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Stingless Bee-Assisted Pollination Improves Yield and Oil Content in Oilseed Crops of Central India

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Abstract
Oilseed crops form a critical component of agricultural economies, providing edible oils, industrial raw materials, and biofuel resources. This study investigated the diversity, phenology, and pollination ecology of twelve cultivated and five non-cultivated oilseed species in Gondia District, Maharashtra, India, with a particular focus on the role of stingless bees (Meliponini) in enhancing crop productivity. Phenological observations revealed staggered flowering and fruiting cycles among cultivated species such as Brassica campestris, Helianthus annuus, and Arachis hypogea, complemented by perennial tree species including Cocos nucifera and Azadirachta indica, further contributed to ecological stability and oilseed resource continuity. Controlled pollination experiments demonstrated that stingless bee pollination significantly enhanced pod and seed set, seed weight, and oil content in major crops such as sunflower, mustard, sesame, and groundnut. Comparative analyses revealed marked improvements in both seed yield and quality under stingless bee-assisted pollination relative to open pollination. These findings are consistent with previous studies demonstrating the positive impact of managed pollinators on Brassica and other oilseed species. The results highlight the complementary roles of honey bees, stingless bees, and wild pollinators in sustaining oilseed productivity. Promoting meliponiculture alongside apiculture offers a viable strategy for ecological intensification, yield stability, and climate-resilient agriculture. Incorporating stingless bee pollination into diversified farming systems can therefore contribute to both enhanced agricultural output and sustainable rural livelihoods.
Keywords: Oilseed crops; Stingless bees; Pollination ecology; Phenology; Crop productivity; Meliponiculture; Sustainable agriculture; Gondia District

INTRODUCTION
Oilseed crops represent a fundamental component of global agriculture, serving as key sources of raw materials for edible oils, industrial applications, and biofuel production (Lafarga, 2021). In the Indian agricultural economy, oilseeds occupy a prominent position, with a wide range of species cultivated across diverse agro-climatic zones (GoI, 2013). The productivity and quality of these crops are shaped by multiple interrelated factors, including genetic diversity, phenological patterns, pollination ecology, and agricultural management practices (Sharma, 2014). A comprehensive understanding of the temporal dynamics of flowering and fruiting cycles, along with the ecological role of pollinators in enhancing yield and oil quality, is therefore essential for optimizing oilseed production.
Pollinators, particularly bees, play a pivotal role in sustaining global agricultural systems. It is estimated that approximately 75% of the major food crops of the world derive benefits from animal-mediated pollination, with honey bees functioning as the principal pollinators of numerous flowering plants, including oilseed crops (Klein et al., 2007; Khalifa et al., 2021). Beekeeping, practiced for centuries, has been integral to human society by contributing to sustainable agriculture, improving crop productivity, maintaining plant genetic diversity, and supporting ecosystem stability. Stingless bees (Meliponini) are effective pollinators owing to their foraging efficiency, floral constancy, and ability to pollinate a wide range of crops (Meléndez Ramírez et al., 2018).
The mutualistic relationship between bees and Brassica species exemplifies this ecological interdependence, as oilseed crops provide nectar and pollen resources, while insect pollination enhances seed set and oil yield (Abrol, 2024). Although many oilseed species exhibit self-compatibility, pollinator activity remains crucial in maximizing reproductive success. Rapeseed–mustard, a predominantly cross-pollinated crop, is highly attractive to a wide spectrum of insect visitors (Abrol, 2007). Recent evidence suggests that stingless bee pollination significantly enhances pod formation, seed set, seed weight, and oil content across diverse oil seed species. Moreover, self-incompatible cultivars are of particular importance

in hybrid seed production, yet their specific pollination requirements remain insufficiently understood, underscoring the need for further research in this area.

The Gondia District of Maharashtra represents an important agro-ecological zone where both cultivated and non-cultivated oil seed species contribute to household sustenance, commercial markets, and traditional oil extraction practices. Cultivated oil seed crops in the region are represented by twelve economically significant species spanning diverse botanical families, including Brassicaceae, Fabaceae, Asteraceae, Pedaliaceae, Euphorbiaceae, Malvaceae, Linaceae, and Poaceae. These crops exhibit marked variation in reproductive phenology, ranging from short seasonal cycles in linseed and sesame to extended or dual cropping systems in rice. Such temporal diversity is particularly relevant for agricultural planning, sequential cropping, and ensuring continuous availability of floral resources for pollinators.

