloth followed by Whatman No. 1 paper. The resulting filtrate constituted the 100% extract; the 50% concentration was prepared immediately before spraying by diluting the stock 1:1 (v/v) with water. Extracts were freshly prepared for each species and concentration before each application. Foliar sprays were applied with a knapsack sprayer at 15-day intervals (30, 45, 60, and 75 DAT) during calm morning conditions until runoff; the control received an equivalent water spray on the same schedule [15, 16, 20].

2.4 Measurement of Flowering Parameters

Observations were recorded from six permanently tagged plants per unit. Days to first flowering were recorded as days after transplanting (DAT) to opening of the first flower per plant; days to 50% flowering as DAT when approximately half the plants in a unit bore at least one open flower. Total flowers per plant were counted at 5-day intervals throughout the flowering period, and cumulative means per plant were derived from the tagged plants for analysis.

2.5 Statistical Analysis

Data were analyzed in RStudio (v2025.05.0+496) using R (v4.6.0; R Core Team, Vienna, Austria). Normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene's tests, respectively. As no significant Year × Treatment interactions were detected for the flowering traits

evaluated, data from both seasons were pooled for analysis. Treatment effects were evaluated using Type III analysis of variance (ANOVA) under a factorial randomized block design, with botanical leaf extract, recommended dose of fertilizers (RDF), and their interaction as fixed effects. Effect sizes were expressed as partial eta squared (η^2). When ANOVA indicated significant treatment effects ($P \leq 0.05$), estimated marginal means (EMMs) were compared using

Tukey's honestly significant difference (HSD) test implemented in the emmeans package. Relationships among flowering traits were examined using Pearson's correlation analysis. Results are presented as EMMs $\pm$ standard error (SE) with statistical significance declared at $P \leq 0.05$.

3. Results

Table 1: Type III ANOVA for Flowering and Flower Production (Pooled Analysis)

Trait	Leaf Extract F	P-value	Partial η^2	RDF F	P-value	Partial η^2	Leaf Extract $\times$ RDF F	P-value	Partial η^2
Days to First Flowering	17.153	<0.0001	0.801	96.012	<0.0001	0.738	8.516	<0.0001	0.667
Days to 50% Flowering	7.297	<0.0001	0.632	38.925	<0.0001	0.534	5.749	0.0001	0.575
Number of Flowers per Plant	29.225	<0.0001	0.873	99.922	<0.0001	0.746	6.225	<0.0001	0.594

Note: RDF, recommended dose of fertilizers; η^2 , partial eta squared (effect size). Values are presented as Type III ANOVA F-statistics, corresponding P-values, and partial η^2 . P-values < 0.0001 are reported as "<0.0001".

3.1 Effects of Botanical Leaf Extracts and Recommended Fertilizer Dose (RDF) on Flowering Traits

Type III ANOVA indicated significant main effects of leaf extract and RDF, as well as a significant Leaf Extract $\times$ RDF interaction, for days to first flowering, days to 50% flowering, and number of flowers per plant (Table 1). Partial η^2 values were consistently high for both main effects across all three traits, with leaf extract accounting for a greater proportion of explained variation than RDF. The Leaf Extract $\times$ RDF interaction also explained a substantial proportion of the total variation, with the largest interaction effect observed for days to first flowering. Complete F-values, P-values, and partial η^2 estimates are presented in Table 1.

3.1.1 Flowering Responses to Botanical Leaf Extracts and RDF: Across the three flowering traits, Jackfruit leaf extract

at 50% consistently ranked as the superior treatment, recording the fewest days to first flowering, the fewest days to 50% flowering, and the maximum number of flowers per plant, with Jackfruit leaf extract at 100% forming a statistically comparable group in most instances (Table 2). Mango leaf extract at 50% and Jamun leaf extract at 50% also performed favourably for one or more traits, whereas the untreated Control consistently registered the poorest performance, showing the maximum number of days to first flowering and to 50% flowering together with the minimum number of flowers per plant. The effect of RDF depended on the leaf extract treatment; however, RDF generally promoted earlier flowering and higher flower production, with the most pronounced responses observed with Jackfruit 50%. Among treatment combinations, Jackfruit leaf extract 50% with RDF consistently produced the most favourable response across all three traits, while Control without RDF consistently produced the least favourable response; several combinations involving Mango, Jamun, and Jackfruit extracts with RDF formed statistically comparable clusters at the favourable end of the response range (Figures 1-3).

