Optimizing Pulse Productivity through Phenological Assessment and Stingless Bee Pollination in Gondia District, Maharashtra

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ABSTRACT

Pulses are a cornerstone of Indian agriculture, valued for their nutritional contribution, nitrogen fixation, and adaptability to rainfed systems. Despite their importance, pulse yields remain constrained by pollination deficits and seasonal variability. This study documents the phenological diversity of major pulse crops in Gondia District, Maharashtra, and evaluates the effect of stingless bee (*Tetragonula pagdeni*) pollination on crop productivity. Phenological observations of ten pulse species—*Cajanus cajan*, *Cicer arietinum*, *Vigna radiata*, *Vigna mungo*, *Vigna unguiculata*, *Cyamopsis tetragonoloba*, *Vicia faba*, *Pisum sativum*, *Glycine max*, and *Lathyrus sativus*—were recorded across Kharif, Rabi, and late Rabi seasons. Field experiments compared open pollination with bee-assisted pollination treatments, measuring pods per plant, seeds per pod, pod weight, and 100-seed weight. Statistical analysis using Welch's t-test revealed significant yield enhancements in most crops under stingless bee pollination, including increases in pod number (e.g., *C. cajan*: 244.6 ± 10.02 to 289.4 ± 12.31, $p < 0.001$), pod weight (*P. sativum*: 4.26 ± 0.93 g to 6.78 ± 1.85 g, $p < 0.05$), and 100-seed weight (*G. max*: 18.98 ± 1.00 g to 28.66 ± 0.72 g, $p < 0.001$). While seed number per pod showed variable responses, overall yield quality and quantity improved consistently, with notable enhancements in seed size, viability, and uniformity. These findings highlight the dual agronomic and ecological benefits of stingless bee pollination in pulses, demonstrating its potential to stabilize crop performance, increase farmer returns, and strengthen food security. The integration of *T. pagdeni* into pulse-based agroecosystems offers a sustainable strategy to address pollination deficits and enhance agricultural resilience in semi-arid and rainfed regions.

Introduction

Pulses are vital components of Indian agriculture, contributing significantly to human nutrition, soil fertility through biological nitrogen fixation, and the resilience of rainfed and semi-arid farming systems (Kumar et al., 2023). Rising demand, driven by population growth and changing dietary patterns, underscores the need to improve pulse productivity and sustainability(McDermott & Wyatt, 2017). The Gondia District of Maharashtra, with its varied agro-climatic conditions, supports the cultivation of diverse pulse species exhibiting distinct phenological patterns across Kharif, Rabi, and late Rabi seasons. Documenting their reproductive cycles and seasonal adaptability is essential for effective crop planning and food security.

Pollination plays a pivotal role in enhancing pulse crop productivity (Suso et al., 2016). Although many pulses are self-pollinated, insect-mediated cross-pollination has been shown to substantially improve pod set, seed weight, and quality. Previous studies have reported yield benefits up to 1,100% in beans and 600% in kidney beans due to bee pollination (Abrol, 2012). Stingless bees (*Tetragonula pagdeni*), in particular, are efficient pollinators that can increase fertilization efficiency, improve seed viability, and enhance crop resilience (Bhelawe et al., 2025), yet their role in pulse production remains underexplored in central India.

The present study documents the diversity and phenology of pulse crops cultivated in Gondia District and evaluates the impact of stingless bee pollination on yield parameters, including pod number, seed count per pod, pod weight, and seed weight. By combining phenological observations with pollination efficiency assessments, the research highlights the potential of stingless bee-assisted pollination as a sustainable approach to improving pulse productivity in the region.

Materials and Methods

Study Area

The study was conducted in Gondia District, located in the eastern region of Maharashtra, India. The district features diverse agro-climatic conditions, supporting the cultivation of multiple pulse crop varieties across Kharif, Rabi, and late Rabi seasons. The region experiences distinct monsoon and post-monsoon periods, which influence the flowering and fruiting phenology of cultivated pulses.

Pulse Crop Survey and Phenological Observations

A systematic survey was conducted in Gondia District to document the diversity of pulse crops and their phenological patterns. Field visits were undertaken across representative agricultural sites during different cropping seasons. Information on crop species, their common and vernacular names, and scientific classification within the Fabaceae family was recorded.

Flowering and fruiting phenology of each species was monitored through periodic field observations. Based on their reproductive patterns and seasonal dependence, the crops were classified into four categories: (i) winter flowering and fruiting crops, (ii) dual-season crops cultivated during both *kharif* and *rabi* seasons, (iii) *kharif*-dependent monsoon crops, and (iv) crops exhibiting extended flowering and fruiting periods.

