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DIAGNOSING MISMATCH: A FOUR-TIER FRAMEWORK FOR GRADING EVIDENCE ON CROP–POLLINATOR PHENOLOGICAL SYNCHRONY

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ABSTRACT

Crop pollination depends on the overlap between crop flowering and pollinator activity, yet phenological mismatch is often claimed without directly measuring their timing. We developed a four-tier framework to assess the strength of evidence, ranging from geographical overlap without timing data (Tier 0), through measurement of one partner (Tier 1) and both partners (Tier 2), to experimental manipulation of timing (Tier 3). Tier 3 distinguishes managed-pollinator timing studies (Tier 3a) from experiments testing altered crop–pollinator timing relationships and their effects (Tier 3b). Applying the framework to 40 empirical studies published between 2003 and 2026, selected from 541 records, we classified 37 studies: 9 in Tier 0, 13 in Tier 1, 11 in Tier 2 and 4 in Tier 3; three remained unassigned. Only 13 studies measured both partners' timing, increasing to 16 when three studies of wind-pollinated nuts were reclassified. One fig study remained in Tier 1 because wasp timing was not measured. Research focused mainly on pome fruits, oilseed Brassicas and wild bees. Although 22 studies used "mismatch" or "asynchrony", none of the four experimental studies used these terms. The framework distinguishes potential mismatch from measured timing differences and experimentally tested effects, highlighting the need for more studies linking both partners' phenologies to crop pollination outcomes.

KEYWORDS: *Phenological Mismatch; Crop Pollination; Evidence Grading; Synchrony; Climate Change Adaptation; Research Design*

1. INTRODUCTION

Pollination security depends not only on pollinator availability and abundance but also on whether pollinator activity coincides with crop flowering. Flowering and pollinator emergence follow separate seasonal patterns influenced by climate, and differences in their responses to temperature, rainfall and winter chilling can alter their timing and reduce seasonal overlap (Hegland et al., 2009; Memmott et al., 2007; Bartomeus et al., 2011; Forrest & Thomson, 2011; Scaven & Rafferty, 2013). Long-term studies show that changes in the timing of interacting species can disrupt ecological interactions and functions, even when both partners advance at different rates (Burkle et al., 2013; Gérard et al., 2020; Kudo & Cooper, 2019). In crop systems, this may result in insufficient pollination when flowers open before pollinators become active or after their activity declines. However, the term phenological mismatch is used to describe different types of evidence, including geographical overlap projections, changes in one partner's timing, comparisons of both partners' seasonal timing, and experiments manipulating flowering or pollinator activity (Polce et al., 2014; Reeves et al., 2022; Wyver et al., 2023; Chambó et al., 2014). These approaches address different questions and cannot be treated as equivalent evidence of temporal mismatch. Although existing frameworks examine fitness consequences, timing trends, temperature sensitivity, study design and crop pollination outcomes (Visser & Both, 2005; Renner & Zohner, 2018; Iler et al., 2021; Kharouba & Wolkovich, 2020; Samplonius et al., 2021; Mupepele et al., 2016; Christie et al., 2019; Senapathi et al., 2021), a crop-specific framework for distinguishing the evidential strength of different study designs remains lacking.

We propose a four-tier framework based on the principle that demonstrating temporal mismatch requires evidence of the timing relationship between two interacting partners (Figure 1). Tier 0 identifies spatial co-occurrence, Tier 1 measures one partner's timing, Tier 2 compares both partners, and Tier 3 covers experimental timing studies. Tier 3 has two distinct branches: Tier 3a examines managed-pollinator feasibility against a named crop's flowering period without independently measuring actual crop flowering, whereas Tier 3b experimentally manipulates the timing relationship between crop and pollinator partners and measures biological or production outcomes. Tier 3a is a feasibility category, not a higher level of relational evidence than Tier 2; Tier 3b provides experimental evidence about altered synchrony. The framework focuses on animal-pollinated crops, while treating wind-pollinated systems as a boundary case in which male and female reproductive phases may be considered partners under an alternative classification. In fig systems, the obligate fig wasp must be included to assess synchrony. We apply the framework to address three questions: how directly studies measure temporal mismatch (RQ-A); which crops and pollinator groups are studied or under-represented (RQ-B); and which climate drivers, mechanisms, consequences and adaptation or agronomic options are reported or tested (RQ-C).