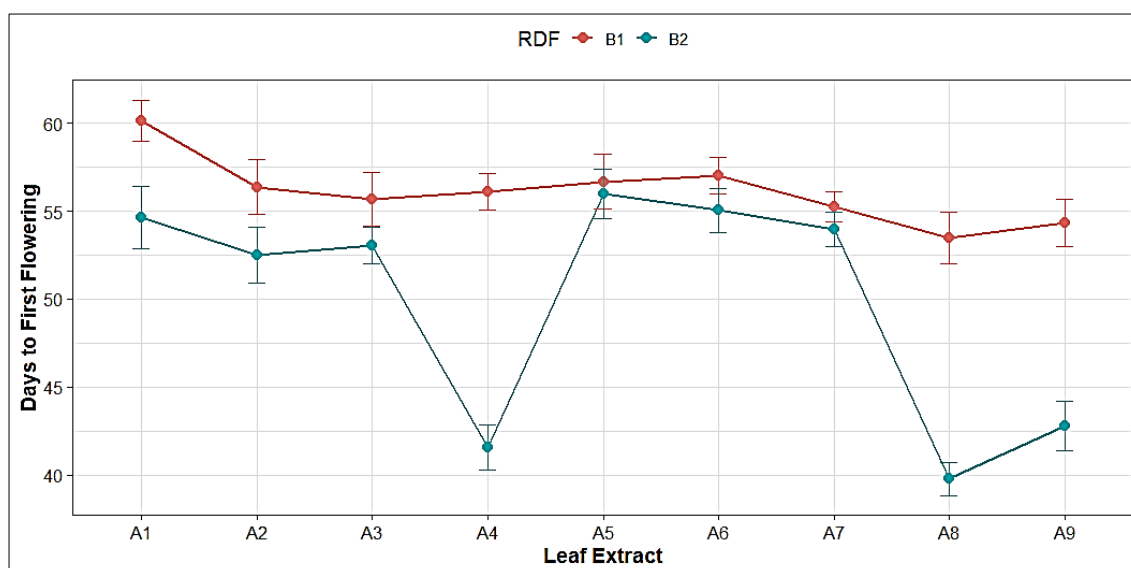


Fig 1: Interaction plot showing the estimated marginal means ($\pm$ SE) of days to first flowering under different leaf extract $\times$ RDF combinations.