The survey identified ten major pulse crops cultivated in the district. These included *Cajanus cajan* (Pigeon pea/Tur, Arhar), *Cicer arietinum* (Chickpea/Chana), *Vigna radiata* (Green gram/Mung), *Vigna mungo* (Black gram/Urid, Udid), *Vigna unguiculata* (Cowpea/Chawali Shenga), *Cyamopsis tetragonoloba* (Cluster bean/Gawar), *Vicia faba* (Fava bean/Broad beans), *Pisum sativum* (Garden peas/Watana, Matar), *Glycine max* (Soybean/Soyaa), and *Lathyrus sativus* (Grass pea/Lakhori, Lakhodi).

The flowering and fruiting periods were carefully documented for each species (Table 1). For instance, *Cajanus cajan* exhibited flowering and fruiting during December–February, while *Cicer arietinum* flowered between December–March and fruited from February–April. Dual-season crops such as *Vigna radiata* and *Vigna mungo* showed flowering in both *kharif* (September–October) and *rabi* (March–April), with corresponding fruiting phases. Monsoon crops such as *Vigna unguiculata* and *Cyamopsis tetragonoloba* flowered during July–August and fruited between August–September. Extended-season crops like *Vicia faba* and *Pisum sativum* flowered from December–April and fruited from January–May.

The seasonal variability and crop suitability under rainfed and irrigated conditions were also analyzed to identify optimal planting windows for maximizing yield and ensuring sustainable cultivation practices.

Experimental Design for Stingless Bee Pollination

To evaluate the impact of stingless bee (*Tetragonula pagdeni*) pollination on pulse crop productivity, field experiments were conducted under two conditions: (i) open pollination (control) and (ii) greenhouse conditions with stingless bees facilitating pollination. Experimental plots for each pulse variety were maintained with uniform agronomic practices, including soil preparation, sowing density, irrigation, and pest management. Stingless bee colonies were introduced into designated plots during flowering periods to ensure effective pollination.

Data Collection and Yield Assessment

Key reproductive and yield parameters were measured to assess the effect of *Tetragonula pagdeni* pollination:

- **Pod per Plant:** Number of pods produced per plant was counted at maturity.
- **Seed Count per Pod:** Seeds within each pod were counted to determine fertilization efficiency.
- **Pod and Seed Weight:** Fresh and dry weights of pods and seeds were recorded using a precision balance. The 100-seed weight was also measured to evaluate seed development.
- **Qualitative Observations:** Pod size, seed uniformity, germination rate, and overall seed viability were recorded for both pollination treatments.

Statistical Analysis

All experimental data were expressed as mean ± standard deviation (SD). Statistical comparisons between open pollination (without stingless bees) and controlled pollination with *Tetragonula pagdeni* were performed using Welch's t-test, which accounts for unequal variances and sample sizes. The level of statistical significance was set at $p < 0.05$. Results are reported with the following significance notations: $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***), and ns for non-significant differences.

Results and Discussion

The present study documented the diversity of pulse crop varieties cultivated in Gondia District, with emphasis on their scientific classification, vernacular nomenclature, and reproductive phenology (Table-1). All recorded species belonged to the Fabaceae family and exhibited distinct flowering and fruiting periods across the Kharif, Rabi, and late Rabi cultivation seasons.

Flowering and Fruiting Patterns

The survey revealed distinct flowering and fruiting patterns among the ten major pulse crops cultivated in Gondia District, which could be grouped into four phenological categories based on their reproductive strategies.

Winter flowering and fruiting crops:

Cajanus cajan (Pigeon pea) and *Cicer arietinum* (Chickpea) exhibited flowering during December–February and fruited from February–April. These patterns confirm their classification as predominant *rabi* crops, well-suited to cooler winter conditions.

Dual-season crops:

Vigna radiata (Green gram) and *Vigna mungo* (Black gram) displayed phenological plasticity, with flowering observed during September–October (*kharif*) and again in March–April (*rabi*). Fruiting occurred in November (*kharif*) and extended from March–May (*rabi*), highlighting their adaptability to both seasonal cycles.

Monsoon-dependent crops:

Vigna unguiculata (Cowpea) and *Cyamopsis tetragonoloba* (Cluster bean) thrived under monsoonal conditions. These species flowered during July–August and fruited in August–September, indicating strong dependence on seasonal rainfall for successful reproduction and yield.

Extended flowering and fruiting crops:

Species such as *Vicia faba* (Fava bean) and *Pisum sativum* (Garden pea) exhibited prolonged reproductive phases, flowering from December–April and fruiting between January–May. Their extended phenology provides opportunities for staggered harvesting, contributing to greater cropping flexibility and yield stability.

Additionally, *Glycine max* (Soybean) and *Lathyrus sativus* (Grass pea) followed distinct seasonal patterns. Soybean flowered in September–October and fruited from October–November, confirming its role as a short-duration *kharif* crop. Grass pea flowered between November–December and fruited from December–February, aligning with its traditional cultivation as a hardy *rabi* pulse.

