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NECTAR-PRODUCING PLANTS AND CROP ROTATION: IMPACTS ON POLLINATORS AND YIELD IN HADYACH UTC, UKRAINE

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Abstract. This study examined the composition, phenology, and ecological significance of nectar-producing flora in the agricultural landscapes of the Hadyach Urban Territorial Community (UTC), Poltava region, Ukraine. A total of 78 species, including native trees, ruderal herbs, meadow forbs, and cultivated crops, provided continuous nectar and pollen availability for honey bees (*Apis mellifera*) and wild pollinators from early spring to late autumn. Key species such as *Tilia cordata*, *Robinia pseudoacacia*, *Helianthus annuus*, and *Phacelia tanacetifolia* were identified as major contributors across different seasons. Field experiments demonstrated that the choice of preceding crop strongly influenced flowering phenology, floral density, nectar sugar content, pollinator visitation, and seed yield of *Fagopyrum esculentum* and *H. annuus*. Leguminous and nectariferous predecessors, including *Melilotus alba*, *Phacelia tanacetifolia*, and *Glycine max*, enhanced flowering duration, increased flower density by 5–49 %, raised nectar sugar concentration by 41–136 %, and improved seed yield by 17–46 %. Current crop rotations, dominated by non-nectar-producing species, occupy only 18–20 % of arable land, limiting temporal continuity of nectar supply. Expanding the share of nectariferous crops to 40–60 % of cultivated area is recommended to stabilize nectar flows, support pollinator health, and enhance agroecological sustainability. Strategic integration of high-value nectar plants and perennial legumes into crop rotations can fill seasonal flowering gaps, improve soil fertility, and strengthen the resilience of agroecosystems.

Keywords: nectariferous plants, flowering phenology, pollinator activity, crop rotation, buckwheat (*Fagopyrum esculentum*), sunflower (*Helianthus annuus*).

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1. Introduction

In the contemporary ecological and economic paradigm, ecosystem services are viewed as a combination of material and non-material benefits provided by ecosystems to humans and other biological systems (Costanza et al., 1997; Millennium Ecosystem Assessment [MEA], 2005; TEEB, 2010). These services arise as a result of ecological functions (informational, energetic, and biogeochemical) that depend on the structural organization, species composition, and spatio-temporal dynamics of ecosystems (de Groot et al., 2010). Within this framework, an ecosystem function is interpreted as the biophysical contribution of natural systems to human well-being, whereas an ecosystem service is a socially significant manifestation of this function (Sukhdev et al., 2010; Díaz et al., 2018).

Against the backdrop of growing climate instability and land-use intensification, increasing attention is paid to ecosystem services in agroecosystems, particularly pollination (IPBES, 2016; Katumo et al., 2022). Insect pollination is critically important for global agriculture, as approximately 75 % of crops depend directly or indirectly on pollinators (Klein et al., 2007). This service ensures not only crop yields but also supports biodiversity, ecological stability, and rural community well-being (Potts et al., 2010; Dainese et al., 2019; Bencharki et al., 2025). However, despite extensive research on pollination ecology, there remains a substantial gap in understanding how local nectariferous flora structure, species composition, and phenological continuity influence pollinator dynamics under varying agroecological management regimes. Current studies often emphasize either the economic valuation of pollination or the physiological responses of pollinators, while the integrative evaluation of floral resources within specific landscape contexts remains limited, particularly in Eastern Europe and the Forest-Steppe zone of Ukraine.

Nectar-producing plants form the trophic base for pollinator populations, supplying essential energy resources for the honey bee (*Apis mellifera*) as well as for a wide range of wild insect pollinators (Garibaldi et al., 2013; Rader et al., 2020). In the Forest-Steppe zone of Ukraine, nectariferous representatives of Rosaceae, Asteraceae, and Fabaceae dominate, thriving in agroecosystems, shelterbelts, and transitional habitats. Some serve as sources of major honey flows, while others maintain pollinator activity during gaps between mass blooms. In degraded or simplified agro-landscapes, wild species growing along forest edges, ruderal areas, and abandoned lands are increasingly important (Amman et al., 2024). Nevertheless, the ecological roles and adaptive potential of these nectariferous species remain underexplored, particularly regarding their contribution to sustaining pollination services and ecosystem resilience under anthropogenic stress.