In addition to cultivated species, Gondia District harbors non-cultivated oil seed trees of considerable ecological and economic value. Species such as Cocos nucifera (Coconut), Elaeis guineensis (Oil palm), Pongamia pinnata (Indian beech), Madhuca longifolia (Mahua), and Azadirachta indica (Neem) provide sustainable sources of oil, supporting both traditional practices and emerging demands for renewable bio-resources. Their varied flowering and fruiting phenology offers year-round or seasonally staggered seed production, enhancing ecological resilience and contributing to rural livelihoods.

Given the agricultural, ecological, and economic importance of oil seeds, the present study was undertaken to (i) document the diversity and phenology of cultivated and non-cultivated oil seed crops in Gondia District, (ii) evaluate their reproductive cycles in relation to resource availability, and (iii) assess the role of stingless bee pollination in enhancing yield, seed quality, and oil content. The findings provide critical insights for agricultural planning, pollination management, and the sustainable intensification of oil seed production.

MATERIALS AND METHODS

Study Area

The present investigation was conducted in Gondia District, Maharashtra, an agrarian region characterized by subtropical climatic conditions and diverse cropping systems. The area supports both cultivated oil seed crops and non-cultivated oil seed tree species that contribute significantly to local agricultural production and traditional oil extraction practices. Field surveys were undertaken across representative agricultural fields and natural habitats between 2022 and 2024, covering both Kharif and Rabi cropping seasons.

Documentation of Cultivated Oil Seed Crops

A total of twelve cultivated oil seed crops were selected for the study based on their economic importance and prevalence in Gondia District. These included species from diverse botanical families such as Brassicaceae (Brassica campestris, Brassica nigra, Brassica napus), Fabaceae (Arachis hypogea, Glycine max), Asteraceae (Helianthus annuus, Carthamus tinctorius), Pedaliaceae (Sesamum indicum), Euphorbiaceae (Ricinus communis), Malvaceae (Gossypium arboreum), Linaceae (Linum usitatissimum), and Poaceae (Oryza sativa). For each species, phenological observations were recorded to document the flowering and fruiting periods. Data collection was carried out through fortnightly field visits, and flowering and fruiting stages were determined by direct visual assessment and farmer interviews. In the case of rice, observations were made separately for both Kharif and Rabi cropping cycles.

Documentation of Non-Cultivated Oil Seed Tree Species

Five non-cultivated oil seed tree species commonly found in the district were also studied, namely Cocos nucifera (Coconut), Elaeis guineensis (Oil palm), Pongamia pinnata (Indian beech), Madhuca longifolia (Mahua), and Azadirachta indica (Neem). For these species, flowering and fruiting data were obtained through seasonal field surveys and complemented by discussions with local farmers and forest dwellers. Species with extended or continuous reproductive phases, such as coconut and oil palm, were monitored throughout the year to record periodicity and intensity of flowering and fruiting.

Experimental Design for Pollination Studies

To evaluate the role of stingless bees in enhancing oil seed crop productivity, controlled pollination experiments were conducted on selected cultivated species. Two experimental conditions were established:

1. Open Pollination (Control): Plants were exposed to natural field conditions without stingless bee intervention.

2. Stingless Bee Pollination (Treatment): Plants were enclosed within greenhouse cages (dimensions 3 × 3 × 2 m) containing established colonies of stingless bees (Tetragonula pagdeni). Colonies were maintained under standard apicultural practices to ensure adequate foraging activity.

For each crop species, a minimum of 20 plants per treatment were selected randomly, and experiments were replicated in three independent trials across different cropping seasons to minimize environmental bias.

Data Collection

Reproductive parameters were recorded to assess the impact of stingless bee pollination. These included:

- Pod and seed set: Number of pods per plant, seeds per pod, and seeds per flower head (in the case of sunflower).
- Seed weight: Mean seed weight per pod and weight per 100 seeds.
- Oil content: Oil percentage was determined using the Soxhlet extraction method with petroleum ether as solvent.
- Seed quality and uniformity: Evaluated by measuring seed size, shape, and consistency across treatments.

Data Analysis

The collected data were subjected to **comparative analysis** between open pollination and stingless bee pollination treatments. Mean values, ranges, and percentage improvements were calculated for each parameter.

RESULTS AND DISCUSSION

Diversity and Phenology of Cultivated Oil Seed Crops

The survey of Gondia District revealed twelve economically significant cultivated oil seed crops belonging to diverse botanical families, each exhibiting distinct flowering and fruiting phenologies. Species from the Brassicaceae family, such as Brassica campestris (Mustard), B. nigra (Black mustard), and B. napus (Rape seed), flower between January and May with fruiting from February to June. In contrast, members of the Fabaceae (Arachis hypogea – groundnut, Glycine max – soybean) showed extended reproductive cycles, flowering from February to October and fruiting from March to November. Similarly, Asteraceae representatives (Helianthus annuus – sunflower, Carthamus tinctorius – safflower) displayed flowering from February to May, followed by fruiting until June.