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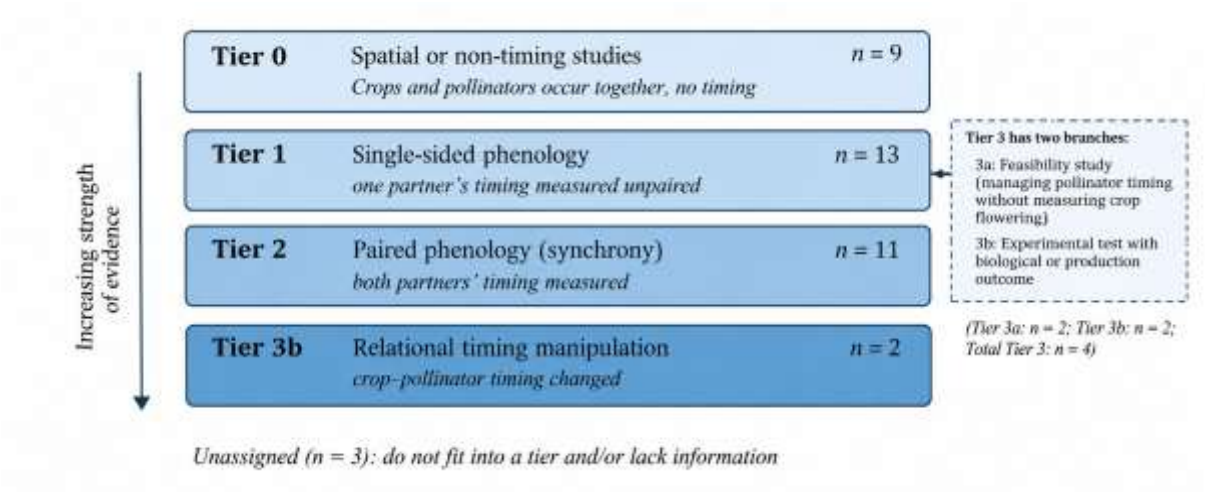

Figure 1. Four-tier framework: Tier 0 (spatial overlap), Tier 1 (single-partner phenology), Tier 2 (paired synchrony), Tier 3b (relational manipulation) and Tier 3a (managed-pollinator feasibility without measuring actual crop flowering).

2. FRAMEWORK FOR CLASSIFYING EVIDENCE OF PHENOLOGICAL MISMATCH

Phenological mismatch occurs when the timing of two interacting biological events does not align, measured by differences between their dates or by the overlap of their active periods. Measuring only one partner identifies a phenological change but cannot establish mismatch. Both partners must be assessed in the same place and season; geographical overlap alone does not demonstrate synchrony. Accordingly, the framework classifies studies by their evidence (Table 1): Tier 0 examines spatial distribution or climatic suitability without timing data; Tier 1 measures one partner's phenology; Tier 2 measures both partners' timing in the same crop system and season, providing evidence that allows their timing relationship to be assessed, even when the original study does not analyse synchrony directly; and Tier 3 covers experimental timing studies. Tier 3a tests managed-pollinator feasibility against a crop-referenced schedule without independently measuring actual crop flowering. Tier 3b requires a controlled timing manipulation, a contemporaneously documented crop flowering window, a recorded pollinator activity or introduction schedule, and a biological or production outcome. For crop-side manipulations, pollinator activity must be recorded across the shifted flowering windows; for pollinator-side manipulations, crop flowering must be documented while pollinator introduction or activity is recorded across the timing treatments. Visitation alone without a reproductive or production outcome does not qualify for Tier 3b. Comparisons of flowering periods or agronomic conditions without a controlled timing manipulation remain Tier 2 when both partners' timing can be compared. Studies with pollinator activity absent or pooled across the relevant periods remain Tier 1. Non-crop forage studies and experiments without a defined crop flowering window also remain Tier 1. Tier 3a is a parallel feasibility category, not a higher level of relational evidence than Tier 2; where a study contains both designs, its paired relational evidence takes precedence. For wind-pollinated crops, male pollen release and female receptivity are reproductive phases of the same crop, but may be treated as partners under an alternative classification. Fig and caprifig phases alone cannot establish synchrony without timing data for their obligate fig wasp pollinator.

Each tier also defines the conclusions that the evidence can support: Tier 0 indicates potential spatial separation, Tier 1 demonstrates phenological change in one partner, Tier 2 establishes observed synchrony and its associations, and Tier 3b tests whether experimentally changing the timing relationship affects biological or production outcomes. Tier 3a supports only conclusions about managed-pollinator feasibility under crop-referenced conditions. The framework was applied using study methods and measured evidence rather than the terminology used by the authors. Each study received a tier assignment and justification. For combined approaches, paired relational evidence (Tier 2) takes precedence over a Tier 3a feasibility assay, while Tier 3b is assigned only when a controlled timing manipulation documents the crop flowering window, the pollinator's activity or introduction timing, and a biological or production outcome. Of the 40 studies examined, 37 received tier assignments, while three studies measuring floral traits, nectar resources or visitor abundance were retained as contextual records without tier classifications. The assigned studies comprised nine Tier 0, thirteen Tier 1, eleven Tier 2, two Tier 3a and two Tier 3b studies. Under the primary animal-pollination framework, the three wind-pollinated nut studies remain in Tier 1 because male pollen release and female receptivity are phases of the same crop rather than a crop–pollinator pair. In a secondary classification based on intrinsic relational design, these studies move to Tier 2 because both reproductive phases were measured; the fig study remains in Tier 1 because its wasp pollinator was not dated. This alternative classification increases the number of Tier 2 and Tier 3 studies from 15 to 18 of 37 (48.6%), and the number of studies directly examining relationships between partners (Tiers 2 and 3b) from 13 to 16 of 37 (43.2%). These classification rules and permitted inferences are summarised in Table 1 to support consistent application across researchers (Chambó et al., 2014; Delgado et al., 2026; de Oliveira et al., 2025; Dzekashu & Hoover, 2026; Sheffield, 2008; Scalici et al., 2023).

