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RESEARCH ARTICLE

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The pick of the plot: An evidence-based approach for selecting and testing suitable plants to use in annual seed mixes to attract insect pollinators

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Societal Impact Statement

Concern regarding wild pollinator declines has increased motivation to plant pollinator-friendly plants in gardens and urban areas, but 'plants for pollinators' recommendations are often anecdotal and inaccurate. Here, we use a scientific evidence base to design and test annual flowering seed mixes for bees and hoverflies. Seed mixes combining non-native and native plants had better establishment, flowered for longer, had more pollinator visits and were more aesthetically pleasing to the public. Using a scientific evidence base to design seed mixes has the potential to enhance their societal value, by increasing their attractiveness to insects and enhancing public well-being.

Summary

- Annual seed mixes are frequently grown in gardens and urban areas because they are considered to be 'pollinator-friendly', but choice of which plant species to include is often based on anecdotal evidence. Here, we build an evidence-base for which plants to use in annual seed mixes to attract bumblebees, solitary bees and hoverflies. We conduct a systematic review of plant–insect interactions and use field trials to assess the attractiveness of different seed mixtures.
- We determined which annual plant species are attractive to bees and hoverflies using interaction data extracted from 447 peer-reviewed articles. We then carried out field trials using four commercially available seed mixes to assess insect visitation. The plant list compiled from the literature and the results of the commercial trials were used to develop two novel experimental seed mixes that were assessed for insect visitation and aesthetic appeal.
- We found that seed mixes including non-native, along with native flowering plants, had higher establishment, a longer flowering period, a greater number of pollinator visits and were more aesthetically pleasing to the public. A small number

of key plant species were visited frequently in the seed mixes, and these differ between pollinator groups.
- Our findings can be used to provide evidence-based guidance in the selection of plant species to be used in horticultural areas.

KEYWORDS
bumblebees, gardens, hoverflies, pollinator-friendly, seed mixes, solitary bees, urban areas, wildlife gardening

1 | INTRODUCTION

The decline of pollinating insects is of critical concern globally (Potts et al., 2010; van Klink et al., 2020). These insects play a vital role in the provision of pollination services, transferring pollen between plants both between pollinator-dependent native plants within the wider ecosystem and for economically important crops (Turo et al., 2024). Both rare and formerly abundant pollinator species have declined in urban and rural landscapes, with the loss and fragmentation of floral resources considered one of the most prominent causes of decline (Baldock, 2020; Dicks et al., 2021; Gill et al., 2016; Wagner et al., 2021). To address the global issue of pollinator decline, various governments across countries including Belgium, Mexico, Colombia, the United States and the United Kingdom have developed strategies and policies to specifically protect pollinators across local, national and international scales (DEFRA, 2014; European-Commission, 2021; Giovanetti & Bortolotti, 2023; IPBES, 2019; Nalepa & Colla, 2023). Within these strategies, there is considerable focus on increasing floral resource availability in anthropogenic landscapes, including farms, gardens and amenity spaces. Floral resource availability refers to the presence of sufficient, accessible and nutritionally valuable floral resources (nectar and pollen) that support pollinators' survival and reproduction. To sustain a diverse population of wild pollinators, it is crucial to ensure a continuous and overlapping supply of floral resources, to accommodate varying forage preferences and flight periods of different species (Havens & Vitt, 2016; Lowe et al., 2022).

In gardens and amenity spaces, seed mixes designed to attract a diverse suite of pollinators can deliver useful environmental and societal benefits, including the provision of pollen and nectar for flower-visiting insects (Blackmore et al., 2014; Howlett et al., 2021; Nichols et al., 2022), increased public engagement with nature (Burke et al., 2022) and improved human well-being (Bretzel et al., 2016). Introducing seed mixes into agricultural landscapes can also facilitate pollinator-dependent crop production by increasing pollinator abundance and diversity (Carvalheiro et al., 2012). Seed mixes should be designed with specific goals in mind, as the optimal composition may differ for each objective (Müller et al., 2024). In amenity spaces, such as parks and gardens, annual flowering seed mixes are commonly used for their relative ease of establishment and ability to rapidly deliver aesthetic impact (Schueller et al., 2023). However, there is concern that some of the plant species within annual mixes may provide limited value for pollinators, as they are primarily designed for aesthetic appeal (Barry & Hodge, 2023; Erickson et al., 2020; Garbuzov & Ratnieks, 2014; Hicks et al., 2016). Bees and hoverflies are important pollinators with many species frequently seen within gardens and urban areas (Baldock et al., 2015; Baldock et al., 2019; Poole et al., 2025). However, less is known about the foraging preferences of hoverflies and solitary bees compared with bumblebees and honeybees, and currently available seed mixes often provide limited resources for these groups (Moquet et al., 2018; Wood et al., 2016).