However, pollinators are increasingly affected by factors such as pesticide use, habitat fragmentation, and declining floral diversity (Grass et al., 2023; Le Féon et al., 2013). The synergistic impact of nutritional deficiencies and pesticide residues significantly disrupts pollinator physiology and behavior (Wizenberg et al., 2023; Gaivão et al., 2025; Tkach et al., 2025). These so-called "stressor syndromes" are particularly pronounced in intensively managed landscapes with limited nectar resources. Recent studies also emphasize not only the quantitative availability of forage but also its botanical quality and continuity across space and time (White et al., 2021; Ilina & Ilina, 2024). Addressing these challenges requires a landscape-level perspective that integrates floristic diversity, functional traits of nectariferous species, and spatio-temporal dynamics of flowering resources.

Agroecological practices – such as introducing cover crops, green manures, and honey plants into crop rotations – hold significant potential for improving pollinator nutrition and soil conditions (Snapp & Swinton, 2020; European Commission, 2022; Hil-Mykhailivska & Kozyr, 2020). For example, the use of legumes and nectariferous species such as Melilotus officinalis, Onobrychis viciifolia, Phacelia tanacetifolia, and Sinapis alba contributes to enhancing floral diversity, nitrogen fixation, and the stability of forage resources (Shulha, 2021; Husiev & Humeniuk, 2023; Didukh, 2022). These crops act not only as food resources but also as elements of ecological infrastructure supporting pollination processes. Yet, empirical data on their effectiveness in regional agroecosystems remain fragmented, underscoring the need for targeted research integrating floristic, ecological, and functional assessments.

In this context, nectariferous flora should be considered not only as an apicultural resource but also as a bioindication tool for assessing the functional state of agroecosystems, maintaining biodiversity, and evaluating landscape resilience. Assessing species composition, flowering phenology, and the degree of integration of nectariferous species into agroecological models is essential for developing pollinator-friendly, ecologically balanced, and productive land-use systems (Rahimi et al., 2021a; Rahimi et al., 2021b; Kremen & Miles, 2012). Therefore, this study aims to identify the structural and functional characteristics of nectariferous flora in agroecosystems of the Forest-Steppe of Ukraine, evaluate their role in supporting pollination services, and develop criteria for their inclusion in adaptive agroecological management systems. The working hypothesis assumes that the composition and phenological stability of native and cultivated nectariferous species determine the spatial and temporal continuity of pollination services, thereby enhancing the resilience and productivity of agroecosystems.

2. Experimental part

The research was carried out within the territory of the Hadyach urban territorial community (UTC), Myrhorod district, located in the northeastern part of Poltava Region, Ukraine (49°23′ N, 33°59′ E), within the Left-Bank Forest-Steppe. The study area includes an ecologically diverse mosaic of wetlands, floodplain complexes, agrocenoses, field margins, shelterbelts, and ruderal habitats, which together support high landscape heterogeneity and pollinator-dependent plant diversity. These environmental conditions form a representative model system for assessing nectariferous plant resources and pollination-related ecosystem functions. The climate is temperate continental, with a mean annual temperature of 7.6 °C and mean annual precipitation of approximately 520 mm.

Floral survey and phenological observations. From March to October 2020, a systematic survey of nectariferous and polleniferous plant species was conducted across all major habitat types. Species identification was performed using Flora Europaea (Tutin et al., 1964–1980) and the Ukrainian floristic key Flora of the Ukrainian SSR (Komarov, 1934–1960). For each taxon, flowering period, habitat affiliation, and relative apicultural value were recorded. Phenological observations were carried out weekly following the guidelines of Didukh (2012). Species with high nectar productivity were selected for quantitative assessment.