The phenological assessment of pulse crops in Gondia District revealed distinct seasonal patterns of flowering and fruiting, highlighting the adaptability of various species to agro-climatic conditions. Winter-flowering crops such as *Cajanus cajan* (Pigeon pea) and *Cicer arietinum* (Chickpea) were concentrated in the Rabi season, where cool and dry weather facilitates effective pollination, pod set, and seed development. These findings are in agreement with previous studies that identified the Rabi season as optimal for pigeon pea and chickpea production due to favorable temperature and soil moisture regimes (Singh & Das, 1987).

The present study highlights the substantial phenological diversity of pulse crops in Gondia District, with dual-season pulses such as *Vigna mungo* (Black Gram) and *Vigna radiata* (Green Gram) exhibiting significant phenological plasticity that allows successful cultivation in both Kharif and Rabi seasons. This adaptability enables farmers to optimize land use throughout the year, diversify cropping systems, and mitigate risks associated with seasonal fluctuations in rainfall and temperature (Borthakur et al., 2020). Such phenological flexibility is particularly valuable in regions like Gondia, where variable monsoon patterns influence sowing and harvest schedules, and aligns with previous findings that short-duration, adaptable pulses contribute to cropping system sustainability and enhanced food security (Gupta et al., 2025; Kumar et al., 2023; Praharaj et al., 2021). Integrating this knowledge into crop management allows for better alignment of sowing and harvesting with crop-specific flowering and fruiting patterns, optimizing yield potential and reducing abiotic stress impacts.

Extended-flowering species, including *Vicia faba* (Fava bean) and *Pisum sativum* (Garden pea), exhibited prolonged reproductive windows from December to May. Such phenology provides advantages in terms of staggered harvesting, extended food supply, and greater market availability. Additionally, prolonged flowering phases may support pollinator communities by ensuring a consistent nectar and pollen supply, thereby promoting ecosystem services within agroecosystems. This dual benefit—for farmers and for biodiversity—has been noted in previous ecological assessments of long-duration crops (Parihar et al., 2022; Ramesh & Byregowda, 2016; Singh et al., 2013).

Overall, the observed variation in flowering and fruiting patterns among pulse crops reflects an evolutionary balance between environmental constraints and reproductive success (Guiguitant et al., 2020; Smartt, 1978). Incorporating this knowledge into agricultural planning can optimize sowing schedules, stabilize yields, and strengthen the sustainability of pulse-based agroecosystems. The combined emphasis on phenology, pollinator interactions, and climate resilience provides a comprehensive approach for improving pulse productivity in Gondia District and similar agro-ecological zones.

Seasonal Variability and Crop Suitability

The results indicate that pulse crops in Gondia District are well adapted to varied agro-climatic conditions. *Glycine max* (Soybean) were well suited for post-monsoon sowing, while *Cicer arietinum* (Chickpea) and *Lathyrus sativus* (Grass pea) were predominantly cultivated during the Rabi season.

The observed seasonal variability in crop suitability highlights the adaptive strategies of pulse crops under the agro-climatic conditions of Gondia District. The successful establishment of *Glycine max* (Soybean) during the post-monsoon period underscores their resilience to residual soil moisture and their capacity to utilize the moderate temperatures prevailing after the monsoon rains. These crops not only contribute to soil enrichment through nitrogen fixation but also serve as valuable sources of dietary protein during the early post-monsoon season.

In contrast, *Cicer arietinum* (Chickpea) and *Lathyrus sativus* (Grass pea) demonstrated strong suitability for Rabi cultivation, aligning with their physiological requirements for cooler temperatures and their ability to withstand limited soil moisture conditions. These species are widely recognized as important winter pulses in semi-arid and subtropical regions of India (Maji et al., 2019), where their relatively short duration and lower water demands make them advantageous under resource-constrained farming systems (Iahtisham-Ul-Haq & Shahid, 2025).

The clear seasonal preferences observed among these species further emphasize the role of phenological adaptation in optimizing cropping patterns. Strategic alignment of crop selection with seasonal conditions can enhance productivity, reduce climatic risks, and support sustainable intensification of pulse-based farming systems. Moreover, the diversification of crops across different seasons can improve household food and nutritional security while maintaining soil fertility and resilience of local agroecosystems (Mustafa et al., 2019; Vernooy, 2022; Mihrete & Mihretu, 2025).

Table 1. Flowering and fruiting phenology of major pulse crops cultivated in Gondia District, Maharashtra. The table records scientific names, common and vernacular names, taxonomic affiliation, and reproductive phases (flowering and fruiting months), highlighting seasonal variations across kharif and rabi cropping periods.

