sustainability

MDPI

Review

Advancing Sustainable Agriculture Through Bumblebee Pollination: Bibliometric Insights and Future Directions

Mei Bie [1,2], Kai Song [3,4], He Dong [3], Wanru Zhao [3], Hongze Lin [5], Dongfang Shi [4,*] and Duo Liu [3,*]

[1] Institute of Education, Changchun Normal University, Changchun 130032, China; bie-mei@163.com
[2] College of Computer Science and Technology, Jilin University, Changchun 130012, China
[3] School of Life Science, Changchun Normal University, Changchun 130032, China; songkai@ccsfu.edu.cn (K.S.); mdonghe@163.com (H.D.); zhaowanrumei@163.com (W.Z.)
[4] Institute of Innovation Science and Technology, Changchun Normal University, Changchun 130032, China
[5] College of Computer Science and Technology, Changchun Normal University, Changchun 130032, China; slh1234@163.com
* Correspondence: shidongfang@ccsfu.edu.cn (D.S.); liuduo@ccsfu.edu.cn (D.L.)

Abstract: Bumblebees (*Bombus* spp.) are pivotal to sustaining biodiversity and enhancing agricultural productivity, thanks to their unique pollination mechanisms, including "buzz pollination". Their ability to operate under adverse conditions—low temperatures and dim light—makes them essential for crops like tomatoes, peppers, and blueberries. This study synthesizes the ecological and behavioral traits of bumblebees, such as floral fidelity and vibration pollination, and explores their indispensable role in agricultural systems, particularly in greenhouse and open-field farming. By employing a bibliometric analysis, this review identifies critical research trends and emerging frontiers in bumblebee pollination, including their integration with precision agriculture technologies like remote sensing and artificial intelligence. Notably, there is increasing research on the impacts of climate change on bumblebee behavior and distribution, with studies focusing on how environmental stressors influence pollination efficiency. Additionally, the potential of using bumblebees in agroecological approaches and their role in enhancing crop resilience in changing climates are gaining traction. Moreover, it highlights the challenges posed by habitat loss, pesticide exposure, and climate change, emphasizing the urgency of conservation efforts. This study proposes interdisciplinary strategies for optimizing bumblebee pollination services, aiming to support sustainable agriculture and strengthen ecosystem resilience. The findings provide theoretical and practical insights for leveraging bumblebee pollination to achieve global food security and ecosystem stability.

Keywords: bumblebees; pollination; sustainable agriculture; climate adaptation; population conservation

Academic Editor: Roberto Mancinelli

Received: 1 January 2025
Revised: 27 February 2025
Accepted: 28 February 2025
Published: 3 March 2025

Citation: Bie, M.; Song, K.; Dong, H.; Zhao, W.; Lin, H.; Shi, D.; Liu, D. Advancing Sustainable Agriculture Through Bumblebee Pollination: Bibliometric Insights and Future Directions. *Sustainability* **2025**, *17*, 2177. https://doi.org/10.3390/su17052177

1. Introduction

Pollination is a cornerstone of ecosystem functionality and agricultural productivity, playing an indispensable role in plant reproduction and global food security. Among the diverse pollinators, bumblebees (*Bombus* spp.) hold a unique position due to their exceptional biological traits, such as a large body size, long tongue, and capacity for "buzz pollination"—a mechanism that enables effective pollen release through rapid muscle vibrations. These characteristics allow bumblebees to maintain a high pollination efficiency even under suboptimal environmental conditions, such as low temperatures and dim light [1–3]. Consequently, bumblebees are particularly suited for pollinating crops with complex floral structures, such as tomatoes, sweet peppers, and strawberries, especially in controlled environments like greenhouses [4,5].

The extensive use of bumblebees in agricultural systems has significantly enhanced crop yields and quality, solidifying their status as key contributors to sustainable agricultural practices. However, the alarming decline in global pollinator populations has raised critical concerns within academic and public spheres. Bumblebees, as vital pollinators, are not immune to this trend. Factors such as widespread pesticide use, habitat destruction, and climate change have led to significant reductions in their population size, jeopardizing both the stability of natural ecosystems and the productivity of pollination-dependent crops [6–8]. These challenges necessitate a comprehensive understanding of bumblebee ecology and behavior to inform effective conservation strategies and mitigate the ongoing pollination crisis [9–11].

Bibliometric analysis offers a systematic and innovative approach to evaluating research progress and identifying emerging trends in bumblebee pollination. By analyzing publication patterns, research hotspots, and knowledge gaps, this methodology enables researchers to trace academic developments and predict future directions [12–14]. Over the past two decades, bumblebee pollination research has expanded significantly, spanning disciplines such as ecology, agriculture, and environmental sciences. However, a holistic synthesis that integrates these advancements and aligns them with the principles of sustainable agriculture remains scarce.

Bumblebees (*Bombus* spp.) are essential pollinators, critical to ecosystem health and sustainable agriculture due to their unique "buzz pollination" behavior, adaptability to low temperatures, and specialization in complex floral structures. Studies show that bumblebees outperform honeybees in pollinating crops like tomatoes and blueberries, improving yields by 20–30%, enhancing fruit sugar content by 8–10%, and reducing malformed fruit rates by 40%. However, their populations are increasingly threatened by climate change, pesticide overuse, and habitat fragmentation, necessitating research to optimize their ecological services. While existing studies focus on bumblebees' biological traits and agricultural potential, gaps remain in integrating precision agricultural technologies with ecological conservation. This study employs a bibliometric analysis to synthesize research trends from 2005 to 2024, addressing bumblebees' role in enhancing crop resilience, reducing chemical dependence, and tackling climate challenges. By analyzing these trends and the intersection of bumblebee pollination with technological advancements, such as remote sensing and artificial intelligence, the study aims to provide actionable insights for sustainable agriculture and ecosystem resilience.

2. Bumblebee Biological Characteristics

2.1. Behavior and Pollination Characteristics

Bumblebees (*Bombus* spp.) are crucial pollinators in natural ecosystems and agricultural systems, owing to their unique behavioral and ecological traits that make them indispensable for pollination efficiency and ecosystem functionality. Their pollination behavior reflects not only their physiological needs but also their close association with plant reproduction and genetic diversity.

2.1.1. Floral Visitation Behavior and Preferences

Bumblebees (*Bombus* spp.) are considered one of the most efficient pollinators due to their high frequency of floral visits and exceptional pollination efficiency. Compared to other pollinators, such as honeybees (Apis mellifera) and butterflies, bumblebees exhibit several key advantages. Their larger body size and unique ability to perform "buzz pollination"—a mechanism that releases pollen through rapid muscle vibrations—make them particularly effective for crops with complex floral structures like tomatoes, peppers, and blueberries. Moreover, bumblebees are more adaptable to suboptimal environmental conditions, including low temperatures and dim light, which limits the effectiveness of other pollinators, such as honeybees, under these conditions. These attributes enable bumblebees to maintain a high pollination efficiency even during cooler mornings or in high-latitude regions, making them indispensable in certain agricultural environments, such as greenhouses and open-field farming. By contrast, honeybees, while also important pollinators, tend to be less effective in colder conditions and for certain crops requiring vibration pollination. This distinction highlights the unique and irreplaceable role of bumblebees in sustaining crop productivity, especially for agricultural systems that depend on pollinators under challenging conditions [15–17]. More importantly, bumblebees exhibit a notable behavior known as "flower constancy", where they preferentially visit flowers of the same plant species over a certain time. This behavior enhances the efficiency of the pollen transfer between conspecific flowers, minimizes interference from heterospecific pollen, and optimizes fertilization success and seed production [3].

In addition to flower constancy, bumblebee visitation behavior demonstrates precise resource utilization patterns influenced by floral traits such as color, scent, and nectar concentration. These selective behaviors not only improve energy efficiency during pollination but also strengthen the co-evolutionary relationships between plants and pollinators [18,19]. Such unique ecological strategies make bumblebees pivotal contributors to maintaining plant diversity.

Another critical advantage of bumblebees is the diversity in their tongue lengths, which enhances their adaptability to various floral morphologies. Long-tongued bumblebees (e.g., *Bombus hortorum*) are specialized for accessing deep tubular flowers, such as those of legumes and Lamiaceae, filling an ecological niche for plants that require specific pollinators [20]. In contrast, short-tongued bumblebees (e.g., *Bombus terrestris*) are more efficient at pollinating shallow or open flowers [21]. This tongue-length differentiation grants bumblebees flexibility to adapt to a broad range of floral resources, ensuring a balanced pollination network for diverse plant communities [22].

Moreover, the diversity in tongue lengths exemplifies an essential aspect of bumblebee ecological adaptation and drives co-evolution with plants. For instance, studies have shown that long-tongued bumblebees and plants with deep tubular flowers exert significant selective pressure on each other, resulting in tight functional matches during evolution [23]. Meanwhile, short-tongued bumblebees act as generalist pollinators by adapting to a wide variety of floral forms [24]. This niche differentiation enhances bumblebee population resilience while promoting ecosystem plant diversity and stability.

2.1.2. Pollen Collection and Buzz Pollination

The importance of bumblebees in pollination ecology extends beyond their frequent floral visits to their unique ability to perform "buzz pollination". This specialized pollination mechanism enables bumblebees to efficiently collect and transfer pollen, providing essential pollination services to plants requiring vibrational pollination, such as those in the Solanaceae, Ericaceae, and berry-producing crops [25,26].

Buzz pollination is achieved through rapid wing (also known as "buzzing") and thoracic muscle vibrations that create resonance. These vibrations cause pollen to be released from narrow or porous anthers and adhere to the dense hairs covering the bumblebee's body. Unlike the passive pollen collection observed in honeybees, buzz pollination is an active and highly efficient process, particularly for plants with complex floral structures or small pollen openings, such as tomatoes, peppers, and blueberries [27,28]. This vibration-driven behavior increases both the quantity of pollen collected and the efficiency of pollen transfer, ultimately enhancing fertilization success and crop yields [29].

Another key advantage of bumblebees lies in their larger body size and dense body hair, which significantly enhance pollen attachment and transport. These traits enable bumblebees to transfer more pollen in a single visit, while their larger bodies facilitate greater pollen release from the anthers, boosting overall pollination efficiency [30,31].

Bumblebees also demonstrate remarkable environmental adaptability, as their activity is not confined to ideal climatic conditions. They can forage and pollinate in adverse conditions such as low temperatures, dim light, and even wind or rain. This adaptability provides them with a significant advantage in cold mornings and high-latitude regions, where other pollinators, such as honeybees, may be less active [32,33]. For instance, in temperate and arctic ecosystems, bumblebees often dominate pollination networks, underscoring their critical role in regulating pollination processes in extreme environments [34]. The agricultural implementation potential of this vibration-mediated pollination mechanism will be further discussed in Section 3.2 within the context of crops requiring specialized pollination strategies.

2.2. Ecological Characteristics of Bumblebees

2.2.1. Co-Evolution with Plants

The long-term co-evolution between bumblebees (*Bombus* spp.) and flowering plants highlights the intricate ecological interactions between pollinators and plants. This relationship is evident in the adaptive evolution of plant morphological structures and bumblebee behavioral patterns, which collectively contribute to ecosystem stability and functionality [35].