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Table 1. Tier definitions, decision rules and permitted inferences.

Tier	Design requirement	What is measured	Permitted inference	Corpus (n)
0	Occurrence, range or climatic suitability modelling	Spatial overlap of suitable area; no timing variable	Risk of spatial separation	9
1	Single-partner phenology, or observations that do not establish a dated relationship between a focal crop and its animal pollinator; includes non-crop forage studies and crop-side timing experiments in which pollinator activity is absent or pooled across flowering windows.	One partner's timing, or observations insufficient to compare timing across the relevant flowering period	Phenological change in one partner; no demonstrated crop–pollinator synchrony	13
2	Both partners' timing documented in the same focal crop system and season, allowing their timing relationship to be assessed, but without meeting the Tier 3b requirements for a controlled timing manipulation with a reproductive or production outcome.	Crop flowering and time-resolved pollinator activity or phenology	Observed synchrony and its associations	11
3a	Managed-pollinator feasibility trial using a schedule linked to a named crop, without contemporaneous measurement of actual crop flowering	Pollinator survival, development or emergence under a crop-referenced schedule	Feasibility of managed-pollinator timing	2
3b	Controlled timing manipulation with crop flowering documented and pollinator activity or introduction timing recorded across treatments	Effects of altered timing on reproduction, seed or fruit set, or yield	Effects of altered synchrony on biological or production outcomes	2
—	Floral traits and visitor abundance only	Resource quantity and quality, no dated pair	Context on the resource environment	3

3. METHODS

Records were identified in Scopus on 10 November 2026 using a TITLE-ABS-KEY search covering 2000–2027 to capture early-online publications. The search returned 541 records (2003–2026) using three Boolean blocks covering crops, pollinators and phenology-related terms. No initial language or document-type filters were applied. The complete search strings are provided in Supplementary material. After removing three duplicates, 538 records were screened using titles, abstracts and indexed keywords against four criteria: empirical research; a crop or crop-referenced managed-pollinator context; information on at least one relevant phenological, timing, climatic-suitability or floral-resource variable; and relevance to crop pollination or its resource context (Figure 2). Screening was conducted by one reviewer, without separate full-text eligibility screening. Records were retained when indexed information reported or explicitly indicated measurement of a relevant variable. Screening was conducted by one reviewer, without separate full-text eligibility screening. Records were retained when indexed information reported or explicitly indicated measurement of a relevant variable. Of the 538 records, 498 were excluded: 171 lacked a crop system, seven lacked a pollinator component, 21 lacked a relevant variable, and 299 provided no evidence of measurable data, including 26 reviews and 273 other records. Forty studies were retained, including three unassigned contextual studies measuring floral resources or visitation without establishing a dated crop–pollinator relationship. Borderline classifications were conservatively resolved during full-text coding and recorded in Table S2. Because retrieval required matching the phenology search block, spatial studies without dates could only be identified when their indexed records included terms such as mismatch or asynchrony. This limitation was considered when interpreting terminology patterns (Section 4.4) and is discussed in Section 5.1.

Each study was coded using 58 fields covering bibliographic information, study systems, crop and pollinator identities, research design, climate drivers, mechanisms, outcomes and management options. A single reviewer extracted information from published methods and results, recorded borderline decisions and assigned tiers according to the criteria in Table 1, rather than authors' terminology. Table S2 provides the classifications and justifications. A separate language audit examined mismatch*, asynchron*, desynchron* and mistim* in titles and abstracts, excluding keywords. Morphological variants were included, while synchron* was excluded. Matches were checked for affirmative references to crop–pollinator or trophic decoupling; within-crop flowering differences and negated claims were excluded. References to geographical or distribution patterns, including spatial mismatch and asynchronous range shifts, were classified as spatially qualified. Analysis was descriptive, using counts and cross-tabulations to examine study distributions across tiers,

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crops, pollinator groups and research designs. Effect sizes were not pooled because studies lacked a common measure. RQ-A used tier assignments and the language audit, RQ-B examined crop and pollinator distributions, and RQ-C examined climate drivers, mechanisms, consequences and adaptation or management options.