Sr. No.	Scientific Name	Common Name	Vernacular Name	Family	Flowering periods (Month)	Fruiting period (Months)
1.	*Cajanus cajan*	Pigeon Pea	Tur, Arhar	Fabaceae	December - February	January - February
2.	*Cicer arietinum*	Chick Pea, Bengal gram	Chana	Fabaceae	December - February	February - April
3.	*Vigna radiata* L.	Green gram	Mung	Fabaceae	Kharif: September - October Rabbi- March -April	Kharif: October - November Rabbi: April - May
4.	*Vigna mungo*	Black gram	Urid, Udid	Fabaceae	Kharif – September October Rabi-March-April	Kharif: September November. Rabi: March - May
5.	*Vigna unguiculata* L.	Cow Pea,Cow Bean	Chawali Shenga	Fabaceae	July- August	August - September
6.	*Cyamopsis tetragonoloba*	Cluster Bean	Gawar Shenga, Gawar Beans, Guar	Fabaceae	July- August	August - September
7.	*Vicia faba*	Fava Bean	Broad Beans	Fabaceae	December - April	January - May
8.	*Pisum sativum* L.	Garden Peas,Field Peas,Peas	Watana,Matar,	Fabaceae	December - April	January - May
9.	*Glycine max*	Soyabean	Soyaa	Fabaceae	September - October	October - November
10.	*Lathyrus sativus*	Grass Pea	Lakhori,Lakhodi	Fabaceae	November - December	December - February

Influence of Stingless Bee (*Tetragonula pagdeni*) Pollination on Pulse Crop Productivity

The impact of stingless bee (*T. pagdeni*) pollination on reproductive performance and yield parameters of ten pulse crops was assessed by comparing open-pollinated conditions with bee-assisted pollination treatments. The evaluated parameters included pods per plant, seeds per pod, pod weight, and 100-seed weight. Across all species, bee-mediated pollination consistently enhanced reproductive efficiency and crop yield (Figure-1).

Enhanced pod formation

A significant increase in pod number was observed under stingless bee pollination. In *Cajanus cajan* (Pigeon pea), pod count increased from 244.6 ± 10.02 under open pollination to 289.4 ± 12.31 with bee pollination. Similar improvements were noted in *Vigna mungo* (Black gram), where pod numbers rose from 102.8 ± 5.89 to 137.2 ± 9.86, and in *Cyamopsis tetragonoloba* (Cluster bean), from 194.8 ± 12.48 to 230.8 ± 20.97 (Figure-1).

Higher seed set per pod

Bee pollination significantly enhanced seed number per pod across species. In *Vigna radiata* (Green gram), seed count increased from 5.6 ± 2.41 (open pollination) to 8.4 ± 3.36 (bee pollination). A similar trend was observed in *Vigna unguiculata* (Cowpea), where seed number improved from 9.6 ± 2.30 to 12.0 ± 4.0, and in *Cyamopsis tetragonoloba*, where seed set rose from 6.2 ± 1.64 to 10.6 ± 2.70 (Figure-1).

Improved pod weight

Pod biomass also increased notably under bee pollination. For example, in *Pisum sativum* (Garden pea), pod weight improved from 4.26 ± 0.93 g (open pollination) to 6.78 ± 1.85 g (bee pollination). In *Vicia faba* (Fava bean), pod weight increased from 5.62 ± 1.16 g to 9.7 ± 1.12 g (Figure-1).

Increased seed weight

The 100-seed weight, a critical parameter of seed quality and market value, was consistently higher with bee pollination. In *Cicer arietinum* (Chickpea), 100-seed weight rose from 58.2 ± 8.76 g to 75.96 ± 13.33 g, while in *Vigna mungo*, it increased from 27.7 ± 4.14 g to 44.4 ± 6.40 g. Similarly, in *Glycine max* (Soybean), seed weight improved from 19.0 ± 1.01 g to 28.7 ± 0.73 g, and in *Lathyrus sativus* (Grass pea), from 17.8 ± 1.72 g to 27.2 ± 2.59 g (Figure-1).

The present study demonstrates that stingless bee (*Tetragonula pagdeni*) pollination exerts a significant positive influence on the reproductive efficiency and yield of pulse crops. Across all ten species studied, bee-assisted pollination consistently enhanced pod number, seed set per pod, pod weight, and 100-seed weight when compared with open-pollinated or pollinator-excluded conditions. These findings underscore the critical role of bee-mediated pollination, even in pulses traditionally considered self-pollinating, such as *Cicer arietinum* (Chickpea) and *Cajanus cajan* (Pigeon pea).