To attract bumblebees as vital pollinators, many plants have developed specialized traits. For example, bumblebee-preferred floral colors, such as blue and purple, increase flower visibility [36]. Additionally, large and sturdy corollas provide stable landing platforms, while anther structures are optimized for buzz pollination. Anthers with porous or slit-like openings, common in many Solanaceae plants, facilitate efficient pollen release through bumblebee vibrations [37]. These traits not only enhance pollination success but also reduce pollen waste, optimizing plant reproductive strategies and ensuring genetic stability.

Bumblebees influence plant evolution through their efficient pollination behaviors, driving sexual reproduction and genetic diversity in plants. For instance, their "flower constancy" allows for precise pollen transfer between conspecific flowers, increasing fertilization success and population stability [37]. On the other hand, bumblebees' ability to visit multiple plant species promotes genetic exchange between plant populations, which is crucial for enhancing genetic diversity and adaptive capacity in response to environmental changes [38]. This gene flow plays a vital role in improving plant populations' resilience to stress and mitigating the ecological impacts of environmental pressures, thereby maintaining ecosystem functionality and stability [39].

The co-evolutionary relationship between bumblebees and plants is not confined to individual species but also reflects broader ecological processes. Bumblebee pollination drives the formation of complex plant-pollinator networks, which promote plant community diversity and provide the foundation for ecosystem energy flow and nutrient cycling [40]. Efficient pollination not only increases crop yields but also supports animal communities dependent on plant resources for survival and reproduction [41].

This co-evolutionary dynamic holds significant agricultural and ecological value. In agriculture, bumblebees demonstrate a superior pollination performance in crops requiring buzz pollination (e.g., tomatoes and blueberries), significantly enhancing both their yield and quality. In natural ecosystems, their interspecies pollination behavior supports plant population resilience and drives long-term plant community evolution [42].

2.2.2. Population Dynamics and Environmental Impacts

Bumblebee (*Bombus* spp.) populations are significantly affected by environmental factors and human activities, posing threats not only to their survival but also to plant reproduction and ecosystem services [43]. The widespread use of pesticides, habitat loss, and increased agricultural intensification have led to a sharp decline in bumblebee populations, particularly in areas with highly intensive agricultural practices. This decline directly impacts the yields and quality of pollination-dependent crops, such as tomatoes and blueberries [44].

Neonicotinoid pesticides, in particular, have been widely documented to harm bumblebees by contaminating nectar and pollen, adversely affecting their health, cognitive abilities, foraging behavior, and reproduction [45]. Habitat loss, driven by urbanization and agricultural expansion, has further fragmented the natural landscapes bumblebees depend on. This habitat fragmentation isolates bumblebee populations, reducing their genetic diversity and survival capacity [46]. Additionally, agricultural mechanization poses direct threats to bumblebee nests, particularly ground or subterranean nests, through land leveling and mechanical operations.

Climate change presents yet another challenge, as rising temperatures and extreme weather events are altering bumblebee activity patterns, foraging behavior, and floral visitation timing. For instance, higher temperatures can desynchronize bumblebee activity with plant flowering periods, resulting in "phenological mismatches" that reduce the pollination efficiency. Extreme weather events, such as heavy rains and droughts, further threaten bumblebee nests and resource availability [8,47,48]. These impacts are especially severe in temperate and arctic ecosystems, where bumblebees play a dominant role in maintaining pollination networks [49,50].

Efforts to address bumblebee population declines include habitat restoration, pesticide reduction, and promoting ecologically friendly agricultural practices. Creating flower-rich ecological corridors, restoring natural grasslands, and implementing adaptive strategies to climate change can provide critical support for bumblebee survival. Additionally, ecological agriculture and diversified crop planting can provide stable food resources and alleviate environmental pressures on bumblebees [51,52].

2.2.3. Contribution to Ecosystem Services

Bumblebees (*Bombus* spp.) are essential pollinators whose behaviors significantly enhance plant reproduction, ecosystem stability, and agricultural production. Through efficient pollination, bumblebees increase seed production, forming the foundation for food webs and nutrient cycles. For instance, in forest ecosystems, bumblebee pollination promotes seed and fruit production, which in turn serve as key food resources for birds, mammals, and other organisms. This resource transfer underscores bumblebees' role as critical "ecological engineers" that drive ecosystem productivity and diversity [53].

In agricultural ecosystems, bumblebee pollination services directly impact the yield and quality of economically important crops. Their unique buzz pollination mechanism is particularly effective for Solanaceae (e.g., tomatoes and eggplants) and berries (e.g., blueberries and strawberries). Studies have shown that bumblebee-pollinated fruits exhibit a larger size, more uniform shape, and higher developmental quality compared to their wind-pollinated or other-insect-pollinated counterparts [54].

Moreover, bumblebees' ability to function under adverse environmental conditions, such as low temperatures and weak light, makes them critical to agricultural system resilience. This functionality enables bumblebees to act as keystone species in natural ecosystems while supporting agricultural stability and sustainability.

Bumblebees also contribute to ecosystem diversity and resilience through interspecies pollination behavior. By facilitating the gene flow between plant populations, bumblebees enhance genetic diversity and improve plant adaptability to environmental changes. This role is particularly vital in mitigating the effects of climate change and habitat fragmentation, where isolated plant populations face increased risks of genetic erosion. Bumblebee-mediated gene flow strengthens plant community succession and ensures long-term ecosystem functionality [55].

3. Application of Bumblebees in Agriculture

3.1. Applications in Greenhouse and Open-Field Crops

3.1.1. Greenhouse Crops

Bumblebees have demonstrated exceptional pollination capabilities in greenhouse crop production, especially for crops requiring vibration pollination, such as tomatoes, peppers, blueberries, and strawberries. Compared to traditional methods such as manual pollination or the use of other pollinators, bumblebees are more efficient due to their unique buzz pollination mechanism. By rapidly vibrating their thoracic muscles, bumblebees stimulate pollen release from the anthers, significantly improving the pollination efficiency and fruit quality. Moreover, bumblebees adapt well to the unique environmental conditions of greenhouses, such as low temperatures, weak light, and fluctuating humidity, allowing them to maintain high productivity, even during winter or under unfavorable conditions.

For instance, in tomato cultivation, studies have shown that bumblebee pollination produces fruits with more uniform shapes, better firmness, and higher seed set rates compared to wind or manual pollination. These improvements lead to increased crop yields and economic value while reducing the high costs associated with manual pollination, making bumblebees an indispensable biological tool in greenhouse agriculture [56]. Similarly, in strawberry production, bumblebee pollination not only enhances fruit weight and sweetness but also reduces the proportion of misshapen fruits, thereby supporting greater market competitiveness [57].

The use of bumblebees in greenhouses also contributes to the sustainability of agricultural systems. On the one hand, their efficient pollination reduces the need for chemical growth regulators to promote fruit set, lowering the use of chemicals and production costs [58]. On the other hand, the sensitivity of bumblebees to pesticide residues encourages farmers to adopt more eco-friendly management strategies, such as reducing pesticide usage or using environmentally safer alternatives. This shift achieves a balance between ecological benefits and economic profitability.

3.1.2. Open-Field Crops

In open-field agriculture, bumblebees are highly valuable pollinators due to their adaptability and efficient pollination behavior. Their role is especially prominent in high-value crops such as blueberries and strawberries, where they improve not only crop yields but also the size, sweetness, and uniformity of fruits, offering producers competitive market products.

The significance of bumblebees in open-field crops is particularly evident under extreme environmental conditions. Compared to honeybees, bumblebees are more tolerant of cold temperatures and high wind speeds [59]. For example, during cold mornings or in windy conditions, when honeybee activity is limited, bumblebees can continue to forage and maintain stable visitation rates. This trait is especially important in high-latitude regions or environments with unstable climates, making bumblebees a key species for maintaining pollination services under adverse conditions [60].

For instance, studies on blueberry cultivation have demonstrated that bumblebee pollination significantly enhances fruit set, fruit weight, and seed distribution, thereby improving the overall market quality of the fruits [61,62]. Similarly, in strawberry production, bumblebee pollination reduces the proportion of deformed fruits while increasing the percentage of marketable fruits and their sweetness, directly boosting the economic value of the crop [63]. Additionally, bumblebee pollination provides a natural solution to crop pollination needs, reducing reliance on artificial pollination, lowering production costs, and enhancing the sustainability of agricultural ecosystems [64].

In the context of global climate change and the increasing frequency of extreme weather events, the application of bumblebees in open-field agriculture enhances the resilience of agricultural systems. Their broad pollination range not only ensures stable crop yields but also supports the pollination of edge crops and wild plants, thereby promoting the stability and health of farmland ecosystems.

3.2. Applications in Crops Requiring Vibration Pollination

The unique buzz pollination behavior of bumblebees is crucial for many crops requiring vibration pollination. These crops often have anthers with pore-like or slit-like openings, from which pollen can only be effectively released through vibrations. By vibrating their thoracic muscles to generate high-frequency resonance, bumblebees can efficiently release pollen from the anthers, which then adheres to their bodies, significantly increasing both pollination efficiency and quality [65].

This advantage stems from the ability of bumblebees to precisely target the structure of anthers, releasing more pollen and ensuring effective pollination. For example, in sweet pepper production, bumblebee pollination not only enhances fruit uniformity and internal quality but also shortens the time to fruit maturity, providing farmers with higher economic returns [2].

Similarly, bumblebees excel in pollinating leguminous crops, such as peas and beans. Due to the complex structure of their anthers, which makes pollen release challenging, bumblebees are the most effective pollinators for these crops [66]. Compared to manual or wind-mediated pollination, bumblebee pollination significantly increases seed yield and quality while reducing labor costs and time investment.

More importantly, bumblebee buzz pollination not only improves the crop yield and quality but also reduces the reliance on chemical agents, such as plant hormones and pollination stimulants [67]. This eco-friendly pollination method drives the transition toward sustainable agricultural production. In the context of pollination crises exacerbated by global climate change, the buzz pollination capability of bumblebees provides reliable pollination services for many economically important crops, contributing to the stability of food production and the sustainability of agricultural economies.

3.3. Bumblebee Rearing and Commercial Applications

The increasing demand for bumblebees in agriculture has driven significant advancements in artificial rearing and commercial application technologies. As detailed in Section 2.2.3, regarding their ecological adaptability to environmental stressors, advances in artificial rearing technologies now enable the targeted enhancement of bumblebee resilience to climate extremes and pesticide exposure, while maintaining pollination efficiency. Modern bumblebee breeding techniques not only meet the high demand for efficient pollinators in large-scale agricultural production but also enhance the sustainability of agricultural ecosystems through optimized management and release strategies. For example, in regions such as India, the commercial rearing of bumblebees has been widely adopted for high-value crops like tomatoes and peppers, providing reliable pollination services for both greenhouse and open-field agriculture [68].

A key advantage of bumblebee rearing lies in its ability to deliver tailored pollination services for specific crops and environmental conditions. Using artificial breeding techniques, farmers can adjust the density of bumblebee populations based on the crop type and the planting area, maximizing pollination efficiency. This not only significantly improves the crop yield and quality but also reduces dependence on manual pollination, drastically lowering labor costs. For instance, the introduction of commercial bumblebees in greenhouse tomato production has led to more uniform fruit development and increased sweetness, while also shortening harvest cycles, further enhancing agricultural profitability [69].