As demand for 'pollinator-friendly' seed mixes increases, it is important to ensure that designed mixes can provide optimal benefits to the greatest diversity of pollinating insects. The plant species composition of these mixes should therefore be founded on a strong evidence base of known interactions between flowering plants and a diversity of pollinator groups. There is abundant and wide-ranging data available from peer-reviewed scientific journals in the form of plant–insect interaction records, which can be used to inform the selection of plant species that may be suitable for seed mixes (Howlett et al., 2021; Nichols et al., 2022; Rader et al., 2020).

Here, we aim to provide guidance on the most suitable plants to include in annual flowering seed mixes to attract a diverse range of bees and hoverflies throughout the season. To achieve this, we first conducted a systematic review to collate plant–insect interaction data from peer-reviewed journals, using a standardised and repeatable approach adapted from the Collaboration for Environmental Evidence systematic mapping guidelines (James et al., 2016). In addition to this, in 2018, we trialled four commercially available seed mixes, grown in a replicated block design to test which mix was visited most by pollinators. The results from both the systematic review and commercially available seed mix trials in 2018, were then used to guide plant species selection for two novel experimental seed mixes in 2019, one containing species considered to be native or archaeophytes in the United Kingdom, the other containing natives, archaeophytes and neophytes (archaeophytes are species introduced to the United Kingdom before 1500 CE, whereas neophytes are those introduced after this year). In 2019, the two novel experimental mixes were grown alongside two of the commercial seed mixes from 2018 in a replicated block design. Across all seed mixtures, we assessed the overall plant species composition of the sown plots and compared species richness, abundance and diversity for bumblebees, honeybees, solitary bees and hoverflies. Because aesthetic impact is an important consideration for gardens and amenity spaces (Dunnett, 2008; Hitchmough, 2017) and there may be potential trade-offs between ecological value to pollinators and the social benefit to the public (Garbuzov & Ratnieks, 2013), we also assessed how aesthetically pleasing each seed mix was to the public. Finally, we assessed which plant species were visited most by pollinators across all the seed mixes.

2 | MATERIALS AND METHODS

2.1 | Summary

In May 2019, two novel experimental seed mixtures, designed to attract bumblebees, hoverflies and solitary bees, were trialled in the United Kingdom. The plant species that were trialled were selected using evidence from both plant–insect interaction data extracted from international peer-reviewed journals and a trial of commercially available annual seed mixtures, conducted in May 2018.

2.2 | Evidence used to inform plant species selection in novel experimental seed mixtures

2.2.1 | Systematic review to extract plant–insect interaction data

To inform the development of novel experimental seed mixtures, a systematic review was carried out to extract plant–insect interaction data from published peer-reviewed literature. The systematic review was conducted in July 2018 and updated in May 2020, using a standardised and repeatable approach adapted from the Collaboration for Environmental Evidence systematic mapping guidelines (James et al., 2016) (Methods S1, Table S1). Published, peer-reviewed articles were reviewed from the Web of Science 'all collections database', and all articles that were returned from the database were screened using a three-stage process (Methods S1, Table S2). Interactions between plant and pollinator species were extracted from the resulting list of selected articles. We determined the number of interactions as the total number of articles in which a plant–insect interaction was recorded (Methods S1). Plant species from the systematic review were prioritised for selection in the seed mix if there were greater than 10 interactions for at least one pollinator group (Figure S1).

The list of plant species selected from the systematic review was then reviewed, following a decision matrix (Figure 1). Plant species from this list were excluded if they were recorded as non-native invasive species (NNIS) and/or injurious weeds in the United Kingdom (Weeds Act 1959; Wildlife & Countryside Act 1959) as they were considered a potential risk to wild plants. Horticultural suitability and cost effectiveness were determined using the RHS horticultural database (Figure S2; RHS, 2024). Those plant species that were not listed as annual flowering plants and not commonly grown from seed for commercial use were considered horticulturally unsuitable and not cost effective, as these species were not available in sufficient quantities to be used in the trials (Figure S2).