Experimental design. To assess the influence of preceding crops on the reproductive performance of entomophilous plants, a randomized complete block design (RCBD) was implemented using two test crops – *Fagopyrum esculentum* Moench (cv. *Antariia*) and *Helianthus annuus* L. (hybrid *Atlanta*). Four preceding crop variants were established:

(1) maize (Zea mays, control),

(2) phacelia (Phacelia tanacetifolia),

(3) white sweet clover (Melilotus alba),

(4) soybean (Glycine max).

Each treatment was replicated three times with plot dimensions 20 × 10 m, separated by 2 m buffer zones. Field management followed a unified agronomic scheme with identical sowing rate, mechanical weed control, and no use of chemical plant protection products.

Floral and nectar productivity measurements. During full anthesis, 20 plants per replicate were randomly selected for floral counts. Nectar was collected using calibrated microcapillary tubes and analyzed using a hand refractometer (ATAGO PAL-1), with sugar content expressed in °Brix. Total nectar sugar yield (kg ha^{-1}) was calculated following the formula proposed by Crane and Walker (1985), integrating flower density and sugar concentration.

Pollinator observations. Pollinator activity was assessed in 10 m^2 quadrats at peak flowering. Observations were conducted for 15 minutes per quadrat between 10:00 and 13:00 under stable weather conditions ($T > 18$ °C, wind < 2 m s^{-1}). Both Apis mellifera and wild pollinators were recorded. Wild bee taxa were identified to species or genus using identification keys by Proshchalykin & Lelej (2007) and Michener (2007). Visitation frequency (number of individuals per 15 min) was calculated for each pollinator group.

Seed productivity and statistical analysis. After harvest, the seed yield was estimated from 1 m of a central row per plot and converted to t ha^{-1}. The resulting data were analyzed using one-way ANOVA, followed by Tukey's HSD post-hoc test. All values are presented as mean ± standard deviation (SD). Statistical analyses were performed using R v. 4.2.0 (R Core Team, 2022), specifically employing the packages *agricolae* (de Mendiburu, 2021) and *ggplot2* (Wickham, 2016) for statistical testing and data visualization.

3. Results and Discussion

Nectariferous Flora and Flowering Phenology. A total of 78 nectariferous species representing woody plants, ruderal herbs, meadow forbs, and cultivated crops were recorded within the Hadyach Urban Territorial Community (UTC). Their staggered flowering sequence provided continuous nectar and pollen availability from early spring to late autumn (Table 1, Fig. 1).

Early-season resources were dominated by *Salix alba* (March) and *Acer platanoides* (April). Peak nectar productivity occurred in late spring–early summer, particularly in *Tilia cordata* (up to 1000 kg honey/ha) and *Robinia pseudoacacia* (~800 kg/ha). Mid-summer nectar flow was supported by *Echium vulgare*, *Phacelia tanacetifolia*, and *Helianthus annuus*. Late-season supply was maintained by *Solidago canadensis*, although with reduced productivity (~150 kg/ha).

Table 1

Flowering phenology of the major nectariferous plants in the Hadyach district

Scientific Name	Habitat Type	Nectar / Pollen Importance
Salix alba L.	wetlands, riverbanks	early pollen & nectar
Acer platanoides L.	parks, forest edges	early nectar source
Tilia cordata Mill.	forests, urban areas	major nectar source
Robinia pseudoacacia L.	shelterbelts, edges	high nectar productivity
Trifolium pratense L.	meadows, pastures	abundant nectar & pollen
Melilotus officinalis (L.) Lam.	ruderal areas	profuse nectar flow
Echium vulgare L.	dry disturbed soils	high nectar yield
Solidago canadensis L.	ruderal sites, meadows	late-season nectar
Brassica napus L.	agricultural fields	early massive nectar source
Helianthus annuus L.	crop fields	dominant summer nectar plant
Fagopyrum esculentum Moench	crop rotation fields	specialty nectar plant
Phacelia tanacetifolia Benth.	cover crops, field margins	exceptional nectar provider