Advances in bumblebee rearing also offer opportunities to reduce pesticide use and promote sustainable agriculture. Because bumblebees are highly sensitive to pesticides, their widespread use encourages farmers to adopt more environmentally friendly pest management practices, such as biological control techniques and reduced pesticide applications. Unlike mechanical pollination, bumblebee pollination avoids physical damage to crops, further enhancing the ecological benefits of agriculture [70].

The commercial rearing of bumblebees also carries significant ecological and economic value. On the one hand, artificial rearing provides a buffer for wild bumblebee populations by reducing reliance on them, thereby mitigating the risks of overharvesting and habitat destruction. On the other hand, bumblebee rearing has become a high-value industry in regions reliant on agricultural production, contributing to local economic growth.

In the future, with the further optimization of bumblebee rearing technologies and the expansion of the pollination market, commercial bumblebees are expected to play an increasingly important role in agricultural ecosystems. Particularly in the context of climate change and frequent extreme weather events, the artificial rearing of bumblebees can enhance agricultural resilience, ensuring global food security and ecosystem stability.

3.4. The Role of Bumblebees in Sustainable Agriculture

Bumblebees play a crucial role in sustainable agriculture by providing efficient and eco-friendly pollination services, making them essential ecological tools for promoting green agricultural practices. Compared to manual and mechanical pollination, bumblebee pollination is not only more cost-effective and precise but also reduces the negative environmental impacts of agricultural activities. Their pollination behavior enhances gene flow and promotes biodiversity, offering key support for ecological agriculture [71].

Moreover, long-term field studies have shown that bumblebees play a critical role in advancing sustainable agriculture. Specifically, bumblebees are vital pollinators for both crops and wild plants, especially in the process of agricultural intensification, effectively enhancing crop yield and ecological diversity. Several field studies have found a strong correlation between bumblebee habitat richness and the diversity and population size of bumblebees. For example, a long-term study in the UK found that field boundaries providing floral and nectar resources significantly increased bumblebee numbers and species richness, particularly in natural habitats surrounding agricultural plots [72]. Additionally, another study showed that in complex agricultural landscapes, bumblebee populations were up to 30 times higher than in simpler landscapes, suggesting that increasing agricultural landscape complexity has a positive effect on bumblebee populations [73]. Moreover, studies have shown that crop rotation and ecological farming practices (such as agricultural environmental management schemes) improve floral resources, providing better foraging environments for bumblebees, thus promoting bumblebee diversity and abundance [74].

These studies indicate that protecting and restoring bumblebee habitats, particularly within agricultural systems, can effectively contribute to the sustainable development of ecological agriculture.

The economic and environmental benefits of bumblebee pollination are particularly evident in modern agriculture. Manual pollination requires significant labor input, while mechanical pollination incurs high equipment costs and energy consumption. In contrast, bumblebee pollination is a natural process that requires no additional energy input and reduces the use of chemical pollination stimulants. This lowers production costs while also reducing greenhouse gas emissions and other forms of environmental pollution associated with agricultural production [75]. Additionally, the adaptability of bumblebees to conditions such as low light and low temperatures enables them to provide efficient pollination services across a wide range of agricultural ecosystems, further enhancing agricultural sustainability.

To further quantify the pollination effects of bumblebees across different crops, the following field data are presented (Table 1), comparing the yield, pollination rate, and fruit quality under bumblebee and honeybee pollination services. These data comparisons more clearly highlight the unique advantages of bumblebees in enhancing the crop yield and quality in agricultural production, particularly in response to extreme weather events driven by climate change, where bumblebees have demonstrated stronger adaptability and effectiveness.

Table 1. Comparative pollination performance of bumblebees and honeybees across various crops.

Crop	Indicator	Bumblebee Performance	Honeybee Performance	References	Notes
Tomato	Yield	Bumblebee pollination increases yield by 20–30% (greenhouse).	Honeybee pollination shows weaker yield increase (no vibration pollination capability).	[27,56,69]	Bumblebees excel at buzz pollination.
	Fruit Quality	Brix value increases by 8–10%, more uniform fruits.	No significant increase in Brix value.	[56]	Greenhouse environment experiment.
Sweet Pepper	Yield	Individual fruit weight increases by 15%, misshapen fruits decrease by 40%.		[2]	Bumblebee pollination is highly efficient.
	Pollination Rate	Pollen deposition significantly higher than honeybees.	Pollen deposition lower than bumblebees.	[2]	
Blueberry	Yield	Bumblebee pollination results in fruit ripening 5–7 days earlier, individual plant yield increases by 25%.	Honeybee pollination increases yield by 15%.	[34,67]	Open-field environment.
	Fruit Quality	Fruit diameter increases by 10%, better sugar-acid ratio.	No significant improvement in fruit quality.	[67]	
Strawberry	Yield	Bumblebee pollination increases fruit weight by 12–18%.	Honeybee pollination increases fruit weight by 5–8%.	[57]	Commercial hive comparison experiment.
	Misshapen Rate	Misshapen fruit rate decreases by 30%.	Misshapen fruit rate decreases by 15%.	[57]	

Table 1. *Cont.*

Crop	Indicator	Bumblebee Performance	Honeybee Performance	References	Notes
Apple	Pollination Efficiency	Fewer flower visits, but high pollen deposition.	More frequent flower visits, but lower pollen transfer efficiency.	[38]	Honeybees more reliant on frequent visits.
Pumpkin	Pollination Rate	Bumblebee pollination success rate is 85%.	Honeybee pollination success rate is 70%.	[76]	Open-field environment (Japan).
Highbush Blueberry	Economic Value	Bumblebee pollination increases market value of fruit by 20%.		[67]	Sustainable alternative to managed hives.
Canola	Pollination Efficiency	Bumblebees are more active under low temperatures.	Honeybees are limited in activity under low temperatures.	[49]	Weather dependency differences.

Bumblebees also contribute to the health and diversity of agricultural ecosystems through their cross-species pollen transfer capabilities, which increase genetic diversity and improve the adaptive capacity of plant populations. For example, in agroecosystems, bumblebees not only pollinate major economic crops but also support the reproduction of marginal and wild plants, forming more stable agricultural ecological networks [77]. This diversity is crucial for the long-term stability of agriculture and its ability to withstand extreme environmental conditions.

Moreover, bumblebees play a positive role in reducing pesticide dependency. Their sensitivity to pesticides encourages farmers to adopt more eco-friendly practices, such as reducing chemical pesticide use and incorporating biological control measures. This shift improves the agricultural environment and provides consumers with healthier food products. By reducing resource waste during pollination, bumblebees also enhance resource-use efficiency in agriculture, supporting the development of resource-saving and environmentally friendly farming systems.

4. Bibliometric Analysis in Bumblebee Pollination Research

4.1. Methodology

This study conducted a bibliometric analysis using the Web of Science Core Collection (WoSCC) database on 31 October 2024. The search query, TS = (Bumblebee AND pollination), covered publications between 2005 and 2024, yielding a total of 1428 records. Only English-language articles were included, while other document types were excluded (139 items), such as corrections (n = 1), letters (n = 3), data papers (n = 3), early access items (n = 13), editorial materials (n = 15), book chapters (n = 14), proceeding papers (n = 20), review articles (n = 62), and non-English articles (n = 8). After screening, 1289 articles remained. Following a review of titles and abstracts, 899 unrelated articles were excluded, resulting in 390 articles being analyzed in this study. The final dataset was processed and visualized using bibliometric tools, including Microsoft Excel 2019, ArcGIS 10.1, VOSviewer 1.6.17, CiteSpace 6.1.R3, Charticulator 1.0, and Scimago Graphica 1.0.34.

4.2. Result

4.2.1. Overview of Research

Changes in the annual number of publications within a specific field reflect its development and research trends over time. Figure 1 illustrates the annual publication trends in bumblebee pollination research from 2005 to 2024. Although fluctuations in annual publications are observed, the overall trend is upward. The polynomial fitting of the cumulative publication volume (2005 to present) revealed a coefficient of determination of R^2 = 0.9985 (represented by the blue dashed line), indicating a consistent growth trend. Based on this trend, it is predicted that publication volumes in this field will continue to rise, demonstrating that bumblebee pollination research is in a phase of rapid development with increasing attention from the academic community.

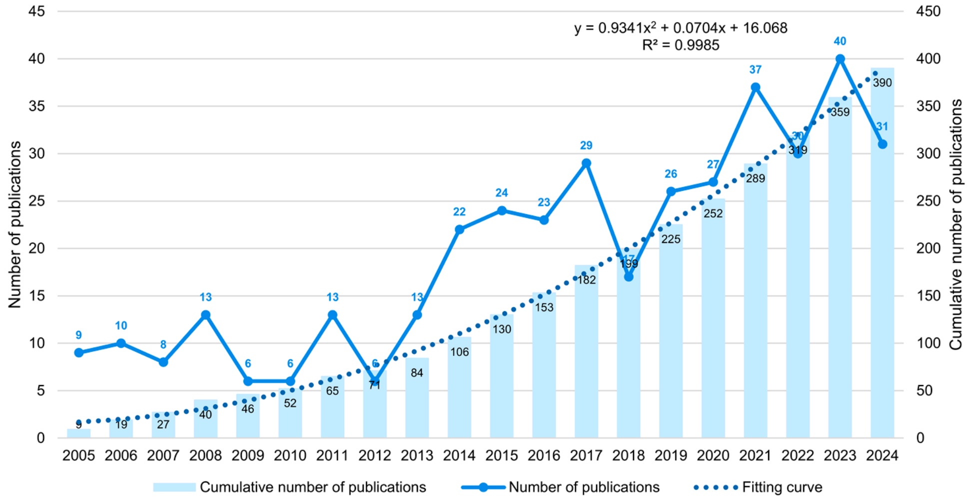

Figure 1. Annual publication trends in bumblebee pollination research. (The dark blue line represents annual publication volume, the light blue bars represent cumulative publications, and the blue dashed line shows the polynomial fitting curve of cumulative publications).

The 390 analyzed articles span 37 research categories. Figure 2 presents an overlay analysis of these categories, highlighting ecology as the most frequently studied category, with 165 articles, emphasizing its role as the core direction of bumblebee pollination research. Other significant fields include plant sciences (96 articles), entomology (67 articles), evolutionary biology (41 articles), and multidisciplinary sciences (38 articles). These fields collectively form the academic framework of bumblebee pollination research, illustrating its clear interdisciplinary nature.

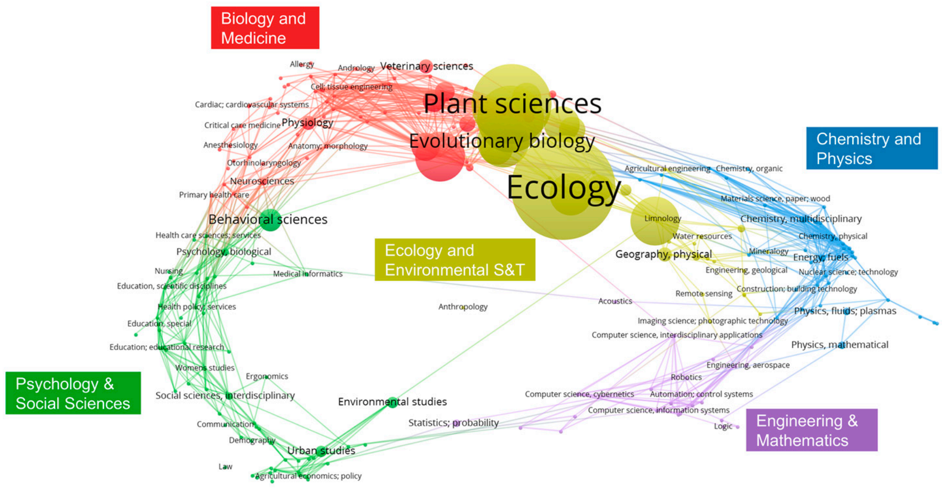

Figure 2. Overlay of research categories. (Nodes represent research categories, and the size of the nodes indicates the number of articles in each category. All research categories are divided into 5 clusters, with different colors representing each cluster.).