Other crops, such as Sesamum indicum (Sesame), Ricinus communis (Castor), Gossypium arboreum (Cotton), Linum usitatissimum (Linseed), and Oryza sativa (Rice), contributed additional temporal diversity, ensuring a staggered availability of floral resources throughout the year. This sequential phenology supports sustained agricultural production and provides nectar and pollen for pollinators across extended periods. These results are consistent with Abrol (2024) demonstrated that staggered flowering of oil seed crops stabilizes pollinator populations and enhances regional agroecosystem resilience.

Contribution of Non-Cultivated Oil Seed Tree Species

The study further documented five non-cultivated oil seed tree species of ecological and economic significance. Cocos nucifera (Coconut) and Elaeis guineensis (Oil palm) of the Arecaceae family flower and fruit continuously throughout the year, making them reliable and sustainable sources of oil. Seasonally restricted phenology was observed in Pongamia pinnata (Indian beech) and Madhuca longifolia (mahua), which are traditionally important oil-yielding trees. Notably, Azadirachta indica (neem) exhibited an extended reproductive cycle, fruiting twice annually, thereby ensuring prolonged seed availability.

These findings emphasize the complementary role of perennial non-cultivated species in supplementing oil production while providing year-round ecological resources. Similar observations have been made by Kumar (2024), who highlighted the dual role of such tree species in livelihood security and biodiversity conservation.

Role of Stingless Bees in Enhancing Oil Seed Productivity

Controlled pollination trials revealed significant positive effects of stingless bee (Tetragonula pagdeni) pollination on multiple reproductive parameters across studied crops. In sunflower, seed counts per head increased to 140-170 under stingless bee pollination compared to 105-145 under open pollination. Mustard showed an increase in pod number per plant from 90-170 to 120-210. Oil content also improved markedly, with groundnut increasing from 39-49% to 46-58% and linseed from 34-41% to 39-46%.

Seed quality and uniformity were enhanced under stingless bee pollination. For example, sesame exhibited higher seed counts per pod (47–90 compared to 40–78 in open pollination), while soybean recorded increases in both seed number and weight per 100 seeds (4 g compared to 4.97 g). Yield enhancement was also evident in castor and cotton, which showed increases in both pod/seed number and seed weight.

These findings confirm earlier reports on the efficiency of stingless bees as pollinators (Heard, 1999) and highlight their role in improving not only crop yield but also seed quality and oil content. The observed improvement in biochemical composition of oil seeds is consistent with Bommarco et al. (2012), who linked effective insect-mediated pollination to enhanced nutritional and commercial value of oil seed crops. Deodikar & Suryanarayana (1972) highlighted the beneficial role of bee pollination in oilseed cultivation, observing a statistically significant increase in seed yield when compared to self-pollinated crops.

The role of insect pollinators, particularly bees, in enhancing the productivity of oilseed crops has been extensively documented. Pollination by managed bee colonies not only increases pod setting and seed weight but also enhances oil content and germination rates (Langridge & Goodman, 1975; Abrol, 2007; Abrol, 2024). Langridge & Goodman (1975) reported that bee visitation significantly increased seed yield and quality in Brassica species, where yield increases of up to 61% have been reported under open-pollinated conditions compared with insect exclusion. Similarly, Deodikar & Suryanarayana (1972) demonstrated that bee-mediated pollination resulted in markedly higher seed yields compared to self-pollinated crops, highlighting the indispensable role of managed pollinators in agricultural systems. Furthermore, complementary findings from studies on Apis cerana and other insect pollinators suggest that native pollinators also contribute significantly to crop productivity (Khalifa et al., 2021; Thapa, 2006). Taken together, the evidence underscores that strategic pollinator management through the maintenance of bee colonies is essential for optimizing rapeseed and other oilseed yields.

Experimental evidence further suggests that pollinator density can directly influence yield outcomes. Steffan-Dewenter (2003) showed that increasing populations of Osmia rufa significantly improved the yield components of both male-sterile and male-fertile lines of winter oilseed rape, thereby illustrating the potential of solitary bees in supplementing pollination services. In India, Rahman (1940) identified Apis florea, Andrena ilerda, Halictus spp., and the syrphid fly Eristalis tenax as key pollinators of Brassica napus, reflecting the diversity of effective floral visitors in different ecological contexts.