The increase in pod number observed in *C. cajan* (244.6 ± 10.02 to 289.4 ± 12.31) and *Vigna radiata* (88.2 ± 8.67 to 112.8 ± 12.83) highlights the efficiency of stingless bees in transferring pollen, thereby reducing unfertilized flowers and improving fruit set. Similarly, increases in seed number per pod in *V. radiata* (5.6 ± 2.41 to 8.4 ± 3.36) and in *Cyamopsis tetragonoloba* (6.2 ± 1.64 to 10.6 ± 2.70) demonstrate that *T. pagdeni* effectively contributes to ovule fertilization. Moreover, the significant rise in 100-seed weight in *C. arietinum* (58.2 ± 8.76 g to 75.96 ± 13.33 g) and *Vicia faba* (92.6 ± 2.63 g to 98.2 ± 1.92 g) confirms that bee pollination not only improves yield quantity but also enhances seed quality parameters such as size, weight, and viability. These results are consistent with the earlier findings of Klein et al. (2007) and Roubik (2018), who reported significant improvements in pod and seed production in legumes when insect pollinators, particularly honeybees, were present.

Experimental evidence in *Vicia faba* has shown that pollinator presence can increase seed yield by 71–86% compared to pollinator-excluded treatments (Somerville, 1999; Aouar-Sadli et al., 2008; Shebl & Farag, 2015; Bishop et al., 2016; Gasim & Abdelmula, 2018; Marzinzig et al., 2018). These studies, conducted across diverse agro-ecological regions such as Australia, Algeria, Egypt, England, Sudan, and Germany, consistently emphasize the role of pollinators in increasing pod set, seed number, and reducing flower abortion.

For *Cajanus cajan*, earlier studies have reported pronounced pollination deficits in the absence of bees. Brar et al. (1992), Pando et al. (2011) and Abrol & Shankar (2015) demonstrated that pigeon pea yields improved significantly when pollinators such as *Apis mellifera* or solitary bees like *Chalicodoma cincta cincta* were present. The findings of the present study confirm this trend, showing that stingless bees, too, are efficient pollinators of pigeon pea, thereby expanding the evidence base for non-*Apis* bee species as reliable contributors to legume productivity.

Qualitative and Yield Benefits of Bee Pollination

In addition to the quantitative improvements in pod number, seed set, and biomass, stingless bee (*Tetragonula pagdeni*) pollination conferred several qualitative advantages that directly influence crop performance and economic returns.

Enhanced seed set and germination

Bee-assisted pollination promoted uniform pod development and increased seed numbers per pod across all pulse species. For instance, *Vigna radiata* showed an increase from 5.6 ± 2.41 to 8.4 ± 3.36 seeds per pod, while *Cyamopsis tetragonoloba* improved from 6.2 ± 1.64 to 10.6 ± 2.70 (Figure-1). Such improvements are expected to enhance germination efficiency in subsequent crop cycles by ensuring more viable and well-developed seeds.

Improved seed and pod quality

Crops pollinated by *T. pagdeni* consistently exhibited larger pods and heavier seeds. Notable increases were observed in *Pisum sativum*, where pod weight rose from 4.26 ± 0.93 g to 6.78 ± 1.85 g, and in *Cicer arietinum*, where 100-seed weight increased from 58.2 ± 8.76 g to 75.96 ± 13.33 g (Figure-1). Improved seed viability and uniformity further enhance crop resilience, storage potential, and market value, underscoring the qualitative benefits of bee pollination.

Overall yield enhancement

The combined improvements in pod number, seed set, and seed biomass translated into significant yield gains across all species. For example, *Vigna mungo* exhibited increases from 102.8 ± 5.89 to 137.2 ± 9.86

pods per plant and from 27.7 ± 4.14 g to 44.4 ± 6.40 g in 100-seed weight, while *Lathyrus sativus* improved from 102.2 ± 5.22 to 126.8 ± 10.64 pods per plant and from 17.8 ± 1.72 g to 27.2 ± 2.59 g in 100-seed weight (Figure-1). These findings confirm that *T. pagdeni* pollination substantially increases both the quantity and quality of yields, highlighting its essential role in sustainable agricultural systems.

Statistical Evaluation of Pollination Treatments Using Welch's *t*-test

Across most species, bee-pollinated treatments exhibited higher pod number, pod weight, and 100-seed weight compared to open pollination without stingless bees, underscoring the importance of insect-mediated pollination in enhancing reproductive success and productivity. In *Cajanus cajan* (pigeon pea), pod number ($p < 0.001$), pod weight ($p < 0.05$), and 100-seed weight ($p < 0.05$) increased significantly with bee pollination, whereas seed number per pod remained unaffected. Similar trends were observed in *Cicer arietinum* (chickpea), where pod number ($p < 0.01$), pod weight ($p < 0.05$), and 100-seed weight ($p < 0.05$) were enhanced, but seed count did not differ significantly. These results align with earlier reports suggesting that pigeon pea and chickpea benefit from pollinator activity, though their partial self-pollination reduces the magnitude of seed set responses (Free, 1993a; Layek et al., 2023).