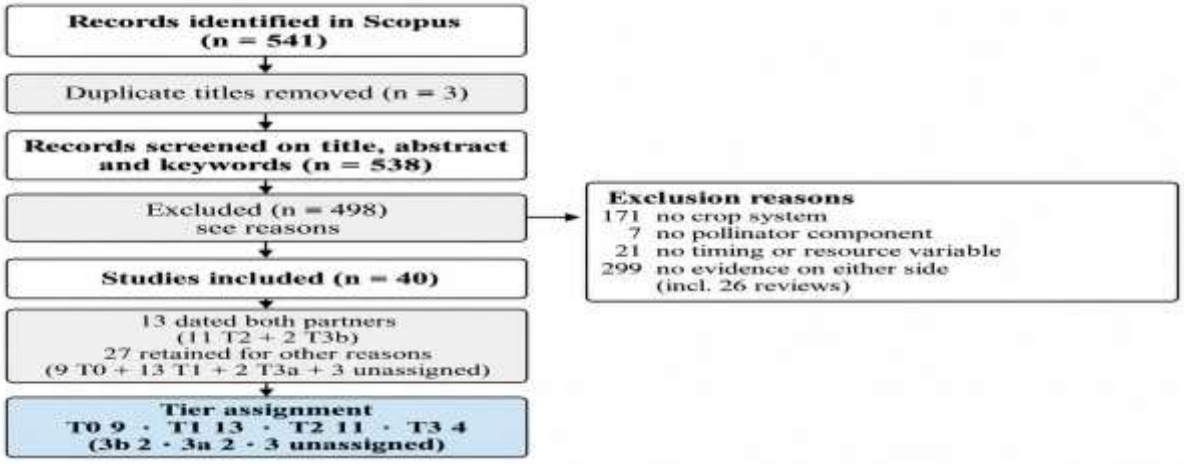

Figure 2: Diagram showing study identification, screening, exclusion and final classification across evidence tiers.

4. RESULTS

4.1 Corpus characteristics and evidence distribution

The 40 studies were published between 2003 and 2026 across 38 journals or edited volumes; 26 (65%) appeared during 2021–2026, including 14 (35%) during 2025–2026 (Table 2). Thirty were open access, 11 involved international co-authorship, and together they received 751 citations (mean 18.8; median 10.5), with Bartomeus et al. (2013) accounting for 218 (29%). Field observations were the most common design (12 studies), followed by species distribution models (9), field experiments (6), laboratory or controlled experiments (5), long-term, citizen-science or museum series (4), and other designs (4). Of the 37 assigned studies, nine (24.3%) were Tier 0, thirteen (35.1%) Tier 1, eleven (29.7%) Tier 2 and four (10.8%) Tier 3, while three remained unassigned (Figure 3). Thus, 22 studies (59.5%) provided spatial or single-partner evidence, whereas 15 (40.5%) reached Tiers 2–3; however, only 13 directly measured both partners' timing, comprising 11 Tier 2 studies and two Tier 3b experiments, while the remaining two were Tier 3a feasibility trials. Of the 13 Tier 1 studies, nine measured one partner in animal-pollinated systems and four measured crop reproductive phases in wind-pollinated nut crops or fig systems. Under an alternative classification that treats male and female reproductive phases as partners in wind-pollinated crops, three nut studies move to Tier 2, increasing the Tier 2–3 total to 18 of 37 (48.6%); the fig study remains Tier 1 because its obligate wasp pollinator was not dated. Tier distribution showed no clear relationship with publication year, with Tier 0 studies occurring throughout the study period and Tier 3 experiments spanning 2008–2026. The three unassigned studies examined floral traits, nectar resources or visitor abundance without comparing partner timing: drought effects on white mustard (Denisow et al., 2025), water and nitrogen manipulation in the same crop (Akter & Klečka, 2022), and a golden currant pollination trial (Kampuss, 2024). Although these studies provide contextual evidence, including a reported 60% reduction in nectar sugar under drought, they do not establish temporal synchrony.

Table 2. Profile of the 40 included studies.

Attribute	Category	n
Publication	2003–2026; 2021–2026; 2025–2026	40; 26; 14
Access and collaboration	Open access; international co-authorship	30; 11
Citations	Total; mean; median; maximum	751; 18.8; 10.5; 218
Design	Field observation; distribution model; field experiment; laboratory or controlled experiment; long-term, citizen-science or museum series; other	12; 9; 6; 5; 4; 4
Tier	0; 1; 2; 3; unassigned	9; 13; 11; 4; 3
Crop group	Pome fruit; oilseed and Brassica; berry; coffee; tropical fruit; wind-pollinated nut; stone fruit; multiple systems; pollinator-only (orchard / generic); other	7; 5; 4; 3; 3; 3; 2; 4; 4; 5
Pollinator group	Wild bee community; managed solitary bee; specialist solitary bee; multiple taxa; honeybee (any); bumblebee; fig wasp; wind; not measured	13; 5; 3; 4; 6; 1; 1; 3; 4