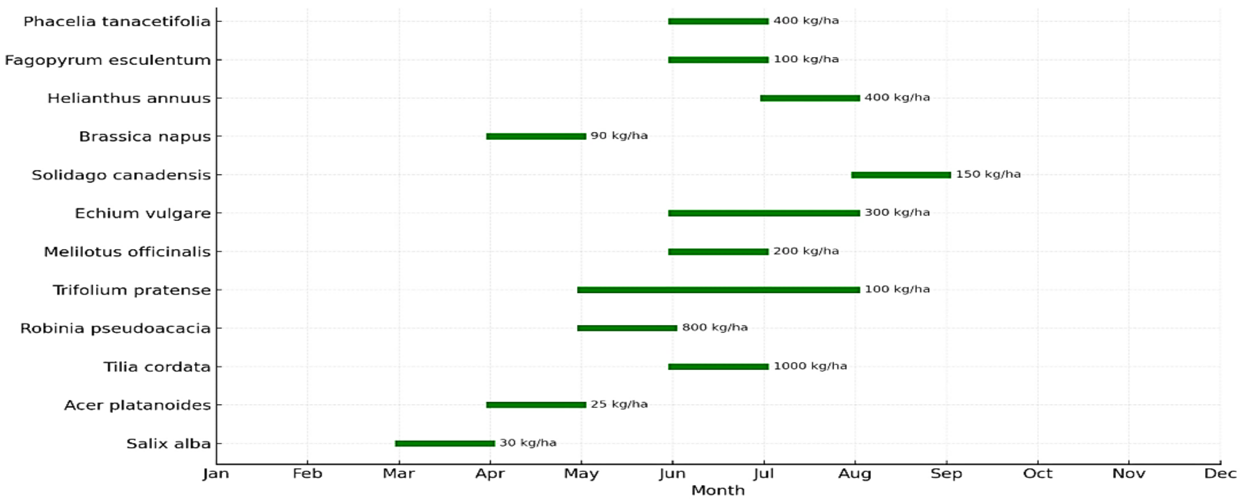

Fig. 1. Flowering period and honey yield on nectariferous plants in hadyach district

Nectariferous Value of Agricultural Crops. Nectariferous crops accounted for 18.64 % of arable land in the studied crop rotations. *Helianthus annuus* occupied 16.31 % of the cultivated area, while *Fagopyrum esculentum* and *Cucurbita pepo* covered 1.44 % and 0.89 %, respectively (Table 2).

Table 2

Structure of crop areas in Hadyach district (Source: Department of Agriculture)

Crop	Area, ha	Percentage, %
Non-honey plants	45.776	81.36
Honey plants	10.488	18.64
Helianthus annuus L.	9.174	16.31
Fagopyrum esculentum L.	812	1.44
Cucurbita pepo L.	502	0.89
Total	56.264	100.00

Despite stable total rainfall, uneven precipitation distribution produced heterogeneous soil moisture patterns, which shaped nectar secretion intensity. Sugar productivity and flowering duration for the main nectariferous crops are presented in Table 3.

Crop structure analysis showed the absence of perennial legumes (alfalfa, clover), sainfoin, and rapeseed – species widely recognized for high nectar value and soil-improving functions (Brodie et al., 2022; Kelton et al., 2020)

Table 3

Productivity and flowering duration of honey plants in crop rotations of Hadyach district (x ± SD)

Crop	Sugar productivity per flower, mg (M±m, n=18)	Sugar productivity per hectare, kg	Flowering duration, days	Seed productivity per hectare, c
H. annuus	0.598 ± 0.002	62.9 ± 0.002	15	21.1 ± 0.002
F. esculentum	0.077 ± 0.002	68.3 ± 0.002	26	12.4 ± 0.003
C. pepo	0.023 ± 0.001	24.3 ± 0.001	30	500.0 ± 0.001

Phenological Response of Fagopyrum esculentum and Helianthus annuus to Preceding Crops. Phenological monitoring demonstrated that both onset and duration of flowering depended on the preceding crop.