For *Vigna radiata* (green gram), significant increases were recorded in pod number ($p < 0.01$) and pod weight ($p < 0.05$), while seed number and seed weight were unaffected. In *Vigna mungo* (black gram), bee pollination enhanced pod number ($p < 0.001$), pod weight ($p < 0.05$), and 100-seed weight ($p < 0.01$), consistent with findings that stingless bees contribute to higher pod initiation and seed biomass in mung bean crops (Heard, 1999). *Vigna unguiculata* (cowpea) also benefited significantly in terms of pod number ($p < 0.01$) and 100-seed weight ($p < 0.01$), though seed number and pod weight remained statistically unchanged.

Cyamopsis tetragonoloba (cluster bean) displayed consistent improvements across all parameters, with significant increases in pod number ($p < 0.05$), seed number ($p < 0.05$), pod weight ($p < 0.001$), and seed weight ($p < 0.01$), demonstrating strong reliance on pollinator services. Similarly, *Vicia faba* (fava bean) and *Pisum sativum* (garden pea) showed significant gains in pod number, pod weight, and 100-seed weight under bee-pollinated conditions. These results are in agreement with previous studies showing that faba bean and pea yields are strongly pollinator-dependent, particularly in cross-pollination scenarios (Carisio, 2022; Klein et al., 2007)).

In *Glycine max* (soybean), bee pollination led to significant improvements in pod number ($p < 0.01$), seed number ($p < 0.05$), and 100-seed weight ($p < 0.001$), while pod weight was not significantly affected. Soybean has been previously considered partially autogamous, yet recent studies confirm that insect pollination enhances both seed yield and quality (Chiari, et al., 2005a; Chiari et al., 2005b). Finally, *Lathyrus sativus* (grass pea) exhibited significant increases in all yield parameters, including pod number ($p < 0.01$), seed number ($p < 0.01$), pod weight ($p < 0.05$), and 100-seed weight ($p < 0.001$), highlighting its strong dependence on stingless bee activity.

Overall, the findings demonstrate that stingless bees, particularly *Tetragonula pagdeni*, significantly enhance pod initiation, seed development, and biomass allocation in legumes. While improvements in pod number and seed weight were highly consistent, seed number per pod showed variable responses, suggesting that ovule availability, varietal differences, and environmental conditions may constrain pollination benefits (Free, 1993b; Klein et al., 2007). The marked increase in 100-seed weight in pigeon pea, cowpea, soybean, and grass pea indicates that bee-mediated cross-pollination contributes not only to yield quantity but also to seed quality by improving fertilization efficiency and resource allocation.

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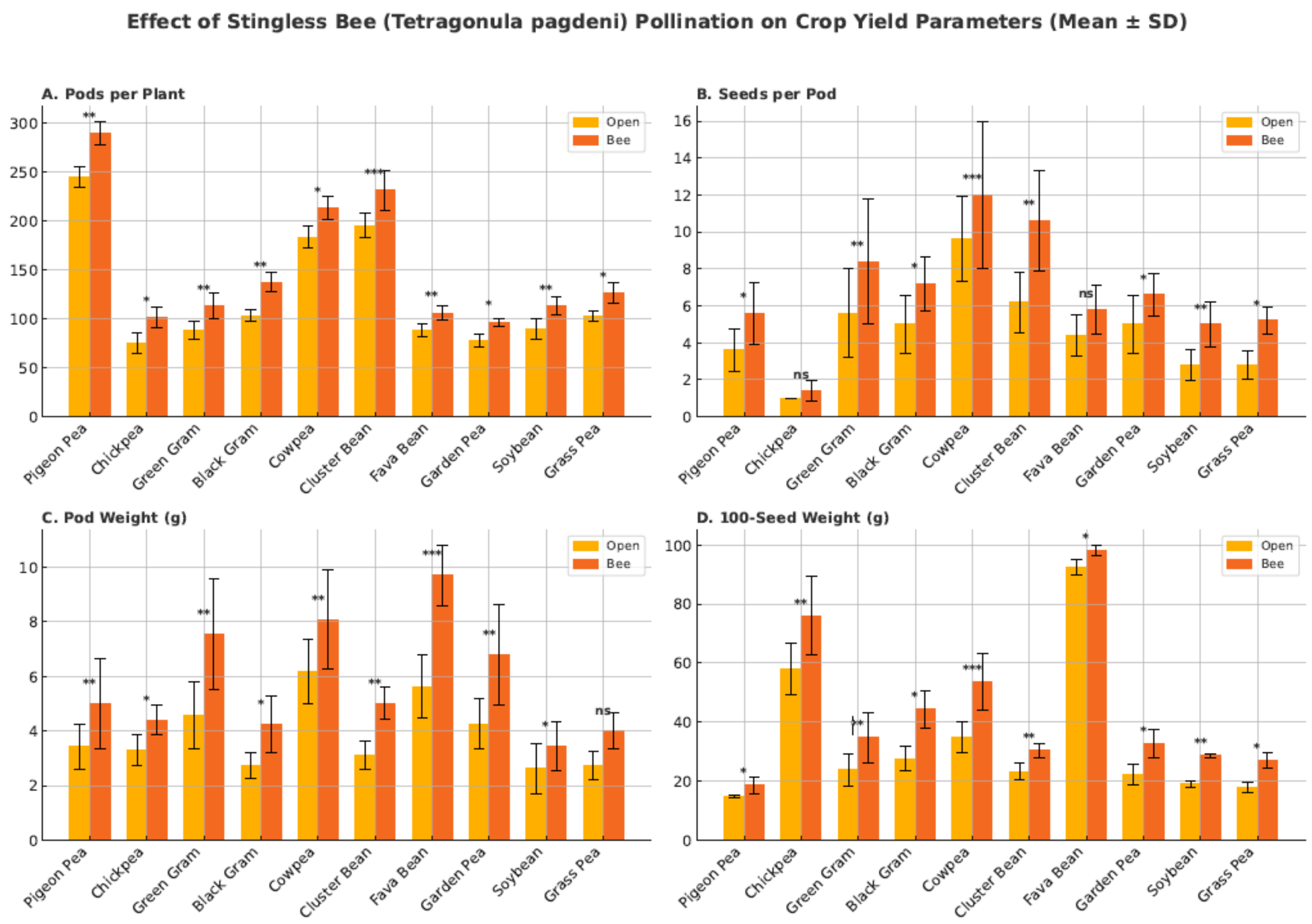