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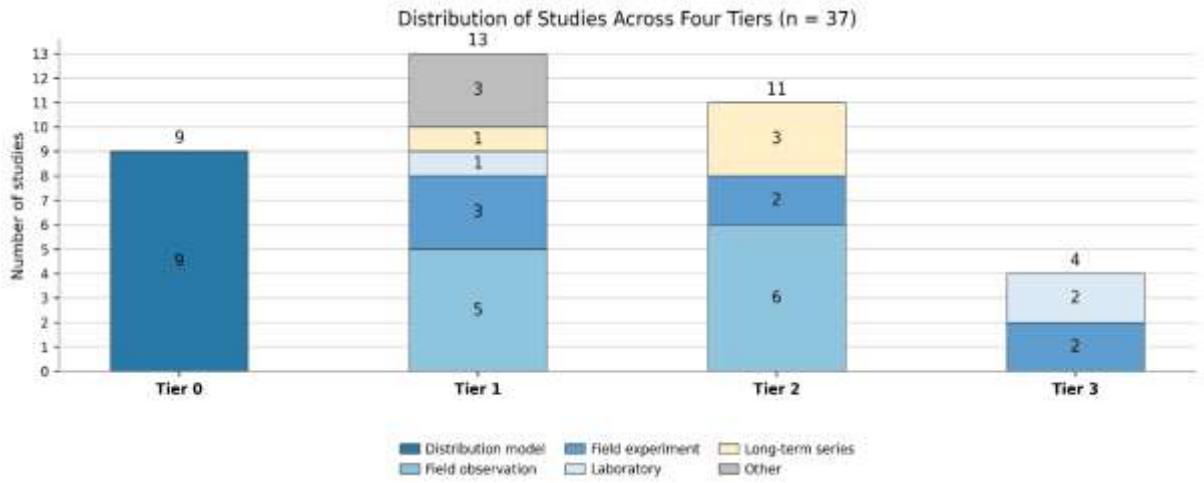

Figure 3. Distribution of the 37 assigned studies across the four tiers, stacked by study-design group.

4.2 Evidence across tiers: spatial projections, phenological observations and experiments

The nine Tier 0 studies used distribution models to project potential geographical separation between crops and pollinators, without measuring seasonal timing. They covered passion fruit, coffee, vanilla, Brazilian food plants, honeybees and crops in Asia and China, *Camellia oleifera*, and British and European orchards (Bezerra et al., 2019; Abrha, 2018; Watteyn et al., 2025; Oliveira et al., 2025; Rahimi & Jung, 2025; Chen et al., 2026a, 2026b; Polce et al., 2014; Marshall et al., 2023). The thirteen Tier 1 studies measured only one partner's timing or crop reproductive phases. These included changes in pear, apple, apricot, almond and rapeseed phenology (Reeves et al., 2022; Ru et al., 2023; Delgado et al., 2026; Socias i Company et al., 2003; Chambó et al., 2014), reproductive overlap in fig, hazelnut, pistachio and pecan systems (Chmarkhi et al., 2025; Taghavi et al., 2021; Burgos-Miranda et al., 2025; Ajamgard et al., 2026), and changes in pollinator emergence or activity (Lee et al., 2018; Farzan & Yang, 2018; Slominski & Burkle, 2021; Samra et al., 2014). Although some studies reported incomplete reproductive overlap or changes in pollinator phenology, they did not establish synchrony between a dated crop and its animal pollinator. Under an alternative classification, the three wind-pollinated nut studies qualify as Tier 2 because both reproductive phases were measured; the fig study remains Tier 1 because fig-wasp timing was not assessed.

The eleven Tier 2 studies directly compared both partners' timing and reported variable patterns of overlap and associations with visitation or crop production (Table 3). The four Tier 3 studies manipulated timing or pollinator schedules and measured biological consequences, including managed-bee responses and reproductive outcomes in blueberry, cherry, canola and buckwheat systems (Table 4). The two Tier 3b studies reported reproductive or yield-related outcomes, but neither quantified continuous crop–pollinator overlap or demonstrated a marketable yield response specifically attributable to experimentally altered synchrony.

Table 3. The eleven Tier 2 studies: what is paired, what is reported, and what is concluded.

Study	System	Phenophases paired	Reported metric	Outcome reported
Peters & Carroll 2012	Coffee, wild bees	Flowering density and bee richness/abundance, 3 years	Richness 9.8 → 26 during mass flowering	Fruit set varied with flowering density
Bartomeus et al. 2013	Apple, wild bee community	Flowering and bee activity, 46 years	Community-level synchrony	Synchrony stable through complementarity
Krishnan et al. 2018	Coffee agroforest, social bees	Flowering type and bee visits	Visits, pollen tubes, seed set	Irrigation-induced asynchrony raised visits and seed set
Kőrösi et al. 2018	Apple, wild bee community	Experimentally shifted tree phenology and pollinator assemblage	Assemblage composition and abundance	Assemblages differed; abundance unchanged
Toivonen et al. 2019	Turnip rape, wild bees	Flowering time and visitation, 34 fields	Visits and seeds per silique	Late-flowering fields better pollinated
Willis Chan & Raine 2021	Squash, *Eucera pruinosa*	Crop flowering window and bee emergence	34.1% overlap; <50% emerged in time	Fewer than half of the bees emerged before the crop pollination window closed; only 34.1% of the flowering period supported bee reproductive activity.