2.2.2 | Trial of commercially available seed mixtures

In May 2018, four commercially available annual seed mixes were trialled in order to inform the selection of plant species to include in the novel experimental seed mixtures (Table 1). These commercially available mixes were selected using an internet search with the search terms 'pollinator friendly seed mixture', to imitate a keen gardener searching for a pollinator friendly seed mix to use in their garden. The search returns were further refined by selecting only seed mixes where the plant species list for the mix was available. The final selected four mixes comprised one native plant mix and three mixes that contained native and non-native species (Table 1).

At two sites in the National Botanic Garden of Wales, Wales, UK, a replicated block design was set up to trial the seed mix treatments (Figure S3). The two sites were located 270 m apart: Site 1 was located within an area of amenity grass lawn close to the Botanic Garden's systematic beds. Site 2 was located within an area of grassland meadow at the edge of the Botanic Garden (Figure S3). At each site, twenty 16 m^2 (4 × 4 m) plots were created by removing the turf and adding a layer of sterilised topsoil, raked to a fine tilth (Karlen, 2005). Plots were separated by 2 m strips of either mown grass or mulch. For each seed mix treatment, there were five replicates at each site for a total of 10 replicates. For each site, seed mix treatments were allocated to plots by numbering each plot and randomly assigning seed mix treatments using a random number generator.

Plots were seeded in May and monitored from July to October, with the percentage cover of the plant species in flower recorded every 2 weeks. Percentage cover was estimated by the percentage of individual plants in flower for each species within each plot. In each year, insect surveys started when at least one seed mix treatment had >5% flower cover, similar to the methodological approach used in Rollings and Goulson (2019). Insect surveys were then conducted once a month with each plot observed for a 15-min period. During this time, any bumblebees, honeybees, solitary bees or hoverflies observed visiting a flower within the plot were recorded to species level, along with the species of flower it was visiting. Any insects that could not be identified in the field were collected for later identification using microscopy. Insect monitoring focused on bumblebees, hoverflies and solitary bees, as these were the target groups for the novel seed mixtures. Honeybees were also monitored in order to gain an understanding of how honeybee plant use compared to that of the other pollinator groups.

2.2.3 | Refining plant species selection for novel experimental seed mixtures

The plant species chosen after the systematic review process (Figure 1) were further refined based on the results of the commercial seed mix trial in 2018, to develop the novel experimental seed mixtures.

An additional consideration when selecting plant species for seed mixes designed for amenity spaces was the overall aesthetic impact of the mix. To determine the appropriate species composition for aesthetic impact, guidance on seed mix design and implementation in