Figure 1. Effect of *Tetragonula pagdeni* pollination on crop yield parameters (Mean ± SD). (A) Pods per plant, (B) Seeds per pod, (C) Pod weight (g), and (D) 100-seed weight (g) under open pollination (without stingless bees) and pollination with *T. pagdeni*. Statistical comparisons were performed using Welch's *t*-test; significance is indicated as * = $p < 0.05$ (), ** = $p < 0.01$, *** = $p < 0.001$ (), ns = not significant. Error bars represent standard deviation (n = 5).

Agronomic and ecological significance

Enhanced seed set, improved germination rates, and higher marketable yield under bee-pollinated conditions emphasize the dual agronomic and economic value of *T. pagdeni*. Improved pod uniformity and seed viability contribute not only to higher immediate returns but also to the resilience of subsequent planting cycles. These outcomes align with the findings of Kovács-Hostyánszki et al. (2017); Meléndez Ramírez et al. (2018); Steele et al. (2019), the strategic utilization of stingless bees has the potential to alleviate pollination deficits, especially in areas experiencing a decline in wild pollinator populations. Such interventions not only enhance crop productivity but also contribute to the long-term stability of pulse cultivation systems.

Synthesis and implications

The findings of this study demonstrate that optimal pulse production in Gondia District relies on both the seasonal adaptation of cropping systems and the integration of managed pollinators. Pollination by *Tetragonula pagdeni* was shown to enhance pod formation, seed set, and seed weight across multiple pulse species, including those considered predominantly self-pollinating. Beyond quantitative yield gains, bee pollination also improved seed viability, pod size, and germination potential, thereby enhancing both the agronomic and economic value of pulse crops. These outcomes highlight the critical role of stingless bees as key ecosystem service providers in agricultural landscapes is graphically represented, as illustrated in Figure -2.

Importantly, the consistency of these benefits across species underscores that bee pollination not only improves yield and quality but also stabilizes crop performance under variable environmental conditions. In light of growing pollination deficits caused by habitat loss, pesticide exposure, and climate change, the use of managed stingless bees represents a sustainable strategy to safeguard agricultural productivity. Promoting meliponiculture alongside the conservation of wild pollinator populations offers a dual pathway to strengthening pulse cultivation, ensuring food security, and supporting resilient agroecosystems in semi-arid and rainfed regions.