Honey bees, however, remain the dominant pollinators of rapeseed, providing both nectar and pollen during foraging activities (Nikitina, 1950; Belozerova, 1960; Vesely, 1962; Radchenko, 1964). High foraging intensities have been reported; Hammer (1952)recorded up to 20,000 bees per hectare in rape fields situated several kilometers from the nearest apiary. In India, multiple species—including A. florea, A. dorsata, A. cerana, and Andrena ilerda—play important roles, with A. florea and A. dorsata recognized as particularly efficient pollinators across crops.

Regional studies provide additional insights into species-specific and habitat-dependent variations in pollination. Bhalla et al. (1983) documented seven insect species visiting rapeseed in the mid-hill regions of Himachal Pradesh, whereas Mishra et al. (1988) identified Apis cerana as the predominant pollinator of Brassica campestris var. sarson, accounting for 69.47% of floral visitors, compared to only 2.95% for A. mellifera. Collectively, these findings highlight that while honey bees form the cornerstone of oilseed pollination, wild and solitary pollinators also play a complementary role, with their relative contributions shaped by regional biodiversity, crop varieties, and agricultural practices.

Implications for Sustainable Agriculture

The combined evidence underscores the critical role of both cultivated and non-cultivated oil seed species in ensuring temporal and ecological stability in oil production systems. The staggered phenology of cultivated crops provides continuous foraging opportunities for pollinators, while perennial non-cultivated trees ensure resource availability during crop off-seasons. Together, these interactions create a resilient agroecological system.

Importantly, stingless bee pollination emerges as a highly effective strategy for enhancing oil seed productivity and quality. Beyond improving seed set and oil content, stingless bees contribute to uniform seed development, which is desirable for both market and seed viability. Their ability to service a wide range of crops strengthens their position as keystone pollinators in diversified farming systems.

From a management perspective, promoting meliponiculture (stingless bee rearing) alongside conventional apiculture could provide ecological intensification, reduce overdependence on honey bees, and ensure stable pollination services under changing climatic conditions. Such integration would not only improve yields but also foster sustainability, aligning with broader goals of climate-resilient agriculture and rural livelihood enhancement.

CONCLUSION

The findings underscore the crucial role of stingless bee pollination in increasing seed yield, seed weight, and oil content in cultivated oil seed crops. The significant improvements in pollination efficiency, pod formation, fertilization rates, and overall seed quality suggest that incorporating stingless bees in agricultural practices can enhance productivity and economic returns in oil seed crop cultivation.

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Table:-1 Phenological characteristics of cultivated oil seed crops in Gondia District, including scientific name, common and vernacular names, family, and flowering and fruiting periods

Sr.No.	Scientific Name	Common Name (C.N.)	Vernacular Name (V.N.)	Family (Fam.)	Flowering periods (Month)	Fruiting period (Months)
1.	Helianthus annus L.	Sunflower	Suryaphul, Surajmukhi	Asteraceae	February-April	March -April
2.	Arachis hypogea L.	Groundnut	Bhuimung, Mungphali	Fabaceae	February - April	March-May
3.	Sesamum indicum L.	Sesamum	Tili, Tir	Pedaliaceae	August-September	September-October
4.	Brassica compestris L.	Mustard	Mohari, Sarsso	Brassicaceae	January-March	February-April
5.	Glycine max Merr.	Soyabean	Soyabin	Fabaceae	September-October	October-November
6.	Ricinus communis	Castor	Arandi	Euphorbiaceae	December-February	January-April
7.	Gossypium arborium L.	Cotton	Kapus	Malvaceae	October-January	December-February
8	Linum usitatissimum	Linseed, Flaxseed	Alsi	Linaceae	January-March	February-April
9.	Carthanmus tinctorius L.	Safflower	Karadi	Asteraceae	March-May	April-June
10.	Brassica nigra konch.	Black mustard	Kali mohari	Brassicaceae	January-March	February-April
11.	Oryza sativa L. (Rice Bran oil)	Rice kerenel	Kukas	Poaceae (Gramineae)	1.Kharif-September-October 2. Rabi-March-April	1.Kharif-November-October 2. Rabi-April- May
12.	Brassica napus	Rape seed	Rai	Brassicaceae	April-May	May-June

Table:-2 Phenological characteristics of Non-Cultivated Oil Seed Tree Plants in Gondia District, including their scientific, common, and vernacular names, family affiliation, and flowering and fruiting periods.