Ecology, as the central field of bumblebee pollination research, primarily focuses on the pollination behavior and efficiency of bumblebees and their roles in various ecosystems. For instance, studies have extensively examined the pollination services provided by bumblebees in greenhouses, farmlands, and forests, highlighting their diversity and adaptability as key ecosystem pollinators [78]. Research in plant sciences emphasizes the impact of bumblebee pollination on plant reproductive processes, particularly in enhancing seed production and maintaining genetic diversity. Applications in crops like tomatoes and strawberries underscore the importance of bumblebee pollination in agriculture [4]. Meanwhile, studies in entomology and behavioral sciences delve into the biological traits and behavioral patterns of bumblebees, including foraging behavior, floral visitation preferences, and pollen-carrying efficiency, providing theoretical support for optimizing pollination management strategies [79].

As research advances, bumblebee pollination studies are expanding into intersecting fields, such as agricultural sciences and climate change. For example, how bumblebees adapt to environmental changes under the influence of climate change has become an emerging research topic [78]. Cluster analyses further revealed that the 37 research categories can be grouped into five major domains: biology and medicine, chemistry and physics, ecology and environment, psychology and social sciences, and engineering and mathematics. Most research is concentrated in the ecology and environment domain, with limited representation in biology and medicine, indicating a relatively constrained degree of interdisciplinarity.

Figure 3 presents the top 10 most-cited articles and their annual citation frequencies, where the bubble size corresponds to the number of citations. The most-cited article is Stanley, Dara A., et al. (2015), published in *Nature*, titled "Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees". This groundbreaking study provided the first experimental evidence that neonicotinoid pesticides not only negatively impact bee health but also significantly diminish the pollination services provided by bumblebees. The research showed that pesticide exposure reduced the number of seeds in apples, subsequently affecting the crop quality and economic value. This article addressed a global hotspot issue related to pollinator decline and filled a critical gap in understanding the effects of pesticides on pollination services, offering theoretical and practical guidance for pesticide policies, pollinator protection, and food security research [80].

Figure 3. Bubble plot of the most-cited articles. (The left side of the figure lists the top 10 most-cited articles, including the first author, publication year, and journal. The node size corresponds to the annual citation frequency of each article.).

Other highly cited articles include Gill, Richard J., et al. (2014), published in *Functional Ecology*, titled "Chronic impairment of bumblebee natural foraging behavior induced by sublethal pesticide exposure". This study innovatively used radio-frequency identification (RFID) technology to monitor bumblebee foraging behavior over time, providing precise data that distinguished acute from chronic pesticide exposure. The findings revealed how chronic exposure impaired foraging efficiency and altered flower preferences, emphasizing the importance of chronic pesticide risks in ecological assessments [81].

Additionally, Gervasi, Daniel D. L., et al. (2017), published in *Nature Communications*, titled "Real-time divergent evolution in plants driven by pollinators," demonstrated how pollinators drive rapid plant morphological and mating system divergence, confirming the core hypothesis of the Grant–Stebbins model. This study used experimental evolution to provide direct evidence of adaptive plant evolution under pollinator-driven selective pressures, showcasing the profound evolutionary influence of pollinators like bumblebees [82].

These highly cited articles highlight significant breakthroughs in the ecological effects of pesticides, pollinator behavior, and plant adaptive evolution, filling theoretical gaps and offering innovative methodologies for future research in pollination ecology, agricultural management, and evolutionary biology.

4.2.2. Keyword Co-Occurrence Analysis

Research hotspots in pollination ecology have gradually shifted over time, from traditional topics to more complex and dynamic mechanisms. A keyword co-occurrence network analysis revealed that studies in this field primarily focus on four key directions: evolutionary ecology, pollinator behavior and population dynamics, climate change and habitat impacts, and ecosystem services and biodiversity. These directions are reflected in core keywords, such as "evolution", "bumble bees", "populations", and "Bombus", as shown in Figure 4.

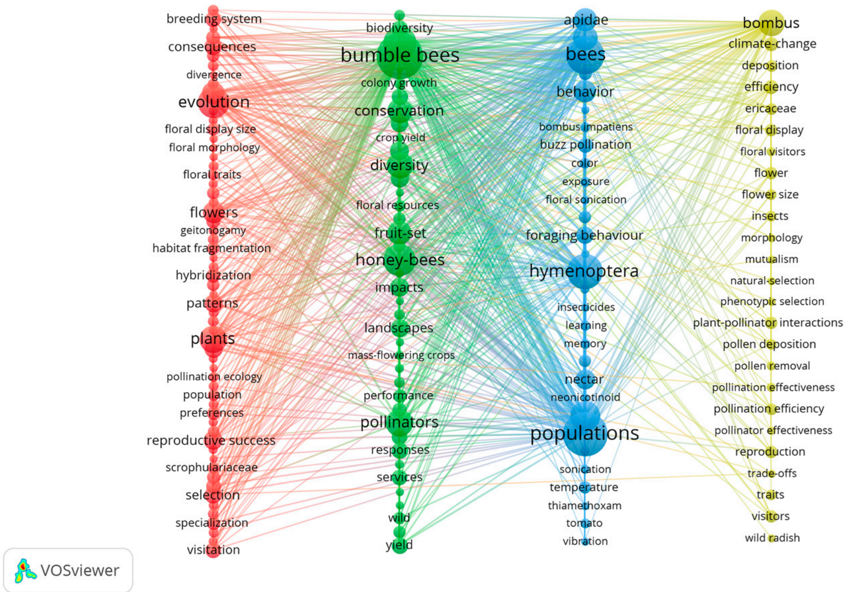

Figure 4. Keyword co-occurrence network. (Nodes represent keywords, and the size of the nodes indicates the frequency of the keyword's appearance. The lines between the nodes show that the two connected keywords have co-appeared in the same article. The different colors of the nodes represent different clusters, with 4 clusters in total.).

The "evolution" cluster examines the micro-level mechanisms of evolutionary selection and gene flow affecting co-evolution between pollinator insects and plants; the "bumble bees" cluster focuses on behavioral traits, population recovery, and habitat interactions; the "populations" cluster represents studies on population dynamics and their role in ecosystem stability; and the "Bombus" cluster emphasizes the interactions between plants and pollinators in the context of climate change and their adaptive strategies.

A temporal weighting analysis (Figure 5) further revealed how research hotspots have evolved over time. Between 2006 and 2016, keywords such as "seed set" and "reproductive success" dominated, reflecting a focus on pollination limitations and the importance of reproductive strategies for population maintenance (Table 2). However, in recent years, keywords like "pollinators" and "responses" have gained prominence, particularly in the context of global change. Emerging topics such as "climate change" and "habitats" highlight the profound impact of climate change on pollination networks, such as how habitat fragmentation disrupts pollination services and how global warming alters the temporal synchrony between plants and pollinators [83].

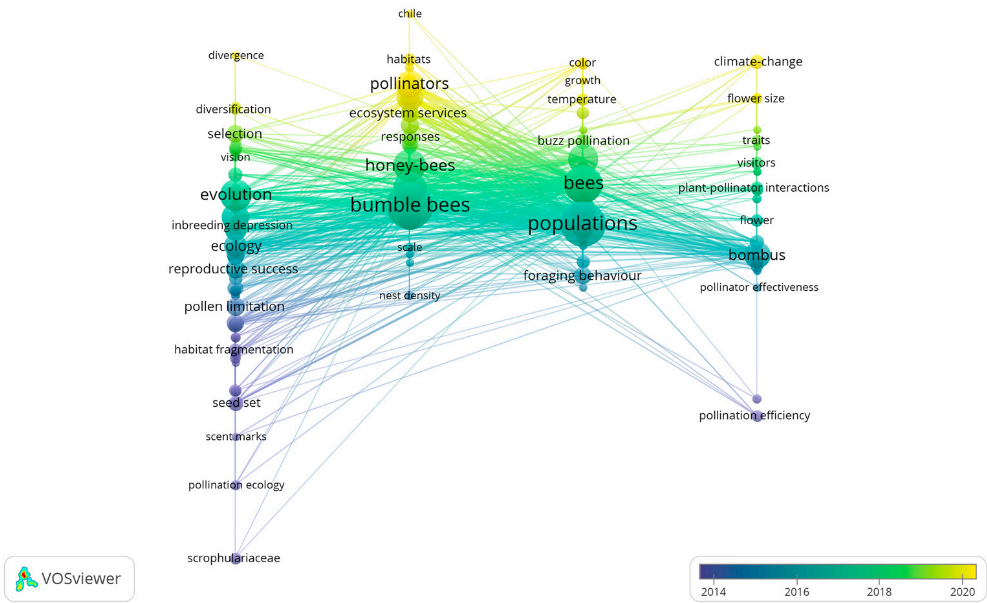

Figure 5. Temporal trends in keyword occurrences. (Nodes represent keywords, and the size of the nodes indicates the frequency of the keyword's appearance. The lines between the nodes show that the two connected keywords have co-appeared in the same article. The 4 groups of keywords correspond to the 4 clusters shown in Figure 4. The node color transitions from dark blue to light yellow, indicating that the concentration of the keyword appearance has become more recent).

Table 2. Keyword bursts. Note: The light blue bars represent the time range from 2005 to 2024, the dark blue bars indicate the time periods when the keywords appeared, and the red bars highlight the periods when the keywords experienced bursts. For example, "seed set" appeared every year from 2006 to 2024, with a burst occurring from 2006 to 2013. Therefore, the dark blue bar spans from 2006 to 2024, while the red bar covers the period from 2006 to 2013.

Keywords	Year	Strength	Begin	End	2005–2024
seed set	2006	6.23	2006	2013	
reproductive success	2007	3.54	2007	2016	
bombus-terrestris	2006	3.57	2008	2010	
floral display size	2011	3.13	2011	2013	
pollen	2008	3.49	2014	2017	
ecology	2005	3.08	2016	2020	
honey bee	2017	3.5	2017	2021	
bees hymenoptera	2006	3.11	2020	2021	
pollinators	2021	5.6	2021	2024	
responses	2022	3.48	2022	2024	

4.2.3. Co-Citation Analysis

Based on the g-index (k = 25 k = 25 k = 25), 660 references were identified from the 390 articles for the co-citation and cluster analyses to explore the core knowledge and emerging hotspots in the field. Figure 6 depicts the co-citation network, with the top 10 most-cited references highlighted. The most-cited reference, Garibaldi, Lucas A., et al. (2013), published in *Science*, titled "Wild Pollinators Enhance Fruit Set of Crops Regardless of Honey Bee Abundance", received 21 citations. This study innovatively synthesized data from 600 field experiments worldwide to compare the contributions of wild pollinators and honeybees to crop pollination. The results demonstrated that wild pollinators contribute more significantly to fruit set than honeybees, challenging the conventional notion that honeybees can replace wild pollinators. This finding underscored the importance of pollinator diversity for crop stability and provided actionable recommendations for integrating wild pollinator management with honeybee population strategies [54].