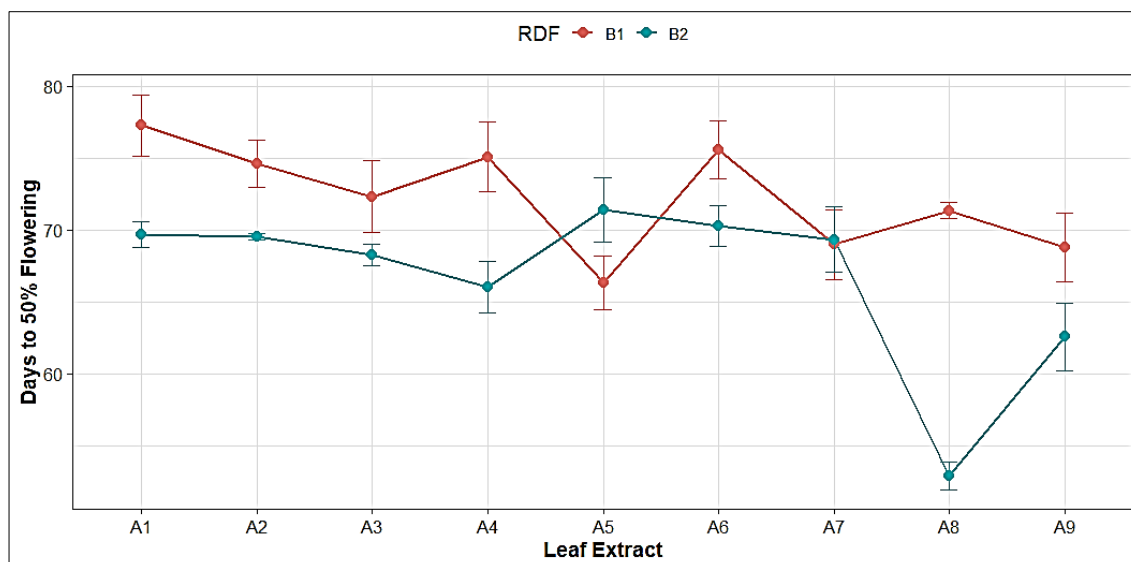


Fig 2: Interaction plot showing the estimated marginal means ($\pm$ SE) of days to 50% flowering under different leaf extract $\times$ RDF combinations.

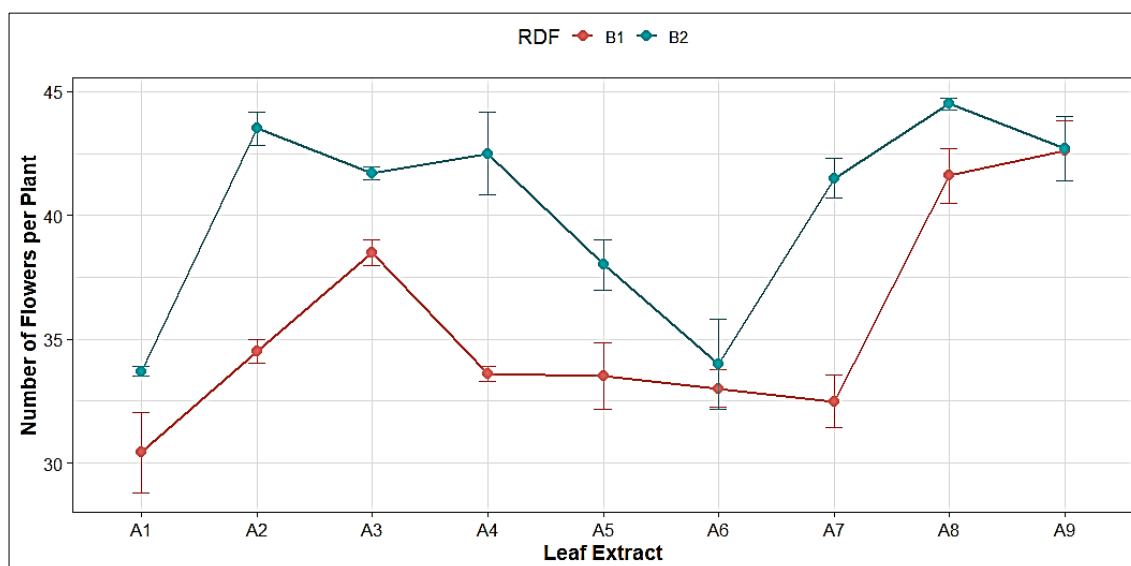


Fig 3: Interaction plot showing the estimated marginal means ($\pm$ SE) of number of flowers per plant under different leaf extract $\times$ RDF combinations.