- *In F. esculentum, flowering began on day 37 after Zea mays and lasted 32 days. Following Phacelia tanacetifolia, Melilotus alba, or Glycine max, flowering extended to 38 days (Fig. 2).*

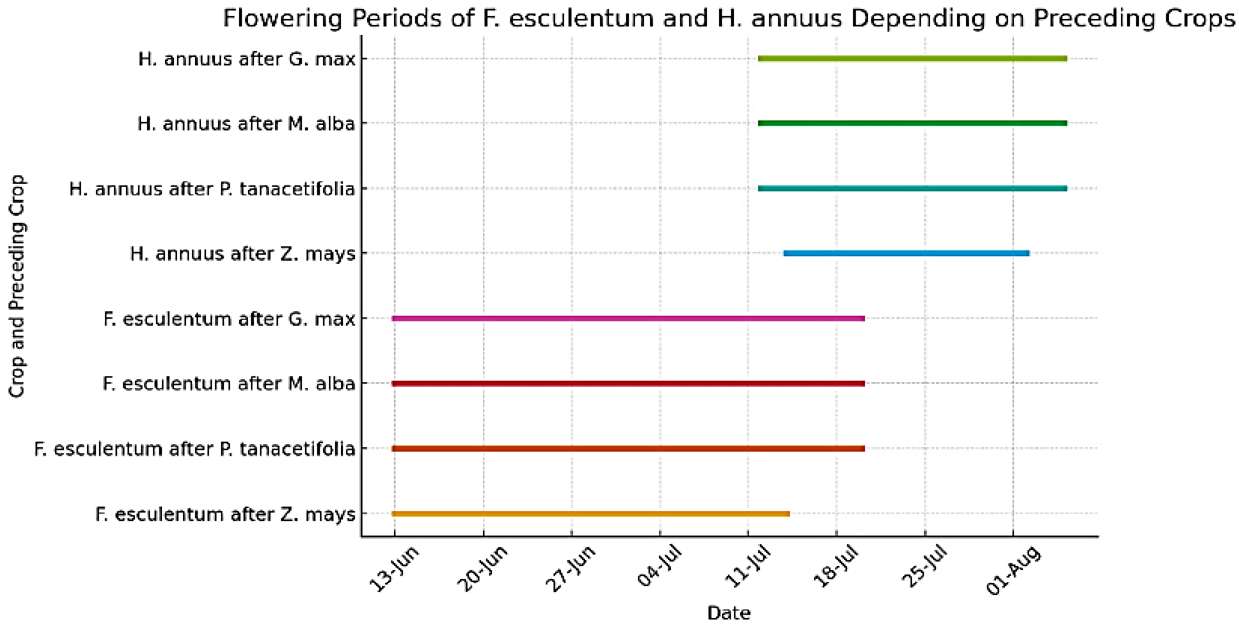

Fig. 2. Phenological observations of *F. esculentum* and *H. annuus depending* on the predecessor crops

- In *H. Annuus*, flowering typically began on day 69, but was delayed by two days after *Z. mays*. Flowering duration ranged from 20 to 25 days, with longer periods after *Ph. Tanacetifolia, M. Alba*, and *G. Max*.

These differences indicate that preceding crops modulated generative development through combined effects on nutrient availability, soil structure, and moisture retention.

Influence of Preceding Crops on Flower Density, Nectar Quality, and Pollinator Activity

Flower density increased substantially after leguminous and nectariferous precursors compared to *Z. mays*.