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Mallinger et al. 2021	Blueberry, managed and wild bees	Visitation and yield, 20 farms	Visitation rates and yield estimates	Yield limited by visitation; specialist constrained by mismatch
Weaver & Mallinger 2022	Blueberry, *Habropoda laboriosa*	Bee and host-plant phenology, 117 years	0.04 days per year per degree latitude	Partners shifting at different rates and directions
Wyver et al. 2023	Apple, wild bee community	Flowering and flight phenology, 48 years	6.7 vs 6.5 days per °C; 0.4 days per 10 mm rain	Shifting mismatch; bee advance plateaued
Lucas-García et al. 2026	Mango, flies, honeybees, stingless bees	Natural and induced flowering seasons, 2 years	Pollen deposition per visit; yield	Wild insects were more strongly associated with yield during induced off-season flowering, whereas honeybees were more strongly associated during the natural season.
Armstrong et al. 2026	Apple, bees and flies	Bloom timing and insect activity, 11 weeks	>14,000 insects; 12% likely flower visitors	Bee genera tracked bloom more closely than flies

Table 4. The four Tier 3 studies: sub-tier, timing manipulation, comparator and consequence.

Study	Tier	System	Timing manipulation	Comparator	Consequence measured
Sheffield 2008	3a	Lowbush blueberry, *Megachile rotundata*	Bee release about one month earlier than for alfalfa	Laboratory temperature assays across development	Survival; 100% mortality at −15 °C
Scalici et al. 2023	3a	Cherry orchard, *Osmia lignaria*	Constant vs orchard-like fluctuating rearing temperatures	Utah and Washington bee populations	Development time, survival, emergence
de Oliveira et al. 2025	3b	Buckwheat, honeybee and stingless bee	Sowing dates shifting flowering	Pollinator exclusion and open pollination	Visitation, seed set, yield components
Dzekashu & Hoover 2026	3b	Canola, *Bombus impatiens*	Early, absent and delayed pollinator introduction	Ambient vs heat and drought treatments	reproductive output

4.3 Crop representation, pollinator groups, drivers and adaptation options

Crop representation was uneven, with pome fruit contributing the most studies (seven), followed by oilseed and Brassica crops (five), berries (four) and coffee (three). Pome fruit studies covered spatial projections, crop phenology and paired crop–pollinator observations, but none tested crop-side timing manipulation against a reproductive or yield outcome. Although apple phenology was experimentally shifted, the study measured pollinator assemblage composition and abundance rather than reproductive outcomes (Kőrösi et al., 2018). Oilseed and Brassica studies included a Tier 3 canola experiment (Dzekashu & Hoover, 2026), a Tier 1 rapeseed sowing-date experiment that recorded crop flowering and yield but did not measure pollinator activity across the separate flowering windows (Chambó et al., 2014), a paired turnip rape study (Toivonen et al., 2019) and two unassigned white mustard studies. Coffee studies examined flowering density, irrigation-induced asynchrony and spatial suitability (Peters & Carroll, 2012; Krishnan et al., 2018; Abrha, 2018). Legumes, root and tuber crops, non-cucurbit vegetables, cacao and citrus were absent as focal systems, although some appeared in multi-crop spatial assessments (Rahimi & Jung, 2025). CropPol also compiles flowering and visitation records across 48 crops, including legumes and vegetables (Allen-Perkins et al., 2022), but such studies may not be retrieved by searches requiring phenology-related terminology. Vanilla was represented only through a spatial projection involving its wild relatives (Watteyn et al., 2025). Wild bee communities dominated the pollinator evidence, with 13 studies, including seven at Tier 2. Managed solitary bees were represented in five studies, including two Tier 3a trials assessing release timing or rearing temperature against crop flowering windows (Sheffield, 2008; Scalici et al., 2023). Specialist solitary bees appeared in three studies: paired studies of Eucera pruinosa and Habropoda laboriosa (Willis Chan & Raine, 2021; Weaver & Mallinger, 2022), and a Tier 0 projection involving Xylocopa (Bezerra et al., 2019). Mallinger et al. (2021), which included managed and wild bees, is classified under honeybee (any) in Table S2. Other studies involved honeybees, multiple pollinator taxa, bumblebees and fig wasps. No study focused on moths or beetles; flies and ants appeared only within mixed assemblages. Four animal-pollinated studies did not measure the pollinator, while three examined wind-pollinated crops. Overall, the evidence base remains strongly dominated by bee-focused studies.