Table 2: Estimated Marginal Means (Mean $\pm$ SE) of Days to First Flowering, Days to 50% Flowering and Number of Flowers per Plant under Different Leaf Extract $\times$ RDF Combinations (Pooled Analysis)

Leaf Extract	Days to First Flowering		Days to 50% Flowering		Number of Flowers per Plant	
	B ₁	B ₂	B ₁	B ₂	B ₁	B ₂
Control (A ₁)	60.15 $\pm$ 1.34 (a)	54.63 $\pm$ 1.34 (ab)	77.29 $\pm$ 1.90 (a)	69.70 $\pm$ 1.90 (abc)	30.42 $\pm$ 0.99 (a)	33.70 $\pm$ 0.99 (abc)
Jamun leaf extract 50% (A ₂)	56.37 $\pm$ 1.34 (ab)	52.51 $\pm$ 1.34 (b)	74.64 $\pm$ 1.90 (ab)	69.54 $\pm$ 1.90 (abc)	34.50 $\pm$ 0.99 (abc)	43.50 $\pm$ 0.99 (df)
Jamun leaf extract 100% (A ₃)	55.67 $\pm$ 1.34 (ab)	53.03 $\pm$ 1.34 (ab)	72.34 $\pm$ 1.90 (abc)	68.27 $\pm$ 1.90 (abc)	38.50 $\pm$ 0.99 (bde)	41.70 $\pm$ 0.99 (def)
Mango leaf extract 50% (A ₄)	56.11 $\pm$ 1.34 (ab)	41.56 $\pm$ 1.34 (c)	75.10 $\pm$ 1.90 (ab)	66.04 $\pm$ 1.90 (bc)	33.60 $\pm$ 0.99 (abc)	42.50 $\pm$ 0.99 (def)
Mango leaf extract 100% (A ₅)	56.67 $\pm$ 1.34 (ab)	55.96 $\pm$ 1.34 (ab)	66.30 $\pm$ 1.90 (bc)	71.40 $\pm$ 1.90 (abc)	33.50 $\pm$ 0.99 (abc)	38.00 $\pm$ 0.99 (bce)
Guava leaf extract 50% (A ₆)	57.03 $\pm$ 1.34 (ab)	55.03 $\pm$ 1.34 (ab)	75.60 $\pm$ 1.90 (ab)	70.27 $\pm$ 1.90 (abc)	33.00 $\pm$ 0.99 (ac)	34.00 $\pm$ 0.99 (abc)
Guava leaf extract 100% (A ₇)	55.22 $\pm$ 1.34 (ab)	53.96 $\pm$ 1.34 (ab)	69.00 $\pm$ 1.90 (abc)	69.34 $\pm$ 1.90 (abc)	32.48 $\pm$ 0.99 (a)	41.50 $\pm$ 0.99 (def)
Jackfruit leaf extract 50% (A ₈)	53.48 $\pm$ 1.34 (ab)	39.78 $\pm$ 1.34 (c)	71.34 $\pm$ 1.90 (abc)	52.90 $\pm$ 1.90 (d)	41.60 $\pm$ 0.99 (def)	44.50 $\pm$ 0.99 (f)
Jackfruit leaf extract 100% (A ₉)	54.33 $\pm$ 1.34 (ab)	42.80 $\pm$ 1.34 (c)	68.80 $\pm$ 1.90 (abc)	62.57 $\pm$ 1.90 (cd)	42.60 $\pm$ 0.99 (def)	42.70 $\pm$ 0.99 (def)

Note: Values are estimated marginal means $\pm$ standard error (SE). Means sharing at least one common letter among treatment combinations within each parameter are not

significantly different according to Tukey's honestly significant difference (HSD) test at $P \leq 0.05$. B₁ = without RDF; B₂ = with RDF.

3.1.2 Relationship among Flowering Traits

Pearson correlation analysis among the flowering parameters revealed a distinct pattern of positive and negative associations (Figure 4). Days to first flowering and days to 50% flowering were strongly and positively correlated ($r = 0.84$), representing the strongest relationship among the three traits. In contrast, number of flowers per plant was negatively correlated with both days to first flowering ($r = -0.71$) and days to 50% flowering ($r = -0.62$), with the former representing the strongest negative association in the matrix. The two flowering-time parameters were strongly and positively associated with each other, while both were moderately to strongly and negatively associated with number of flowers per plant, indicating a consistent inverse correlation structure between flowering time and flower number.