- *In F. esculentum, flower numbers increased by 5–6 %.*
- *In H. Annuus, flower density rose by 43–49 % (Table 4).*

Table 4

Number of flowers and sugar productivity of *Fagopyrum esculentum* and *H. annuus* (x ± SD)

Predecessor	Flowers per plant	Flowers per 1 ha (×10³)	Sugar per flower, mg	Sugar productivity per 1 ha, kg
Fagopyrum esculentum				
Zea mays	1772.7 ± 18.45	974.99	0.063 ± 0.001	61.40
Phacelia tanacetifolia	1881.3 ± 14.99*	1,034.72*	0.084 ± 0.002*	86.90*
Melilotus alba	1873.4 ± 12.16*	1,030.37*	0.083 ± 0.002*	85.50*
Glycine max	1869.9 ± 10.46*	1,028.45*	0.078 ± 0.002*	80.20*
Helianthus annuus L.				
Zea mays	1374.9 ± 20.18	76.99	0.436 ± 0.002	33.60
Phacelia tanacetifolia	2043.5 ± 17.96*	114.44*	0.667 ± 0.003*	76.30*
Melilotus alba	2051.4 ± 15.77*	114.88*	0.692 ± 0.002*	79.50*
Glycine max	1974.2 ± 12.53*	110.56*	0.636 ± 0.002*	70.30*

Note: Asterisks indicate statistically significant differences compared to the control (*Z. mays*), $p < 0.05$.

These findings are consistent with reports that legumes and green manure crops stimulate microbial activity and nitrogen accumulation, strengthening subsequent flowering (Napflin et al., 2021; Riedinger et al., 2018).

Nectar sugar content also increased:

- *In buckwheat – by 41.5 % after Ph. tanacetifolia and by 39.3 % after M. alba.*
- *In sunflower – by 127.1 % and 136.6 %, respectively.*

Pollinator visitation rates rose accordingly (Table 5), aligning with Le Féon et al. (Le Féon et al., 2013), who demonstrated that nectar quality and floral density strongly structure pollinator foraging behaviour.

Seed yields increased by 32.1–46.3 % in *F. esculentum* and by 17.2–24.6 % in *H. annuus*, with the highest values after *M. alba* (buckwheat) and *G. max* (sunflower). Similar effects were reported by Zhang et al. (2019), who documented that legumes enhance humus content and nitrogen bioavailability, supporting reproductive development.

The study revealed pronounced spatial and phenological heterogeneity of nectar resources in Hadyach UTC, which forms a stable forage base for *Apis mellifera*. The combination of early-flowering woody species, mid-season agricultural crops, and late-season herbs results in an extended nectar flow an essential prerequisite for colony stability, honey accumulation, and pre-winter strengthening (Goulson et al., 2015).

Table 5

Flower visitation by honey bees and wild pollinators and seed productivity of buckwheat and sunflower (x ± SD)

Predecessor	Honey bees (ind./10 m²/min)	Wild pollinators (ind./10 m²/min)	Seed weight (g/m row)
	Honey bees	Wild pollinators	
Fagopyrum esculentum			
Zea mays	9.60 ± 0.34	3.30 ± 0.21	56.45 ± 0.55
Phacelia tanacetifolia	15.70 ± 0.30*	6.20 ± 0.33*	74.61 ± 0.33*
Melilotus alba	18.40 ± 0.27*	7.10 ± 0.31*	82.61 ± 0.54*
Glycine max	18.10 ± 0.31*	7.20 ± 0.25*	76.68 ± 0.70*
***Helianthus annuus* L.**			
Zea mays	11.20 ± 0.44	1.40 ± 0.22	37.72 ± 0.42
Phacelia tanacetifolia	13.20 ± 0.43*	3.20 ± 0.20*	44.19 ± 0.21*
Melilotus alba	16.10 ± 0.20*	6.60 ± 0.31*	44.89 ± 0.33*
Glycine max	15.80 ± 0.33*	3.80 ± 0.25*	47.00 ± 0.23*

Note: Asterisks indicate statistically significant differences compared to the control (*Z. mays*), $p < 0.05$.