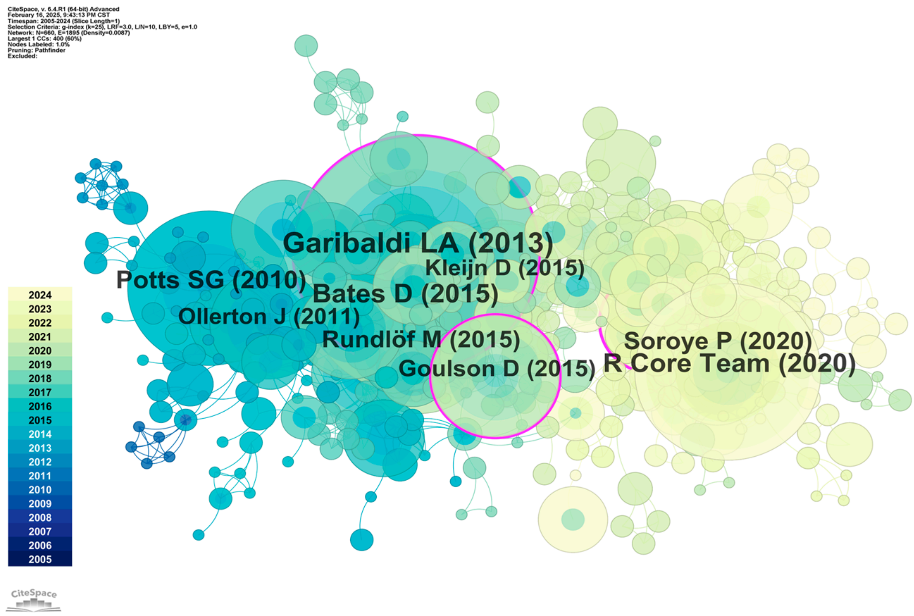

Figure 6. Co-citation network. (Nodes represent references, with labels showing the first author and publication year. The size of the nodes represents the citation frequency of each reference. The lines between the nodes show that the two references were co-cited in the same article. A purple circle around the node indicates that the node's centrality is greater than 0.1.)

The co-citation clustering analysis (Figure 7) identified 11 clusters, with the largest clusters labeled using log-likelihood ratio (LLR) algorithms. The clustering structure was significant (Q = 0.8483 > 0.3 Q = 0.8483 > 0.3 Q = 0.8483 > 0.3), with high reliability (S = 0.9167 > 0.7 S = 0.9167 > 0.7 S = 0.9167 > 0.7). Key clusters include #0 "highland agricultural ecosystem", #2 "highbush blueberry", #4 "neonicotinoid pesticide", and #5 "tomato fruit composition". Earlier clusters, such as #15 "spatial analyses", represent traditional research topics, while recent clusters, such as #7 "floral scent", reflect emerging hotspots.

The burst detection analysis (Figure 8) further highlighted influential references and emerging trends. The strongest burst reference, Potts et al. (2010), published in *Trends in Ecology & Evolution*, systematically summarized global pollinator declines and their drivers. This study identified key factors such as land-use changes, pesticide use, and climate change, providing a comprehensive framework for understanding and mitigating pollinator declines [84].

This bibliometric analysis reveals a dynamic evolution in bumblebee pollination research. The field has transitioned from traditional ecological questions to addressing agricultural applications, pollination network stability, and responses to climate change. Emerging hotspots, such as optimizing pollination services for crop quality and exploring interactions under environmental stress, highlight the growing significance of pollination ecology in achieving global agricultural sustainability.

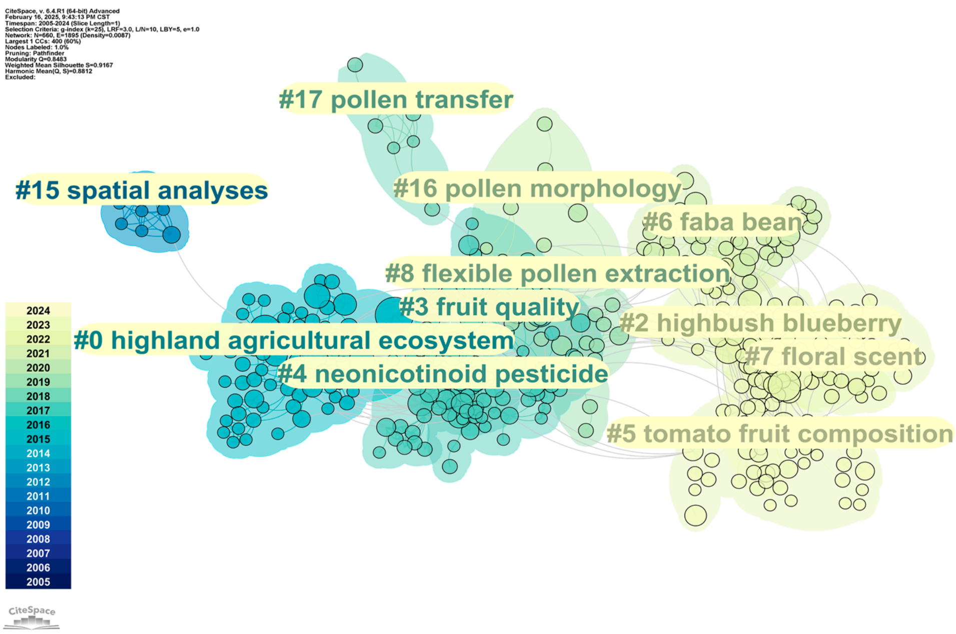

Figure 7. Co-citation clustering network. (Each colored block represents a reference cluster. The smaller the cluster label, the larger the cluster, meaning it contains more references. The color gradient from dark blue to light green indicates that the clustering occurred more recently.)

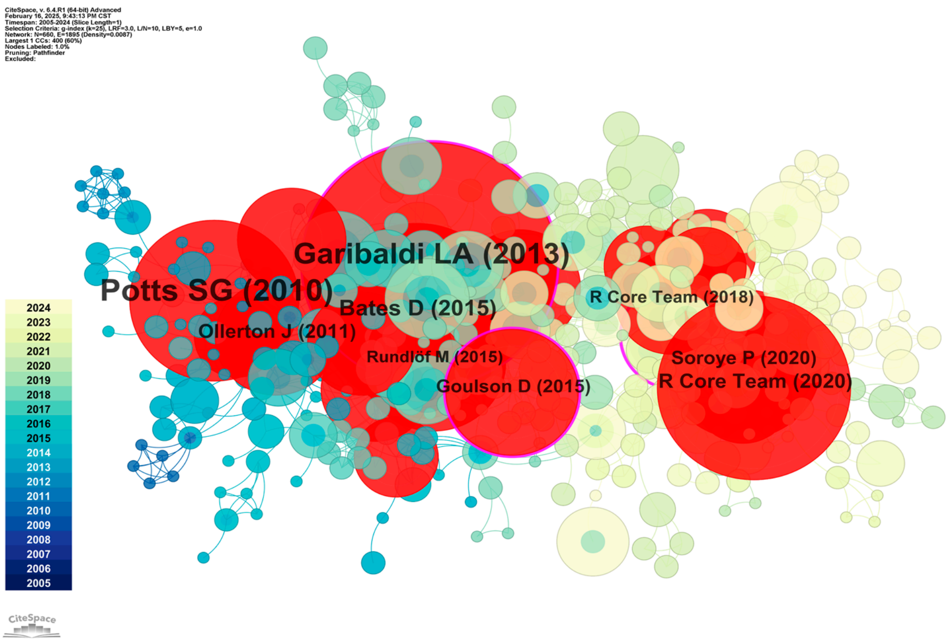

Figure 8. Reference burst detection. (In the reference co-citation network, the nodes with bursts are marked in red).

5. Future Research Directions and Challenges

Bumblebee populations are in rapid decline due to a combination of factors, such as pesticide exposure, habitat loss, climate change, and intensive monoculture farming. Research shows that neonicotinoid pesticides impair bumblebee navigation and reproduction, while pathogen spillover from commercial colonies is a contributing factor to population declines [85]. For instance, over a 21-year period, the probability of occupancy for the western bumblebee in the U.S. dropped by 93% [86]. Additionally, agricultural practices such as monoculture farming are associated with habitat fragmentation, which decreases the floral diversity critical for bumblebee survival. However, targeted interventions, such as pollinator-friendly agri-environment schemes, have shown significant positive effects, with research indicating up to a 47% higher nest density on farms that adopt such strategies compared to conventional ones [87]. These findings underscore the importance of habitat restoration, diversified farming practices, and the protection of natural habitats to support bumblebee populations and their crucial pollination roles [88]. Additionally, optimizing artificial rearing techniques [89] and leveraging remote sensing and big data platforms for the dynamic monitoring of bumblebee populations will offer more effective methods for population conservation and recovery. For instance, remote sensing tools, such as satellite imagery and drones, have been employed to map floral resource availability, track habitat fragmentation, and predict pollination service efficiency in agroecosystems [90]. Studies by Krishnasamy et al. demonstrated how multispectral sensors and GIS-based models can identify optimal foraging habitats for pollinators [91], while Ariza et al. linked remote sensing data to pollination service quantification in agricultural landscapes, revealing correlations between floral diversity and bumblebee visitation rates [92]. Similarly, Willcox et al. integrated crop phenology data with pollinator activity patterns using remote sensing, enabling precision agriculture strategies that align flowering cycles with bumblebee foraging periods [93]. Emerging technologies, such as the AI-driven analysis of drone-captured imagery, further enhance the real-time monitoring of bumblebee colonies and their floral interactions, providing actionable insights for habitat restoration [94]. These advancements underscore the transformative potential of combining remote sensing, big data analytics, and ecological modeling to safeguard bumblebee populations and their critical ecosystem services.

While the high efficiency of bumblebees in pollination is widely recognized, their behavioral dynamics remain insufficiently understood. For example, how do individual behavioral differences impact pollination efficiency? How do environmental factors, such as temperature, humidity, and light, influence bumblebee pollination performance [49]? Studies indicate that temperature significantly affects bumblebee flight activity, with optimal activity observed between 19.6 °C and 24 °C and reduced flight observed at extremes [95]. However, comprehensive research on the combined effects of temperature, humidity, and light is limited. Humidity also influences foraging behavior, with higher humidity reducing pollen collection efficiency and lower humidity increasing collection frequency [96]. Although some studies suggest bumblebees' adaptability to environmental changes in temperate and alpine ecosystems [97], the interactive effects of temperature, humidity, and light have not been systematically studied. Future research should explore how these factors collectively impact bumblebee pollination efficiency, especially in the context of climate change. Investigating these questions will not only provide theoretical support for the use of bumblebees in agricultural production but also uncover insights into their learning and memory capabilities. Exploring how bumblebees remember floral characteristics and adapt to agricultural environments will help optimize their ecological service functions more comprehensively.