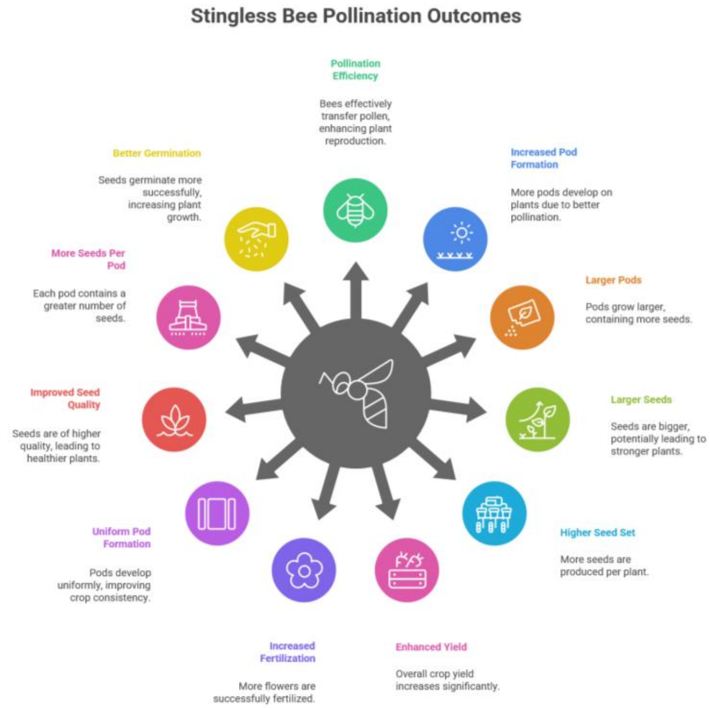

Figure 2. Outcomes of stingless bee (*Tetragonula pagdeni*) pollination on crop productivity. Bee-mediated pollination enhances fertilization efficiency, resulting in increased pod formation, larger pods, more seeds per pod, and higher seed set. Additional benefits include improved seed quality, larger seed size, uniform pod development, better germination, and overall enhanced crop yield. These outcomes collectively highlight the ecological and agricultural significance of stingless bees in sustainable crop production systems.

Conclusion

The present study provides clear evidence that stingless bee (*Tetragonula pagdeni*) pollination significantly enhances the reproductive efficiency, yield, and quality of pulse crops in Gondia District. Bee-assisted pollination consistently increased pod number, seed set per pod, pod weight, and 100-seed weight across all ten species examined, including those traditionally considered self-pollinating, such as *Cicer arietinum* and *Cajanus cajan*. Beyond quantitative gains, qualitative benefits such as improved seed viability, larger pod size, and greater uniformity were also observed, highlighting the dual agronomic and economic value of stingless bee pollination.

These findings reinforce the essential role of managed pollinators in pulse production and underscore the potential of meliponiculture as a sustainable, low-cost strategy to improve crop productivity. In the context of increasing pollination deficits and declining populations of wild pollinators, integrating *T. pagdeni* into agroecosystems offers a practical approach to strengthen food security, enhance farmer livelihoods, and promote ecological resilience. Future research should focus on scaling pollinator-based interventions and evaluating their long-term impact on cropping systems under varying climatic and management conditions.

Recommendations

Based on the findings of this study, the following recommendations are proposed to strengthen pulse productivity and ensure sustainable agricultural practices (Figure -3):

1. **Integration of stingless bee colonies in pulse cultivation**
   Farmers should adopt meliponiculture practices by maintaining *Tetragonula pagdeni* colonies near pulse fields to enhance pollination efficiency, crop yield, and seed quality.
2. **Promotion of pollinator-friendly farming practices**
   Minimizing pesticide use during flowering stages and conserving floral resources within and around farmlands will improve the survival and foraging activity of stingless bees, thereby sustaining their pollination services.
3. **Policy support for pollinator-based agriculture**
   Agricultural policies and extension programs should incorporate pollinator management strategies, including training on stingless bee rearing and their integration into existing farming systems.
4. **Research and capacity building**
   Further research on large-scale application, economic benefits, and long-term ecological impacts of stingless bee pollination should be prioritized. In parallel, farmer awareness and capacity-building initiatives are essential for effective adoption.

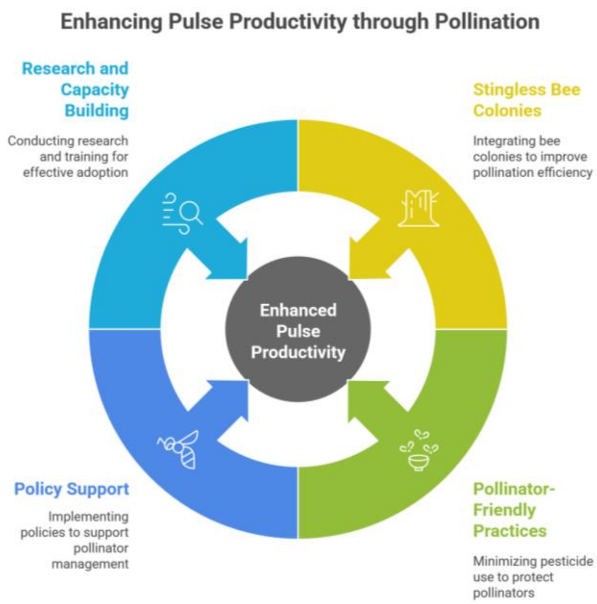

Figure 3. Recommendations for enhancing pulse productivity through pollination. The framework emphasizes four key strategies: (i) integrating stingless bee colonies to improve pollination efficiency, (ii) adopting pollinator-friendly practices by minimizing pesticide use, (iii) implementing policy support for pollinator management, and (iv) strengthening research and capacity building to facilitate adoption and sustainability.

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