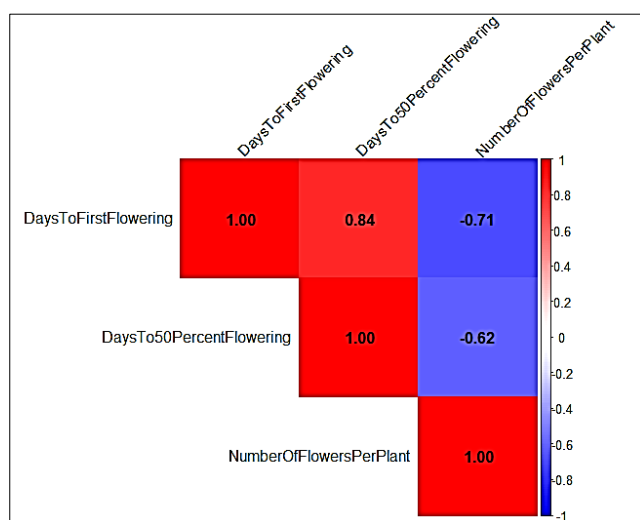


Fig 4: Pearson correlation heatmap showing the relationships among days to first flowering, days to 50% flowering, and number of flowers per plant. Red and blue colors indicate positive and negative correlations, respectively, with correlation coefficients displayed within each cell.

4. Discussion

4.1 Botanical Leaf Extracts and RDF Shape Flowering Behaviour and Reproductive Potential in Strawberry

Flowering marks the transition from vegetative to reproductive growth, and its timing and intensity directly influence fruit set, yield formation, and harvest earliness. Across all flowering traits, botanical leaf extracts, the recommended fertilizer dose (RDF), and their interaction significantly influenced reproductive development. Leaf extracts advanced flowering and enhanced reproductive capacity, while RDF reinforced these effects through improved nutritional status; their interaction indicated complementary physiological action. The responses suggest coordinated improvements in photosynthetic function, carbon partitioning, nutrient availability, hormonal regulation, source-sink relations, and meristem activity. Jackfruit leaf extract, particularly at 50%, consistently produced the most favourable reproductive response, especially when combined with RDF, whereas untreated, unfertilised plants showed the greatest delay and lowest reproductive capacity.

4.2 Days to First Flowering: Days to first flowering indicates the vegetative-to-reproductive transition and crop

earliness. Leaf extract, RDF, and their interaction significantly affected this trait, with substantial partial η^2 values indicating biologically meaningful treatment effects. Jackfruit leaf extract at 50% produced the greatest advancement, while 100% was statistically at par, suggesting saturation of the floral-inductive response at the moderate concentration. RDF also reduced days to first flowering compared with unfertilised plants. The Jackfruit 50% $\times$ RDF treatment flowered earliest, whereas the unfertilised control was most delayed, indicating that earlier flowering reflected greater physiological readiness for reproductive transition rather than simply faster vegetative growth. The response may be associated with phenolics, flavonoids, tannins, and micronutrients in the extracts (Amadi *et al.*, 2018; Sayuti *et al.*, 2020). Their antioxidant activity may reduce oxidative stress and maintain shoot-apical meristem competence (Huang *et al.*, 2021), while cytokinin- and auxin-like activity may influence hormonal balance and source-sink relationships, favouring carbohydrate allocation towards reproductive development (Zhao *et al.*, 2022). Micronutrients, particularly K, Ca, and Mg, may additionally support enzyme activity, assimilate transport, membrane stability, chlorophyll retention, and floral initiation. Similar flowering responses to biostimulants in strawberry have been reported with moringa leaf extract, seaweed extract, and calcium-formate applications (Ngcobo and Bertling, 2021; Mohammed and Majeed, 2023; Bagh and Mishra, 2024; Zydlik *et al.*, 2024) [3, 4, 10, 19, 24, 30, 32].