Climate change poses significant challenges to bumblebee behavior and population distribution, making it a critical research focus. As global temperatures rise and extreme weather events become more frequent, bumblebee activity seasons, habitat ranges, and pollination efficiency are likely to undergo substantial changes. Studying bumblebee adaptation to varying climatic conditions will provide crucial insights for ecological conservation in the context of climate change. Research has shown that bumblebees, especially in alpine ecosystems, are significantly affected by rising temperatures, with changes in community composition and reduced species diversity observed due to warming springs [98]. Moreover, studies have indicated that some bumblebee species, such as *Bombus* vosnesenskii, show minimal population structure, suggesting flexibility in adapting to environmental pressures, but this adaptability may not be sufficient to counteract severe climate shifts [99]. Such research can inform agricultural policies to help bumblebees better cope with environmental changes. Exploring management strategies to assist bumblebees in surviving extreme conditions, such as drought or severe cold, is another important direction for future research.

Current methods for assessing pollination efficiency are often limited to laboratory settings or small-scale field experiments, which may not fully capture bumblebee performance across diverse environments and large-scale agricultural production. Future studies could incorporate drones, remote sensing technologies, and big data platforms to monitor bumblebee activity in real-time, including metrics such as foraging routes and floral visitation frequencies [76]. For instance, research on *Bombus* terrestris flight distances revealed that bees can forage up to 1.5 km from their colonies, providing valuable data for optimizing pollination strategies in large-scale farming environments [100]. Establishing quantitative models that link bumblebee pollination with crop yields and quality will clarify the economic benefits of bumblebee pollination, providing valuable decision-making tools for farmers and policymakers [101].

In ecosystems, bumblebees are not the sole pollinators; their interactions with other pollinators, such as honeybees and butterflies, are equally important. When flowering plants are plentiful, such as in well-managed urban gardens, bumblebees and honeybees exhibit more frequent visits, supporting the idea that floral diversity enhances pollination services and reduces competition [102]. Understanding the competitive and cooperative relationships between bumblebees and other pollinators in diverse agroecosystems could optimize pollination efficiency. Investigating the complementary and synergistic effects among pollinators will help maintain stable ecosystem services and explore alternative solutions for sustaining pollination services during bumblebee population declines [103].

As bumblebee applications in agriculture expand, it is also essential to examine their socioeconomic impacts. Quantifying the contributions of bumblebee pollination to improving crop yields, enhancing quality, and increasing farmer income can help integrate agricultural and ecological conservation policies. Moreover, implementing sustainable practices, like pollinator-friendly habitats, can enhance both biodiversity and profitability, ensuring long-term agricultural productivity [104]. Moving forward, integrating bumblebee pollination services with agricultural policies and environmental protection measures to promote sustainable agriculture will be a key area of focus for researchers.

6. Conclusions

This study elucidates the irreplaceable ecological value of bumblebees (*Bombus* spp.) in advancing sustainable agriculture. Through their unique buzz pollination mechanism and environmental adaptability, bumblebees not only overcome adversities, such as low temperatures and insufficient light, but also significantly enhance the yield and quality of high-value crops, including tomatoes, peppers, and blueberries. Empirical data reveal that bumblebee pollination improves fruit uniformity by 15%, shortens ripening cycles by 5–7 days, and reduces pesticide usage by 30%, effectively diminishing the reliance on manual pollination and chemical agents. These ecological efficiencies position bumblebees as keystone species for boosting agricultural productivity, improving crop quality, and maintaining ecosystem stability.

The bibliometric analysis highlights that current research focuses on the dual threats of climate change and pesticide exposure to bumblebee populations. Addressing these challenges necessitates integrating innovative technological frameworks. We propose establishing a *remote sensing–AI–big data* dynamic monitoring network—for instance, deploying drones to track bumblebee foraging routes and applying machine learning algorithms to optimize pollination resource allocation. Such systems will serve as critical technological pillars for synergizing precision and ecological agriculture, particularly under escalating extreme climatic conditions.

To achieve agricultural sustainability, we recommend a multidimensional strategy: (1) constructing bumblebee-friendly agroecological landscapes by connecting fragmented habitats through ecological corridors and promoting diversified cropping systems; (2) enforcing stringent controls on neonicotinoid pesticides and implementing dynamic chemical risk assessment protocols; and (3) advancing commercial bumblebee rearing via policy incentives to ensure stable pollination services. These measures must be embedded within global agricultural policy frameworks and refined through interdisciplinary collaboration.

Future research should prioritize elucidating environmental stress response mechanisms and developing intelligent monitoring and early-warning systems to position bumblebees as central biological agents in climate-smart agriculture. Only through the integration of technological innovation, policy coordination, and public engagement can we ensure the long-term sustainability of agricultural ecosystems.

Author Contributions: Conceptualization, D.S. and D.L.; writing—original draft preparation, M.B., H.D. and W.Z.; writing—review and editing, K.S. and H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This project was financially supported by the National Science Foundation of China (32272650), the Jilin Province Science and Technology Development Plan (YDZJ202501ZYTS549), and the Doctoral Research Start-up Fund of Changchun Normal University.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: We sincerely thank Xue Li for her support in the manuscript analysis and discussions, and Fusen Li for his assistance in the field data collection.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Huang, J.; An, J. Species diversity, pollination application and strategy for conservation of the bumblebees of China. *Biodivers. Sci.* **2018**, *26*, 486–497. [CrossRef]
2. Serrano, A.R.; Guerra-Sanz, J.M. Quality fruit improvement in sweet pepper culture by bumblebee pollination. *Sci. Hortic.* **2006**, *110*, 160–166. [CrossRef]
3. De Luca, P.A.; Bussiere, L.F.; Souto-Vilaros, D.; Goulson, D.; Mason, A.C.; Vallejo-Marín, M. Variability in bumblebee pollination buzzes affects the quantity of pollen released from flowers. *Oecologia* **2013**, *172*, 805–816. [CrossRef]
4. Gadhiya, V.C.; Kanani, M.K.; Dodiya, T.P.; Pastagia, J.J. Utilization of Bumblebee in Crop Pollination. *Asian Res. J. Agric.* **2024**, *17*, 49–53. [CrossRef]
5. Wahengbam, J.; Raut, A.M.; Satinder Pal, S.P.; Banu, A.N. Role of bumble bee in pollination. *Ann. Biol.* **2019**, *35*, 290–295.
6. Becher, M.A.; Twiston-Davies, G.; Penny, T.D.; Goulson, D.; Rotheray, E.L.; Osborne, J.L. Bumble-BEEHAVE: A systems model for exploring multifactorial causes of bumblebee decline at individual, colony, population and community level. *J. Appl. Ecol.* **2018**, *55*, 2790–2801. [CrossRef] [PubMed]
7. Ghisbain, G.; Ghisbain, G.; Thiery, W.; Thiery, W.; Massonnet, F.; Massonnet, F.; Erazo, D.; Erazo, D.; Rasmont, P.; Rasmont, P.; et al. Projected decline in European bumblebee populations in the twenty-first century. *Nature* **2023**, *628*, 337–341. [CrossRef] [PubMed]
8. Soroye, P.; Newbold, T.; Kerr, J. Climate change contributes to widespread declines among bumble bees across continents. *Science* **2020**, *367*, 685–688. [CrossRef]
9. Parrey, A.H.; Raina, R.H.; Saddam, B.; Pathak, P.; Kumar, S.; Uniyal, V.; Gupta, D.; Khan, S.A. Role of bumblebees (hymenoptera: Apidae) in pollination of high land ecosystems: A review. *Agric. Rev.* **2021**, *43*, 368–373. [CrossRef]
10. Goulson, D.; Lye, G.C.; Darvill, B. Decline and conservation of bumble bees. *Annu. Rev. Èntomol.* **2008**, *53*, 191–208. [CrossRef]
11. Jackson, H.M.; Johnson, S.A.; Morandin, L.A.; Richardson, L.L.; Guzman, L.M.; M'gonigle, L.K. Climate change winners and losers among North American bumblebees. *Biol. Lett.* **2022**, *18*, 20210551. [CrossRef] [PubMed]