Temperature was the most frequently reported climate driver, but its role differed across tiers, from a modelled variable at Tier 0 to an experimental treatment at Tier 3. Chilling influenced crop-side phenology in apricot, apple and pear

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studies (Delgado et al., 2026; Ru et al., 2023; Reeves et al., 2022), while rainfall was important in coffee and mango systems (Peters & Carroll, 2012; Krishnan et al., 2018; Lucas-García et al., 2026). Management-related timing changes included irrigation in coffee (Krishnan et al., 2018), sowing dates in rapeseed and buckwheat (Chambó et al., 2014; de Oliveira et al., 2025), and pollinator release timing in blueberry and canola (Sheffield, 2008; Dzekashu & Hoover, 2026). Reported consequences ranged from changes in visitation and pollinator assemblages to fruit or seed set, yield-related outcomes and pollinator fitness (Table 5). Yield or yield components were reported in two Tier 3 studies (de Oliveira et al., 2025; Dzekashu & Hoover, 2026) and in the Tier 1 rapeseed study (Chambó et al., 2014), which did not measure pollinator timing. Pollinator survival, development and offspring size were examined by Farzan and Yang (2018), Slominski and Burkle (2021), Sheffield (2008) and Scalici et al. (2023). Six adaptation options were identified, although not all were experimentally tested as timing interventions (Figure 4). Sowing date was tested in rapeseed and buckwheat, although only the latter measured pollinator activity in relation to shifted flowering. Pollinator release timing was examined in blueberry and canola, while rearing temperature was tested in *Osmia lignaria* (Sheffield, 2008; Dzekashu & Hoover, 2026; Scalici et al., 2023). Field-scale incubation technology for this species has also been trialled in North American orchards (Bosch et al., 2000; Pitts-Singer et al., 2008), although these studies were not included in the review. Cultivar or pollinizer choice was proposed in four studies (Reeves et al., 2022; Ajamgard et al., 2026; Burgos-Miranda et al., 2025; Socias i Company et al., 2003), while irrigation and off-season induction were discussed but not tested as timing interventions (Krishnan et al., 2018; Lucas-García et al., 2026). Forecasting approaches included distribution, phenology, growing-degree-day and artificial neural-network models (Chen et al., 2026b; Rahimi & Jung, 2025; Ru et al., 2023; Chmarkhi et al., 2025). However, their predictions were not evaluated against observed crop–pollinator overlap. No study demonstrated a marketable yield response to an experimentally measured change in crop–pollinator overlap.

Table 5. Drivers, mechanisms and consequences reported at each tier.

Tier	Climate drivers reported	Mechanism claimed	Consequence endpoint	Studies
0	Temperature and precipitation layers in distribution models	Range separation	Projected area or overlap loss	9
1	Temperature, chilling, rainfall in regression or phenology models	Advance, compression, chill deficit	Dates, indices, risk classes	13
2	Temperature, rainfall, irrigation	Differential rates, overlap change	Visitation, fruit or seed set, yield correlate	11
3b	Temperature, water stress, sowing or introduction date	Altered timing of crop flowering or pollinator introduction relative to the crop flowering window.	Reproduction, yield components	2
3a	Rearing temperature, release date, crop-window benchmark	Ex situ schedule tested against a crop window	Survival, development, emergence	2

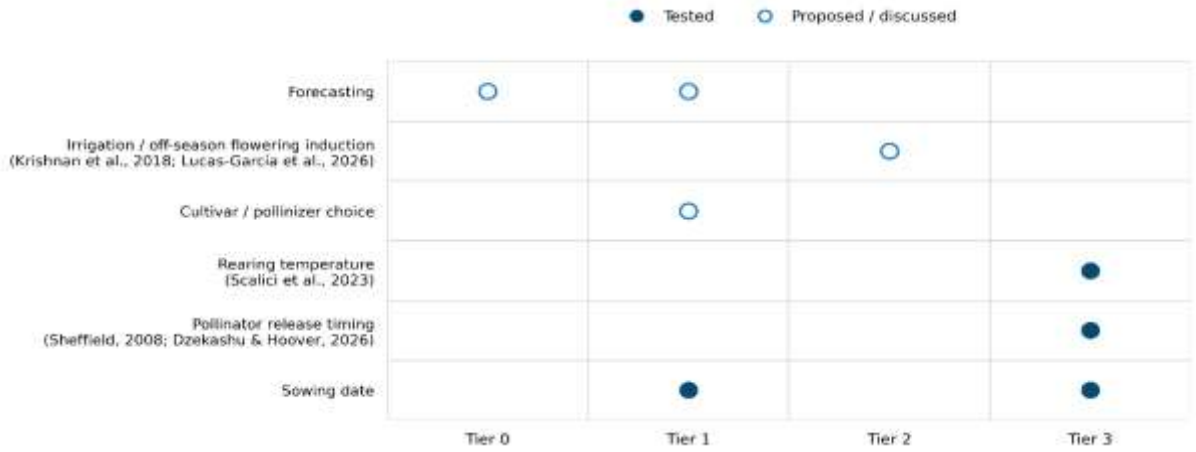

Figure 4. Adaptation options by evidence tier. Filled circles indicate options tested through a manipulated timing comparison; open circles indicate options proposed or discussed without a timing test.