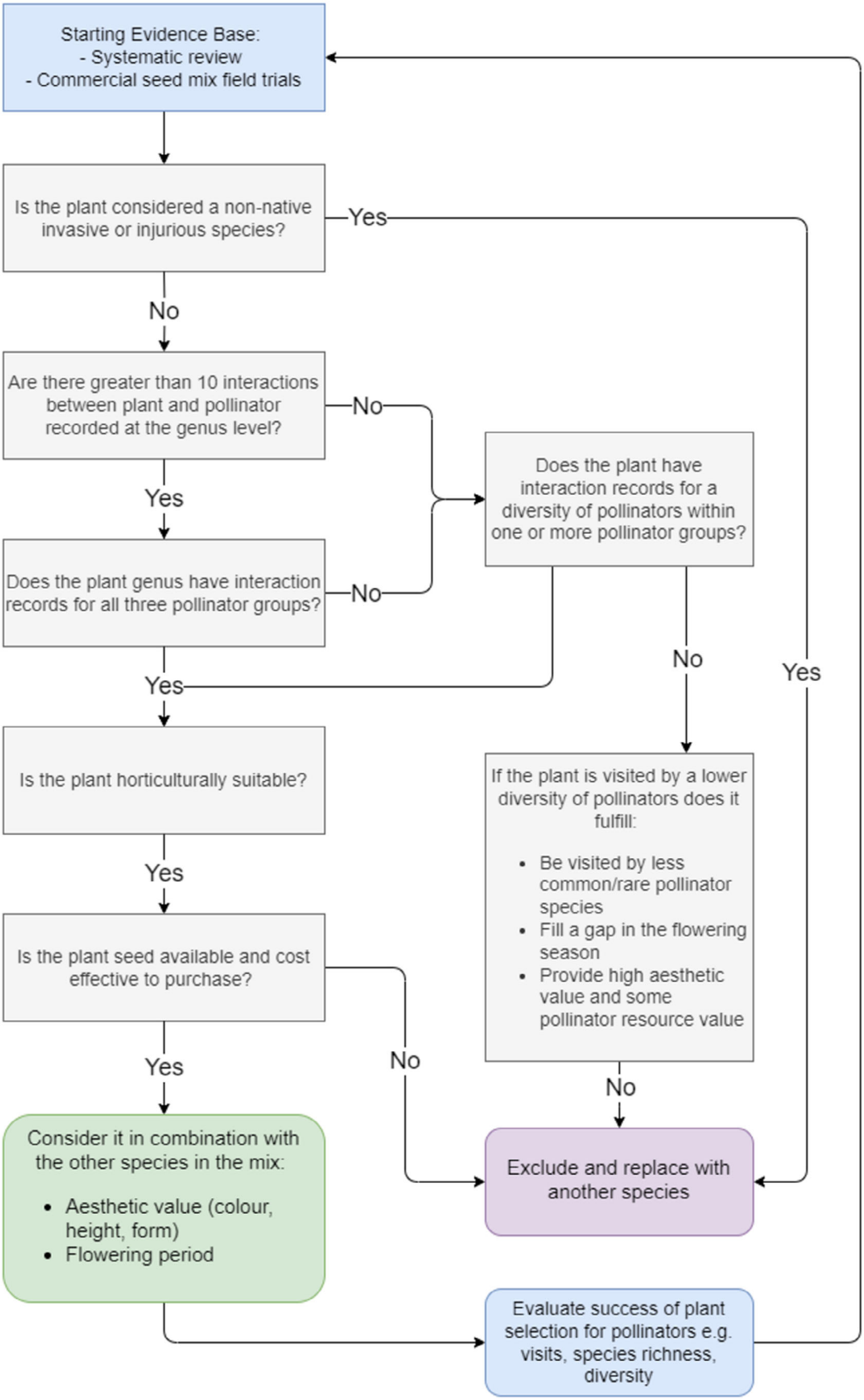

FIGURE 1 Flow diagram illustrating the decisions made when designing annual seed mixes to attract pollinators.

TABLE 1 Description and sowing densities used in trials of the four commercial and two novel experimental seed mixtures that were trialled in 2018 and 2019.

Seed mix	Plant status	Species count	Purpose	Trial year	Sowing density (g/m^2)
N_Commercial	Native	18	Commercial mix of UK native plant species	2018 and 2019	3
NN_Aesthetic commercial	Native and non-native	12	Commercial mix designed for aesthetic impact	2018	3
NN_Pollinator commercial	Native and non-native	33	Commercial mix designed to attract a broad range of pollinators	2018 and 2019	5
NN_Bumblebee commercial	Native and non-native	21	Commercial mix designed to attract bumblebees	2018	3
N_Experimental	Native	20	Experimental mix of UK native and archaeophyte species attractive to a broad range of pollinators	2019	2.5
NN_Experimental	Native and non-native	20	Experimental mix of native, archaeophyte and non-native plant species to the UK attractive to a broad range of pollinators	2019	2.5

Note: See Dataset S1 for full species lists.

amenity spaces was obtained from (Hitchmough, 2017). The criteria used to select species for aesthetic impact is provided in the Supporting Information (Table S3). The final mixes were then assessed and refined by two horticultural experts, working in the horticultural department at the National Botanic Garden of Wales. They considered the overall seed mix composition in a horticultural context using the criterion outlined in Table S3. Two novel experimental mixes were created each containing a final list of 20 species, one 'native mix' (containing native and archaeophyte species) and one 'non-native mix' (containing native, archaeophyte and neophyte species) (Dataset S1).