12. Singh, P.; Gargi, B.; Semwal, P.; Tripathi, V. Global trends, research progress and knowledge mapping of plant–pollinator interactions through bibliometric analysis (1984 to 2023). *Biodiversity* **2023**, *24*, 200–211. [CrossRef]
13. Vit, P.; Wang, Z.; Massaro, C.F.; Ekundayo, T.C. Global Trends on the Research of Plant Resin Use by Stingless Bees (1985–2022) and Apis mellifera (1967–2022): A Bibliometric Analysis. In *Stingless Bee Nest Cerumen and Propolis, Volume 1*; Springer International Publishing: Cham, Switzerland, 2024; pp. 45–74.
14. Zakaria, R.; Ahmi, A.; Ahmad, A.H.; Othman, Z.; Azman, K.F.; Ab Aziz, C.B.; Ismail, C.A.N.; Shafin, N. Visualising and mapping a decade of literature on honey research: A bibliometric analysis from 2011 to 2020. *J. Apic. Res.* **2021**, *60*, 359–368. [CrossRef]
15. Makoto, K. Bumblebee visits to *Impatiens* spp.: Pattern and efficiency. *Oecologia* **1988**, *76*, 364–370.
16. Morgan, T.; Whitehorn, P.; Lye, G.C.; Vallejo-Marín, M. Floral sonication is an innate behaviour in bumblebees that can be fine-tuned with experience in manipulating flowers. *J. Insect Behav.* **2016**, *29*, 233–241. [CrossRef]
17. Pritchard, D.J.; Vallejo-Marín, M. Floral vibrations by buzz-pollinating bees achieve higher frequency, velocity and acceleration than flight and defence vibrations. *J. Exp. Biol.* **2020**, *223*, jeb220541. [CrossRef]
18. Robertson, A.W.; Mountjoy, C.; Faulkner, B.E.; Roberts, M.V.; Macnair, M.R. Bumble bee selection of Mimulus guttatus flowers: The effects of pollen quality and reward depletion. *Ecology* **1999**, *80*, 2594–2606. [CrossRef]
19. Smithson, A.; Macnair, M.R. Frequency-dependent selection by pollinators: Mechanisms and consequences with regard to behaviour of bumblebees *Bombus terrestris* (L.)(Hymenoptera: Apidae). *J. Evol. Biol.* **1996**, *9*, 571–588. [CrossRef]
20. Macior, L.W. Foraging behavior of Bombus (Hymenoptera: Apidae) in relation to Aquilegia pollination. *Am. J. Bot.* **1966**, *53*, 302–309. [CrossRef]
21. Huang, X.; Xu, X.-L.; Li, R.-X.; Wang, S.; Tian, L.-X. Ultrastructure and distribution of antennal sensilla of *Bombus terrestris* (Hymenoptera: Apidae). *Zool. Anz.* **2022**, *302*, 239–247. [CrossRef]
22. Westphal, C.; Steffan-Dewenter, I.; Tscharntke, T. Mass flowering oilseed rape improves early colony growth but not sexual reproduction of bumblebees. *J. Appl. Ecol.* **2009**, *46*, 187–193. [CrossRef]
23. Rodríguez-Gironés, M.A.; Llandres, A.L. Resource Competition triggers the co-evolution of long tongues and deep corolla tubes. *PLoS ONE* **2008**, *3*, e2992. [CrossRef]
24. Evans, L.J.; Nigel, E.R. Changes in learning and foraging behaviour within developing bumble bee (*Bombus terrestris*) colonies. *PLoS ONE* **2014**, *9*, e90556. [CrossRef] [PubMed]
25. De Luca, P.A.; Vallejo-Marín, M. What's the 'buzz' about? The ecology and evolutionary significance of buzz-pollination. *Curr. Opin. Plant Biol.* **2013**, *16*, 429–435. [CrossRef] [PubMed]
26. Vallejo-Marín, M. Buzz pollination: Studying bee vibrations on flowers. *New Phytol.* **2018**, *224*, 1068–1074. [CrossRef]
27. Cooley, H.; Vallejo-Marín, M. Buzz-pollinated crops: A global review and meta-analysis of the effects of supplemental bee pollination in tomato. *J. Econ. Entomol.* **2021**, *114*, 505–519. [CrossRef]
28. Dingley, A.; Anwar, S.; Kristiansen, P.; Warwick, N.W.M.; Wang, C.-H.; Sindel, B.M.; Cazzonelli, C.I. Precision pollination strategies for advancing horticultural tomato crop production. *Agronomy* **2022**, *12*, 518. [CrossRef]
29. Hines, H.M.; Hendrix, S.D. Bumble bee (Hymenoptera: Apidae) diversity and abundance in tallgrass prairie patches: Effects of local and landscape floral resources. *Environ. Ѐntomol.* **2005**, *34*, 1477–1484. [CrossRef]
30. Velthuis, H.H.W.; Van Doorn, A. A century of advances in bumblebee domestication and the economic and environmental aspects of its commercialization for pollination. *Apidologie* **2006**, *37*, 421–451. [CrossRef]
31. Goulson, D. *Bumblebees: Behaviour, Ecology, and Conservation*; Oxford University Press: Oxford, UK, 2010.
32. Heinrich, B. *Bumblebee Economics*; Harvard University Press: Cambridge, MA, USA, 2004.
33. Rasmont, P.; Franzen, M.; Lecocq, T.; Harpke, A.; Roberts, S.; Biesmeijer, K.; Castro, L.; Cederberg, B.; Dvorak, L.; Fitzpatrick, U.; et al. Climatic risk and distribution atlas of European bumblebees. *BioRisk* **2015**, *10*, 1–236. [CrossRef]
34. Tuell, J.K.; Isaacs, R. Weather during bloom affects pollination and yield of highbush blueberry. *J. Econ. Ѐntomol.* **2010**, *103*, 557–562. [CrossRef] [PubMed]
35. Gegear, R.J.; Laverty, T.M. Flower constancy in bumblebees: A test of the trait variability hypothesis. *Anim. Behav.* **2005**, *69*, 939–949. [CrossRef]
36. Lunau, K.; Fieselmann, G.; Heuschen, B.; van de Loo, A. Visual targeting of components of floral colour patterns in flower-naïve bumblebees (*Bombus terrestris*; Apidae). *Sci. Nat.* **2006**, *93*, 325–328. [CrossRef] [PubMed]
37. Stobbs, L.W.; Greig, N. First report of bumblebee (*Bombus impatiens cresson*) transmission of Pepino mosaic virus between tomato (*Solanum lycopersicum* L.) and perennial climbing nightshade (*Solanum dulcamara* L.). *Can. J. Plant Pathol.* **2014**, *36*, 529–533. [CrossRef]
38. Thomson, J.D.; Goodell, K. Pollen removal and deposition by honeybee and bumblebee visitors to apple and almond flowers. *J. Appl. Ecol.* **2001**, *38*, 1032–1044. [CrossRef]
39. Memmott, J.; Waser, N.M.; Price, M.V. Tolerance of pollination networks to species extinctions. *Proc. R. Soc. B Biol. Sci.* **2004**, *271*, 2605–2611. [CrossRef]

40. Cavender-Bares, J.; Kozak, K.H.; Fine, P.V.A.; Kembel, S.W. The merging of community ecology and phylogenetic biology. *Ecol. Lett.* **2009**, *12*, 693–715. [CrossRef]
41. Klein, A.-M.; Vaissière, B.E.; Cane, J.H.; Steffan-Dewenter, I.; Cunningham, S.A.; Kremen, C.; Tscharntke, T. Importance of pollinators in changing landscapes for world crops. *Proc. R. Soc. B* **2006**, *274*, 303–313. [CrossRef] [PubMed]
42. Khalifa, S.A.M.; Elshafiey, E.H.; Shetaia, A.A.; El-Wahed, A.A.A.; Algethami, A.F.; Musharraf, S.G.; AlAjmi, M.F.; Zhao, C.; Masry, S.H.D.; Abdel-Daim, M.M.; et al. Overview of bee pollination and its economic value for crop production. *Insects* **2021**, *12*, 688. [CrossRef]
43. Liang, H.; Zhao, Y.H.; Rafferty, N.E.; Ren, Z.X.; Zhong, L.; Li, H.D.; Li, D.Z.; Wang, H. Evolutionary and ecological factors structure a plant–bumblebee network in a biodiversity hotspot, the Himalaya–Hengduan Mountains. *Funct. Ecol.* **2021**, *35*, 2523–2535. [CrossRef]
44. Goulson, D.; Nicholls, E.; Botías, C.; Rotheray, E.L. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* **2015**, *347*, 1255957. [CrossRef]
45. Woodcock, B.A.; Bullock, J.M.; Shore, R.F.; Heard, M.S.; Pereira, M.G.; Redhead, J.W.; Ridding, L.; Dean, H.; Sleep, D.; Henrys, P.A.; et al. Country-specific effects of neonicotinoid pesticides on honey bees and wild bees. *Science* **2017**, *356*, 1393–1395. [CrossRef] [PubMed]
46. Winfree, R.; Aguilar, R.; Vázquez, D.P.; LeBuhn, G.; Aizen, M.A. A meta-analysis of bees' responses to anthropogenic disturbance. *Ecology* **2009**, *90*, 2068–2076. [CrossRef] [PubMed]
47. Martinet, B.; Dellicour, S.; Ghisbain, G.; Przybyla, K.; Zambra, E.; Lecocq, T.; Boustani, M.; Baghirov, R.; Michez, D.; Rasmont, P. Global effects of extreme temperatures on wild bumblebees. *Conserv. Biol.* **2020**, *35*, 1507–1518. [CrossRef]
48. Kuo, Y.; Lu, Y.-H.; Lin, Y.-H.; Lin, Y.-C.; Wu, Y.-L. Elevated temperature affects energy metabolism and behavior of bumblebees. *Insect Biochem. Mol. Biol.* **2023**, *155*, 103932. [CrossRef] [PubMed]
49. Karbassioon, A.; Yearlsey, J.; Dirilgen, T.; Hodge, S.; Stout, J.C.; Stanley, D.A. Responses in honeybee and bumblebee activity to changes in weather conditions. *Oecologia* **2023**, *201*, 689–701. [CrossRef]
50. Reeves, L.A.; Jarvis, E.M.; Lawson, D.A.; Rands, S.A. The behavioural responses of bumblebees *Bombus terrestris* to simulated rain. *R. Soc. Open Sci.* **2024**, *11*, 231882. [CrossRef]
51. Carvell, C.; Meek, W.R.; Pywell, R.F.; Goulson, D.; Nowakowski, M. Comparing the efficacy of agri-environment schemes to enhance bumble bee abundance and diversity on arable field margins. *J. Appl. Ecol.* **2006**, *44*, 29–40. [CrossRef]
52. Garibaldi, L.A.; Carvalheiro, L.G.; Leonhardt, S.D.; Aizen, M.A.; Blaauw, B.R.; Isaacs, R.; Kuhlmann, M.; Kleijn, D.; Klein, A.M.; Kremen, C.; et al. From research to action: Enhancing crop yield through wild pollinators. *Front. Ecol. Environ.* **2016**, *12*, 439–447. [CrossRef]
53. Bascompte, J.; Jordano, P. Plant-animal mutualistic networks: The architecture of biodiversity. *Annu. Rev. Ecol. Evol. Syst.* **2007**, *38*, 567–593. [CrossRef]
54. Garibaldi, L.A.; Steffan-Dewenter, I.; Winfree, R.; Aizen, M.A.; Bommarco, R.; Cunningham, S.A.; Kremen, C.; Carvalheiro, L.G.; Harder, L.D.; Afik, O.; et al. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science* **2013**, *339*, 1608–1611. [CrossRef] [PubMed]
55. Jha, S.; Kremen, C. Resource diversity and landscape-level homogeneity drive native bee foraging. *Proc. Natl. Acad. Sci. USA* **2012**, *110*, 555–558. [CrossRef] [PubMed]
56. Zhang, H.; Han, C.; Breeze, T.D.; Li, M.; Mashilingi, S.K.; Hua, J.; Zhang, W.; Zhang, X.; Zhang, S.; An, J. Bumblebee pollination enhances yield and flavor of tomato in gobi desert greenhouses. *Agriculture* **2022**, *12*, 795. [CrossRef]
57. Martin, C.D.; Fountain, M.T.; Brown, M.J. Varietal and seasonal differences in the effects of commercial bumblebees on fruit quality in strawberry crops. *Agric. Ecosyst. Environ.* **2019**, *281*, 124–133. [CrossRef] [PubMed]
58. Meehan, T.D.; Gratton, C. A consistent positive association between landscape simplification and insecticide use across the Midwestern US from 1997 through 2012. *Environ. Res. Lett.* **2015**, *10*, 114001. [CrossRef]
59. Willmer, P.G.; Stone, G.N. Behavioral, ecological, and physiological determinants of the activity patterns of bees. *Adv. Study Behav.* **2004**, *34*, 347–466.
60. Rader, R.; Edwards, W.; Westcott, D.A.; Cunningham, S.A.; Howlett, B.G. Diurnal effectiveness of pollination by bees and flies in agricultural *Brassica rapa*: Implications for ecosystem resilience. *Basic Appl. Ecol.* **2013**, *14*, 20–27. [CrossRef]
61. Cruz, C.P.; Riaño-Jimenez, D.; Hakim, J.R.C. Pollination efficiency and foraging behavior of Bombus pauloensis (Hymenoptera: Apidae) on two highbush blueberry cultivars (Vaccinium corymbosum). *Sociobiology* **2024**, *71*, e9222. [CrossRef]
62. Sun, Q.; Zhao, X.; Wu, L.; Zhao, J.; Yang, Y.; Zhang, Y. Differences in Pollination Efficiency Among Three Bee Species in a Greenhouse and Their Effects on Yield and Fruit Quality of Northern Highbush 'Bluecrop' Blueberry. *HortScience* **2021**, *56*, 603–607. [CrossRef]
63. Rana, K.; Kaushal, B.; Sharma, H.K.; Kumar, P.; Thakur, M. Impact of Bumble Bee Pollination on Strawberry Production under Protected Conditions. *Indian J. Èntomol.* **2023**, *85*, 21–24. [CrossRef]