4.4 Language Audit

Twenty-two of the 40 studies (55%) used "mismatch" or "asynchrony" in their titles or abstracts: all nine Tier 0, five Tier 1 and eight Tier 2 studies, but none of the four Tier 3 studies. Six Tier 0 studies explicitly described spatial separation (Polce et al., 2014; Bezerra et al., 2019; Marshall et al., 2023; Oliveira

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et al., 2025; Rahimi & Jung, 2025; Watteyn et al., 2025), while three used these terms without spatial qualification (Abrha, 2018; Chen et al., 2026a, 2026b). Because the search required phenology-related terms, the high frequency in Tier 0 partly reflects retrieval bias. Excluding Tier 0, 13 of the 31 remaining studies used the terms (42%); among the 28 assigned Tier 1–3 studies, 13 did so (46%). Only eight of the 22 studies using the terms measured both partners' timing, all classified as Tier 2. Neither Tier 3b study used mismatch or asynchrony terminology, although both experimentally manipulated crop–pollinator timing.

5. DISCUSSION: EVIDENCE GAPS, EXPERIMENTAL REQUIREMENTS AND FRAMEWORK APPLICATIONS

The review reveals an important gap between the use of mismatch terminology and the strength of evidence supporting temporal mismatch. Spatial studies often use terms such as "mismatch" and "asynchrony" to describe geographical separation, while some studies use them without clearly distinguishing spatial from temporal mismatch (Abrha, 2018; Chen et al., 2026a, 2026b; Polce et al., 2014; Bezerra et al., 2019; Marshall et al., 2023; Oliveira et al., 2025; Rahimi & Jung, 2025; Watteyn et al., 2025). The evidence is concentrated in Tiers 0–2 because spatial models and single-partner studies require less temporal information than paired observations or experiments. Although Tier 2 studies can establish whether two partners' timing coincides, long-term records are needed to identify trends and distinguish them from short-term weather variation. Tier 3 requires controlled timing treatments and measured biological or production outcomes. For example, Kőrösi et al. (2018) remained in Tier 2 because, although apple phenology was experimentally shifted and pollinator assemblages were recorded, reproductive or yield responses to the altered timing were not measured. The minimum requirements for Tier 3 include a timing manipulation, a flowering benchmark for a named crop and a measured survival, reproductive or yield outcome. An ideal experiment would additionally measure both partners' timing, manipulate timing independently of environmental conditions, include an unshifted control and report continuous overlap. The four Tier 3 studies did not meet all these requirements. The feasibility trials of managed bees provide useful information on survival and development but cannot establish effects on crop production without field measurements of both partners (Sheffield, 2008; Scalici et al., 2023). Other experiments also face difficulties separating timing effects from seasonal weather, particularly when sowing dates or temperature treatments are changed (de Oliveira et al., 2025; Dzekashu & Hoover, 2026). For social bees, foraging activity or colony introduction date is more appropriate than emergence date. However, colony introduction alone does not establish pollinator activity across flowering windows, as illustrated by Chambó et al. (2014). Overall, future experiments should prioritise measuring both partners' timing within the same study and linking their overlap to reproductive or production outcomes.

The framework provides a screening standard for evaluating claims, a tool for identifying evidence gaps and a reporting guide for studies of phenological mismatch. It distinguishes the strength of evidence from study quality: a tier indicates what a study can demonstrate, not how well it was conducted. Although developed for crop–pollinator systems, the framework can also be applied to plant–herbivore, host–parasitoid and migratory interactions, as well as wind-pollinated systems where male and female reproductive phases must coincide. Several limitations affect the interpretation of the review. The corpus was retrieved from one database using phenology-related search terms, and therefore may exclude relevant studies that used different terminology or were indexed elsewhere. Screening and coding were conducted by one reviewer, without independent double coding or an inter-rater statistic. Although no language filter was applied, the retrieved corpus was predominantly English-language, which may limit geographical and linguistic representation. In addition, excluded records were not assessed in full text, meaning that relevant timing data reported only in full-text results may have been missed. Of the 299 records excluded for providing no evidence of measurable data, 273 non-review records were excluded without full-text inspection. The three unassigned studies provide contextual information but do not measure dated phenophases or experimentally manipulate timing. Finally, the analysis is descriptive rather than a quantitative synthesis, and conservative tier assignments were used when published methods or supplementary information were unclear.

6. CONCLUSION

Crop pollination depends on the overlap between crop and pollinator phenologies, yet many studies claim mismatch without measuring this relationship. Applied to 40 studies, the four-tier framework shows that over half cannot establish temporal synchrony, while unqualified mismatch claims are concentrated in studies with limited timing evidence. Proposed interventions are also concentrated in the lower evidence tiers. The framework is therefore a screening standard, not a scoring system, helping distinguish demonstrated temporal mismatch from evidence gaps and identify what further measurements are needed.

Data Availability

The dataset supporting this study, including the search blocks (Table S1) and the complete four-tier evidence assignments with justifications (Table S2), is available in the Zenodo repository: Asokakumar Korangode, T. (2026). *Dataset: Crop–Pollinator Phenological Synchrony* [Dataset]. Zenodo. https://doi.org/10.5281/zenodo.24362594.

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