RDF likely supplied the mineral nutrition required for this transition. Phosphorus supports energy transfer, K promotes enzyme activity and assimilate translocation, and balanced N sustains chlorophyll and photosynthetic capacity; excessive N, however, can favour vegetative growth and delay flowering (Choi *et al.*, 2024). Thus, the RDF response supports a threshold-nutrition concept in which adequate mineral availability permits reproductive transition, whereas nutrient limitation delays it, consistent with Raj and Prasad (2023) and Naili *et al.* (2024). The contrasting response reported by Choi *et al.* (2024) may reflect differences in nutrient status, particularly whether N remained below or exceeded the level favouring reproductive development. The earliest flowering under Jackfruit 50% $\times$ RDF suggests physiological complementarity rather than simple additive effects. The extract may have enhanced the acquisition and utilisation of supplied nutrients, promoting resource allocation towards reproductive development, consistent with combined biostimulant-nutrient responses reported by Mohammed and Majeed (2023), Raj and Prasad (2023), and Bagh and Mishra (2024). Conversely, the delayed unfertilised control agrees with reproductive constraints under limited nutrient availability (Naili *et al.*, 2024) [4, 6, 13, 17, 22].

4.3 Days to 50% Flowering: Days to 50% flowering extends the interpretation of flowering earliness by indicating the progression of flowering within the plant population. Leaf extract, RDF, and their interaction significantly affected this trait. Jackfruit leaf extract at its optimum concentration again produced the most favourable response, while RDF reduced the time to 50% flowering relative to unfertilised conditions. Jackfruit 50% $\times$ RDF produced the earliest progression to 50% flowering, whereas the untreated control was slowest. Unlike first flowering, therefore, this response reflects not only earlier reproductive initiation but also more rapid progression of flowering within the plant population. The

physiological basis builds directly on the mechanisms discussed for first flowering. Continued antioxidant protection and hormonal regulation may have reduced variation among developing meristems and promoted more coordinated floral commitment, while improved source-sink regulation could have distributed assimilates more evenly among developing floral sinks. Such coordination could favour more rapid and consistent progression of flowering. Sustained nutritional sufficiency under RDF would similarly support multiple developing buds through continued energy production, assimilate transport, and metabolic activity, consistent with balanced-fertilisation effects reported by Raj and Prasad (2023) and Naili *et al.* (2024).

The interaction further suggests that biostimulant priming enhanced the coordinated utilisation of mineral nutrition across multiple reproductive sinks, consistent with integrated biostimulant-nutrient responses reported by Mohammed and Majeed (2023), Raj and Prasad (2023), and Bagh and Mishra (2024). The earlier progression to 50% flowering may be associated with sustained source-sink and nutritional coordination rather than with an additional increase in vegetative growth. Importantly, the interaction represents enhanced utilisation of supplied mineral nutrition rather than fertiliser substitution [4, 13, 17, 22].

4.4 Number of Flowers per Plant: Number of flowers per plant is an important indicator of reproductive development and yield potential. Botanical leaf extracts, RDF, and their interaction significantly influenced floral production. Jackfruit leaf extract at its optimum concentration combined with RDF produced the highest number of flowers per plant, whereas the unfertilised control recorded the lowest. This response indicates enhanced reproductive development, potentially through improved assimilate allocation and physiological regulation toward floral development. The superior performance of Jackfruit leaf extract may be attributed to its phenolics, flavonoids, amino acids, and phytohormone-like constituents (Amadi *et al.*, 2018; Sayuti *et al.*, 2020), which may promote photosynthetic activity, floral sink strength, and meristematic development. Similar responses to nutrient- and phytohormone-rich biostimulants have been reported by Mohammed and Majeed (2023), Ngcobo and Bertling (2021), and Zydlik *et al.* (2024). RDF likely reinforced these effects by supplying N, P, and K required for photosynthesis, meristem differentiation, assimilate transport, and reproductive metabolism. This agrees with Jiang *et al.* (2023), who reported impaired flower-bud differentiation and reduced yield under N and P deficiency in strawberry. The higher flower production under Jackfruit leaf extract with RDF suggests a beneficial interaction between botanical stimulation and adequate nutrient supply. Comparable responses have been reported with moringa-based nutrition (Mohammed and Majeed, 2023), integrated organic-inorganic nutrition (Raj and Prasad, 2023), and seaweed extract combined with micronutrients (Bagh and Mishra, 2024). The increased floral production provides a greater reproductive base for fruit development and yield formation, supporting Jackfruit leaf extract as a supplementary biostimulant within integrated nutrient management in strawberry [3, 4, 12, 13, 19, 22, 24, 32].