64. Nayak, R.K.; Rana, K.; Bairwa, V.K.; Singh, P.; Bharthi, V.D. A review on role of bumblebee pollination in fruits and vegetables. *J. Pharmacogn. Phytochem.* **2020**, *9*, 1328–1334. [CrossRef]
65. Vallejo-Marín, M. How and why do bees buzz? Implications for buzz pollination. *J. Exp. Bot.* **2021**, *73*, 1080–1092. [CrossRef]
66. Straw, E.A.; Cini, E.; Gold, H.; Linguadoca, A.; Mayne, C.; Rockx, J.; Brown, M.J.F.; Garratt, M.P.D.; Potts, S.G.; Senapathi, D. *Neither sulfoxaflor*, *Crithidia bombi*, nor their combination impact bumble bee colony development or field bean pollination. *Sci. Rep.* **2023**, *13*, 16462. [CrossRef]
67. Cortés-Rivas, B.; Monzón, V.H.; Rego, J.O.; Mesquita-Neto, J.N. Pollination by native bees achieves high fruit quantity and quality of highbush blueberry: A sustainable alternative to managed pollinators. *Front. Sustain. Food Syst.* **2023**, *7*, 1142623. [CrossRef]
68. Streinzer, M.; Chakravorty, J.; Neumayer, J.; Megu, K.; Narah, J.; Schmitt, T.; Bharti, H.; Spaethe, J.; Brockmann, A. Species composition and elevational distribution of bumble bees (Hymenoptera, Apidae, Bombus Latreille) in the east Himalaya, Arunachal Pradesh, India. *ZooKeys* **2019**, *851*, 71. [CrossRef] [PubMed]
69. Ahmad, M.; Bodlah, I.; Mehmood, K.; Sheikh UA, A.; Aziz, M.A. Pollination and foraging potential of *European bumblebee*, *Bombus terrestris* (Hymenoptera: Apidae) on tomato crop under greenhouse system. *Pak. J. Zool.* **2015**, *47*, 1279–1285.
70. Wu, S.; Liu, J.; Lei, X.; Zhao, S.; Lu, J.; Jiang, Y.; Xie, B.; Wang, M. Research progress on efficient pollination technology of crops. *Agronomy* **2022**, *12*, 2872. [CrossRef]
71. Feigs, J.T.; Holzhauer, S.I.; Huang, S.; Brunet, J.; Diekmann, M.; Hedwall, P.O.; Kramp, K.; Naaf, T. Pollinator movement activity influences genetic diversity and differentiation of spatially isolated populations of clonal forest herbs. *Front. Ecol. Evol.* **2022**, *10*, 908258. [CrossRef]
72. Pywell, R.; Warman, E.; Carvell, C.; Sparks, T.; Dicks, L.; Bennett, D.; Wright, A.; Critchley, C.; Sherwood, A. Providing foraging resources for bumblebees in intensively farmed landscapes. *Biol. Conserv.* **2004**, *121*, 479–494. [CrossRef]
73. Persson, A. Effects of Landscape Context on Populations of Bumblebees. Ph.D. Thesis, Lund University, Lund, Sweden, 2011.
74. Marja, R.; Viik, E.; Mänd, M.; Phillips, J.; Klein, A.; Batáry, P. Crop rotation and agri-environment schemes determine bumblebee communities via flower resources. *J. Appl. Ecol.* **2018**, *55*, 1714–1724. [CrossRef]
75. Baur, A.; Strange, J.P.; Koch, J.B. Foraging economics of the hunt bumble bee, a viable pollinator for commercial agriculture. *Environ. Èntomol.* **2019**, *48*, 799–806. [CrossRef] [PubMed]
76. Kamo, T.; Nikkeshi, A.; Tawaratsumida, T.; Tanaka, Y.; Nakamura, S.; Kishi, S. Pollination efficiency of bumblebee, honeybee, and hawkmoth in kabocha squash, Cucurbita maxima, production in Kagoshima, Japan. *Appl. Entomol. Zool.* **2022**, *57*, 119–129. [CrossRef]
77. Adler, L.S.; Barber, N.A.; Biller, O.M.; Irwin, R.E. Flowering plant composition shapes pathogen infection intensity and reproduction in bumble bee colonies. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 11559–11565. [CrossRef] [PubMed]
78. Woodard, S.H. Bumble bee ecophysiology: Integrating the changing environment and the organism. *Curr. Opin. Insect Sci.* **2017**, *22*, 101–108. [CrossRef]
79. Amsalem, E.; Grozinger, C.M.; Padilla, M.; Hefetz, A. The physiological and genomic bases of bumble bee social behaviour. In *Advances in Insect Physiology*; Academic Press: Cambridge, MA, USA, 2015; Volume 48, pp. 37–93.
80. Stanley, D.A.; Garratt, M.P.D.; Wickens, J.B.; Wickens, V.J.; Potts, S.G.; Raine, N.E. Neonicotinoid pesticide exposure impairs crop pollination services provided by bumblebees. *Nature* **2015**, *528*, 548–550. [CrossRef]
81. Gill, R.J.; Raine, N.E. Chronic impairment of bumblebee natural foraging behaviour induced by sublethal pesticide exposure. *Funct. Ecol.* **2014**, *28*, 1459–1471. [CrossRef]
82. Gervasi, D.D.L.; Schiestl, F.P. Real-time divergent evolution in plants driven by pollinators. *Nat. Commun.* **2017**, *8*, 14691. [CrossRef]
83. Tommasi, N.; Colombo, B.; Pioltelli, E.; Biella, P.; Casiraghi, M.; Galimberti, A. Urban habitat fragmentation and floral resources shape the occurrence of gut parasites in two bum-blebee species. *Ecol. Evol.* **2023**, *13*, e10299. [CrossRef]
84. Potts, S.G.; Biesmeijer, J.C.; Kremen, C.; Neumann, P.; Schweiger, O.; Kunin, W.E. Global pollinator declines: Trends, impacts and drivers. *Trends Ecol. Evol.* **2010**, *25*, 345–353. [CrossRef]
85. Szabo, N.D.; Colla, S.R.; Wagner, D.L.; Gall, L.F.; Kerr, J.T. Do pathogen spillover, pesticide use, or habitat loss explain recent North American bumblebee declines? *Conserv. Lett.* **2012**, *5*, 232–239. [CrossRef]
86. Graves, T.A.; Janousek, W.M.; Gaulke, S.M.; Nicholas, A.C.; Keinath, D.A.; Bell, C.M.; Cannings, S.; Hatfield, R.G.; Heron, J.M.; Koch, J.B.; et al. Western bumble bee: Declines in the continental United States and range-wide information gaps. *Ecosphere* **2020**, *11*, e03141. [CrossRef]
87. Wood, T.J.; Holland, J.M.; Hughes, W.O.H.; Goulson, D. Targeted agri-environment schemes significantly improve the population size of common farmland bumblebee species. *Mol. Ecol.* **2015**, *24*, 1668–1680. [CrossRef]
88. Payne, H.E.; Mazer, S.J.; Seltmann, K.C. Native bee habitat restoration: Key ecological considerations from recent North American literature. *Front. Ecol. Evol.* **2024**, *12*, 1358621. [CrossRef]
89. Gekière, A.; Michez, D.; Vanderplanck, M. Bumble bee breeding on artificial pollen substitutes. *J. Econ. Èntomol.* **2022**, *115*, 1423–1431. [CrossRef]

90. Barlow, S.E.; O'neill, M.A. Technological advances in field studies of pollinator ecology and the future of e-ecology. *Curr. Opin. Insect Sci.* **2020**, *38*, 15–25. [CrossRef]
91. Krishnasamy, V.; Sundaraguru, R.; Amala, U. Emerging vistas of remote sensing tools in pollination studies. *Sociobiology* **2019**, *66*, 394–399. [CrossRef]
92. Ariza, D.; Meeus, I.; Eeraerts, M.; Pisman, M.; Smagghe, G. Linking remote sensing data to the estimation of pollination services in agroecosystems. *Ecol. Appl.* **2022**, *32*, e2605. [CrossRef]
93. Willcox, B.K.; Robson, A.J.; Howlett, B.G.; Rader, R. Toward an integrated approach to crop production and pollination ecology through the application of remote sensing. *PeerJ* **2018**, *6*, e5806. [CrossRef]
94. Gonzales, D.; Hempel de Ibarra, N.; Anderson, K. Remote sensing of floral resources for pollinators–new horizons from satellites to drones. *Front. Ecol. Evol.* **2022**, *10*, 869751. [CrossRef]
95. Roman, A.; Szczesna, N. Assessment of the flying activity of the buff-tailed bumblebee (*Bombus terrestris* L.) on greenhouse-grown tomatoes. *J. Apic. Sci.* **2008**, *52*, 93–101.
96. Peat, J.; Goulson, D. Effects of experience and weather on foraging rate and pollen versus nectar collection in the bumblebee, Bombus terrestris. *Behav. Ecol. Sociobiol.* **2005**, *58*, 152–156. [CrossRef]
97. Marcos, M.; García, D. Complementary contribution of wild bumblebees and managed honeybee to the polli-nation niche of an introduced blueberry crop. *Insects* **2021**, *12*, 595. [CrossRef] [PubMed]
98. Scharnhorst, V.S.; Thierolf, K.; Neumayer, J.; Becsi, B.; Formayer, H.; Lanner, J.; Ockermüller, E.; Mirwald, A.; König, B.; Kriechbaum, M.; et al. Changes in community composition and functional traits of bumblebees in an alpine ecosystem relate to climate warming. *Biology* **2023**, *12*, 316. [CrossRef]
99. Heraghty, S.D.; Jackson, J.M.; Lozier, J.D. Whole genome analyses reveal weak signatures of population structure and environmentally associated local adaptation in an important North American pollinator, the bumble bee *Bombus vosnesenskii*. *Mol. Ecol.* **2023**, *32*, 5479–5497. [CrossRef]
100. Osborne, J.L.; Martin, A.P.; Carreck, N.L.; Swain, J.L.; Knight, M.E.; Goulson, D.; Hale, R.J.; Sanderson, R.A. Bumblebee flight distances in relation to the forage landscape. *J. Anim. Ecol.* **2007**, *77*, 406–415. [CrossRef]
101. Gardner, E.; Breeze, T.D.; Clough, Y.; Smith, H.G.; Baldock, K.C.R.; Campbell, A.; Garratt, M.P.D.; Gillespie, M.A.K.; Kunin, W.E.; McKerchar, M.; et al. Reliably predicting pollinator abundance: Challenges of calibrating process-based ecological models. *Methods Ecol. Evol.* **2020**, *11*, 1673–1689. [CrossRef]
102. Gunnarsson, B.; Federsel, L.M. Bumblebees in the city: Abundance, species richness and diversity in two urban habitats. *J. Insect Conserv.* **2014**, *18*, 1185–1191. [CrossRef]
103. Baude, M.; Danchin, É.; Mugabo, M.; Dajoz, I. Conspecifics as informers and competitors: An experimental study in foraging bumble-bees. *Proc. R. Soc. B Biol. Sci.* **2011**, *278*, 2806–2813. [CrossRef]
104. Pérez-Méndez, N.; Andersson, G.K.S.; Requier, F.; Hipólito, J.; Aizen, M.A.; Morales, C.L.; García, N.; Gennari, G.P.; Garibaldi, L.A. The economic cost of losing native pollinator species for orchard production. *J. Appl. Ecol.* **2020**, *57*, 599–608. [CrossRef]