Nectariferous Crops in Crop Rotations. Despite high ecological potential, nectariferous crops currently represent only 18.64 % of the arable area. This proportion appears insufficient for maintaining forage continuity under conditions of intensified agriculture, widespread pesticide use, and landscape simplification. The absence of perennial legumes, sainfoin, meadow clover, and rapeseed reduces both nectar supply and the functional diversity of rotations, limiting nitrogen fixation and soil quality improvement (Brodie et al., 2022).

Expanding the share of nectariferous crops to 40–60 % is justified by:

1. *phenological data from this study*, showing that flowering gaps occur when nectariferous crops occupy <20 %;
2. *yield and nectar quality increases* of 17–46 % following leguminous and nectariferous precursors;
3. *published agroecological models*, which demonstrate that forage continuity for honey bees requires 55–70 kg of sugar equivalents per colony per season (Seeley, 2019; Requier et al., 2015);
4. *evidence from European pollinator-support schemes*, where 40–60 % flexible forage coverage stabilizes colony development and reduces nutritional stress (Vaudo et al., 2020).

Taken together, these lines of evidence substantiate the proposed range of 40–60 % as ecologically realistic and agronomically beneficial.

Mechanisms Behind Preceding Crop Effects. The strong influence of *Ph. tanacetifolia*, *M. alba*, and *G. max* on flowering phenology, nectar sugar concentration, and pollinator activity is consistent with known mechanisms of legume-based rotations.

These mechanisms include:

- improved soil aeration and water retention;
- increased microbial biomass;
- enhanced nitrogen cycling;
- formation of microclimatic conditions favourable for generative development (Molla et al., 2022; Wang et al., 2024).

Thus, preceding crops shaped not only nutrient availability but also soil temperature, moisture patterns, and the physiological readiness of plants for flowering.

Ecological and Practical Implications. The integration of nectariferous species into crop rotations supports ecosystem services such as pollination, soil fertility enhancement, and biodiversity maintenance. Continuous nectar supply also mitigates the effects of "nutritional stress syndrome" documented in bees exposed to simultaneous pressures from pesticides and low-diversity landscapes (Wizenberg et al., 2023).

Landscape-level measures flower strips, legume-based green manure, diversified rotations, and spatial nectar mapping can enhance both pollinator resilience and agronomic performance.

4. Conclusions

The study revealed that the nectariferous flora of the Hadyach Urban Territorial Community comprises 78 species, providing continuous nectar availability from early spring to late autumn, which is crucial for pollinator activity and effective pollination services. The type of preceding crop significantly influenced the flowering phenology, floral density, nectar sugar content, and pollinator visitation of *Fagopyrum esculentum* and *Helianthus annuus*. In particular, leguminous and nectariferous predecessors, such as *Melilotus alba*, *Phacelia tanacetifolia*, and *Glycine max*, enhanced flowering duration, increased flower density by 5–49 %, raised nectar sugar concentration by 41–136 %, and improved seed yield by 17–46 %. Current crop rotations, dominated by non-nectar-producing species, cover only 18.6 % of arable land, limiting temporal continuity of nectar supply. Expanding the proportion of nectariferous crops to 40–60 % of cultivated area is recommended to stabilize nectar flows and provide continuous forage for pollinators throughout the growing season. The positive effects of preceding crops are mediated through improved soil structure, moisture retention, nitrogen availability, and microclimatic conditions that promote generative plant development and nectar productivity. Strategic integration of high-yielding nectar species, perennial legumes, and woody nectar plants such as *Tilia cordata* into crop rotations can fill seasonal flowering gaps, enhance pollinator health, increase honey production, and strengthen agroecosystem resilience. Long-term phenological monitoring combined with GIS-based predictive modeling is suggested to forecast nectar availability and inform regionally adapted, phenology-driven crop management and beekeeping strategies, while further studies of the biochemical and ecological mechanisms behind these effects will support sustainable, pollinator-friendly agricultural practices.

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