4.5 Coordination among Flowering Traits

Correlation analysis revealed strong relationships among flowering traits. Days to first flowering and days to 50%

flowering showed a strong positive association ($r = 0.84$), indicating closely linked progression of flowering. In contrast, days to first flowering was strongly negatively associated with flower number ($r = -0.71$), while days to 50% flowering showed a similar negative relationship ($r = -0.62$). Thus, plants that flowered earlier and progressed more rapidly toward 50% flowering tended to produce more flowers, indicating coordinated reproductive development rather than independent trait responses. This pattern is consistent with shared hormonal and metabolic regulation of floral initiation, flowering progression, and subsequent flower production. Common influences of hormonal regulation, photosynthetic capacity, carbohydrate availability, and assimilate allocation may therefore contribute to the observed covariation among flowering traits. The strong association between flowering earliness and flower number has practical value because days to first flowering, and potentially days to 50% flowering, may serve as early indicators of subsequent reproductive performance. This relationship warrants further evaluation across cultivars to determine whether flowering earliness can serve as an early indicator of reproductive performance.

4.6 Integrating Botanical Leaf Extracts with RDF for Sustainable Reproductive Management

Strawberry reproductive performance, reflected in flowering initiation, progression, and flower number, was significantly influenced by botanical leaf extracts, RDF, and their interaction. Jackfruit leaf extract produced the most consistent reproductive response, while the positive extract $\times$ RDF interaction suggests a beneficial interaction between botanical stimulation and adequate nutrient supply. Botanical extracts may enhance nutrient-use efficiency, assimilate partitioning, and reproductive development, thereby strengthening the response to RDF. The association among flowering earliness, synchrony, and flower number further indicates their interconnected roles in reproductive performance. From an agronomic perspective, botanical extracts may serve a supplementary role within RDF-based nutrient management. The Jackfruit-RDF combination showed potential to promote earlier progression of flowering and greater floral production, which may favour pollination, fruit set, and more uniform harvesting. However, the effects of these responses on productivity and economic returns require direct validation. Further research should evaluate the Jackfruit-RDF combination across cultivars and environments and optimise extract concentration and application timing. Phytochemical, hormonal, transcriptomic, and metabolomic studies, including investigation of flowering-related genes such as *FT*, *SOC1*, *LFY*, and *API*, could clarify the underlying mechanisms and support integration with precision nutrient management (Wang *et al.*, 2025) [28].

5. Conclusion

This study demonstrated that botanical leaf extracts, RDF, and their interaction significantly influenced flowering behaviour and reproductive potential in strawberry. Jackfruit leaf extract 50% + RDF (A_5B_2) was the most effective treatment, while Jackfruit leaf extract 100% + RDF ($A_{10}B_2$) also performed among the best. Mango leaf extract 50% + RDF (A_5B_2) and Jamun leaf extract 50% + RDF (A_2B_2) showed favourable responses, whereas the untreated control without RDF (A_1B_1) recorded the poorest reproductive

performance. The integrated application of botanical extracts with RDF promoted earlier flowering progression and reproductive potential, indicating a beneficial interaction between botanical biostimulation and nutrient supply. Correlation analysis further indicated coordinated reproductive development, with earlier flowering associated with greater flower production. Botanical leaf extracts can serve as supplementary biostimulants within integrated nutrient management for sustainable strawberry production. Further validation across cultivars and agro-climatic conditions is warranted to establish the consistency and practical applicability of these responses.

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Declarations

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- **Data availability:** The data supporting the findings of this study are available from the corresponding author upon reasonable request.
- **Clinical trial number:** not applicable.
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- **Consent to Participate declaration:** not applicable.
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