Sr. No.	Scientific Name	Common Name	Vernacular Name	Family	Flowering periods (Month)	Fruiting period (Months)
1.	Cocus nucifera	Coconut	Nariyal, Narad	Areaceae (Palm)	Throughout the year	Throughout the year
2.	Elaeis guineensis	Oil palm	Tad	Areaceae (Palm)	Throughout the year	Throughout the year
3.	Pongamia pinnata L.	Pongamia, Indian Beech	Karanji plant Seed	Fabaceae	March-May	May-Jun
4.	Madhuca longifolia Koenig	Butter Tree, Madhuca / Mahuaa Plant Seed (Tori Seed)	Mahuaa seed (Toar)	Sapotaceae	March- April	March-April
5.	Azadirachata indica	Neem Tree, Margosa Tree	Neem	Meliaceae	March -May	June-July, Fruit-October -December

Table: 3 - Effect of Stingless Bee (Tetragonula pagdeni) Pollination on Pod Formation, Seed Set, Yield Attributes, and Oil Content of Selected Oilseed Crops under Open and Controlled Pollination Conditions

Sr. No.	Oil Crops Name	Open Pollination /Without Stingless Bees Pollination					Green House caged With Stingless Bees (Tetragonula pagdeni) Pollination					
		Pod per Plant	Per Pod seed	Weight per pod (gm.)	Weight per 100 seed (gm.)	% of Oil Contain (Seed)	Pod per Plant	Per Pod seed	Weight per pod (gm.)	Weight per seed (gm.)	%of Oil Contain (Seed)	Stingless Bees (Tetragonula pagdeni) Pollination Effect
1.	Helianthus annus L. C.N.:- Sunflower V.N.:- Suryaphul Fam.:- Asteraceae	Single Flower Head	Flower Head:105-145 seeds	Flower Head seed-22-45	7	37-45	Single Flower Head	flower Head:140-170seeds	Flower Head seed-33-59	12	46-54	*Improve oil quality &quantity * Pollination Efficiency. *Increased Pod formation *Larger Pod. *Larger Seed *Higher seed set. *Enhanced yield & seed Weight. *Increased Fertilization *Uniform pod formation. *Improve seed Quality & Number *More Seed Per pod.
2.	Arachis hypogea L. C.N.:- Groundnut V.N.:- Mungphali Fam.:- Fabaceae	18-47	1-3	6-9	70	39-49	28-57	2-5	7-12	82	46-58	
3.	Sesamum indicum L. C.N.:- Sesamum V.N.:- Tili, Tir Fam.:- Pedaliaceae	35-72	40-78	1.5	3	55-87	47-90	55-87	2.7	4	52-61	
4.	Brassica compestris L. C.N.:- Mustard V.N.:- Mohari, Fam.:- Brassicaceae	90-170	12-18	1.8	2.6	33-39	120-210	16-25	2.3	4	38-47	
5.	Glycine max Merr. C.N.:- Soyabean	131	2-4	4	30	17-19	197	3-6	4.97	38	20-24	

	V.N.:- Soyaa Fam.:- Fabaceae											
6.	Ricinus communis C.N.:- Castor V.N.:- Arandi Fam.:- Euphorbiaceae	23-49	3-5	9-13	70	39-47	28-60	3.5-6	12-18	87	45-57	
7.	Gossypium arborium L. C.N.:- Cotton V.N.:- Kapus Fam.:- Malvaceae	18-45	25-35	2.5-3.5	11	14-19	23-58	32-44	3.5-5	15	18-27	
8	Linum usitatissimum C.N.:- Linseed, Flaxseed V.N.:- Alsi Fam.:- Linaceae	60-90	9-12	0.7-1.2	5	34-41	74-122	10-15	1-1.6	7	39-46	
9.	Carthanmus tinctorius L. C.N.:- Safflower V.N.:- karadi Fam.:- Asteraceae	27-38	14-24	1.5	3	29-39	32-57	18-32	1.5-3	4	37-48	
10.	Brassica nigra konch. C.N.:- Black mustard V.N.:- Kali mohari Fam.:- Brassicaceae	90-185	25-34	0.7-0.9	2	33-39	100-205	31-55	1.2-1.9	4	35-44	
11.	Oryza sativa L. (Rice Bran oil) C.N.:- Rice kerenel V.N.:- Kukas Fam.:- Poaceae (Gramineae)	Panicle; 87-145 Grain	Grain-40-130	11-18	6	16-21	Panicle; 95-170 Grain	Grain-45-160	13-22	9	19-27	
12.	Brassica napus C.N.:- Rape Seed V.N.:- Rai Fam.:- Brassicaceae	80-145	18-28	1.9	3	41-46	95-160	26-35	2.7	5	44-50	