2.3 | Novel experimental seed mixture trials

In 2019, using the same trial set up and monitoring protocol, as the commercial seed mix trials previously described, two of the commercially available seed mixtures, 'N_Commercial' and 'NN_Pollinator Commercial', were grown, to compare alongside the two newly developed novel experimental mixes, 'N_Experimental' and 'NN_Experimental' (Table 1). The two commercial mixtures selected for trial in 2019 comprised one native 'N_Commercial' and one seed mixture 'NN_Pollinator Commercial', which also contained non-native species. These were selected to assess alongside two novel experimental mixtures which comprised one native seed mixture 'N_Experimental' and one seed mixture also containing species which are not native to the UK 'NN_Experimental' (Table 1). Plots were sown in May. A full species list for each mix is included in Dataset S1. For the novel experimental mixes, sowing densities for each seed mix treatment were calculated based on guidance provided in (Dunnett, 2008; Hitchmough, 2017), whereas densities for commercial mixes were based on the manufacturers' guidance provided.

2.4 | Aesthetics assessment of seed mixtures

In addition, in 2019, a trial to assess the aesthetic appeal of the seed mixtures was conducted with members of the public visiting the National Botanic Garden of Wales. Each seed mix plot was numbered and visitors coming to view Site 1 were approached and given a blank sheet of paper and a pen and asked to vote for which plot was their favourite. Surveys occurred from 1 August to 5 September 2019, when seed mixtures were in the peak flowering period and visitor numbers to the Botanic Garden were highest. Votes were collected in a box at the front of the trial plots and then pooled to see which seed mixture scored the highest overall.

2.5 | Statistics

All statistical analyses were carried out using R (v. 4.2.2) (R Core Team, 2020). To assess the effect of seed mix on visits and species richness, generalised linear mixed-effects models (GLMM) were fitted using the lme4 R package (Bates et al., 2015), for each pollinator group. All models used a negative binomial distribution, except when examining visits within solitary bees, which used a Poisson distribution. The response variable was either visits or species richness and the models included seed mix treatment and month as the fixed effects, with plot nested within site as the random effect term. For 2018, November surveys were excluded from analysis, and for 2019, June and November were excluded due to the large number of null surveys. The effect of the seed mix treatment was tested using a log-likelihood ratio test by comparing models with and without treatment included as a term. Kruskal–Wallis tests were used to assess the effect of seed mix treatment on diversity of pollinator visitors, as mixed models did not produce a suitable fit. It should be noted that this test assumes independence of replicates, which does not fully reflect the nested structure of the data. To assess the difference in visitor preference for seed mix appearance, chi-squared contingency tests were used.

3 | RESULTS

3.1 | Systematic review of plant–insect interactions

Using the search terms (Table S1), 10,185 initial articles were returned from the Web of Science, 447 of which passed the screening process (Table S2) to progress to data extraction. The articles recovered spanned from 1946 to 2020. A total of 263 plant taxa were returned within 37 plant families and 164 genera, and 208 pollinator taxa were returned (90% to species level, 10% to genus, representing 51 genera) (Dataset S1). Bumblebees represented 1408 (46%) of total interactions recorded, solitary bees 954 (31%) and hoverflies 718 (23%). The number of bumblebee species found across all interactions was 22, solitary bees had 104 species and hoverflies had 61 species. In total, 54 plant species or genera were found with more than 10 interactions for at least one of the three pollinator groups, with 63% of these interacting with all three groups (Figure S1).

For bumblebees, 36 plant taxa (covering 25 unique genera) had 10 or more interactions within the literature (Figure S1). The species found most frequently was *Cirsium vulgare* (Savi) Ten. with 75 interactions, followed by *Echium vulgare* L. (70 interactions) and *Phacelia tanacetifolia* Benth. (58 interactions). For solitary bees, 25 plant taxa representing 22 unique genera were found with more than 10 interactions (Figure S1). The top plant was *Sinapis arvensis* L. with 59 interactions followed by *Brassica napus* L. (30) and *Helianthus annuus* L. (28). For hoverflies, 19 plant species had more than 10 interactions, representing 17 different genera (Figure S1). The top plant species were *Fagopyrum esculentum* Moench with 56 interactions, *Daucus carota* L. (34) and *S. arvensis* (31).

The plants with more than 10 interactions that were identified to species level as part of the systematic review (39 species) were considered for suitability in seed mixes using the decision flowchart (Figure 1). Of these, 15 could already be found in commercially available seed mixes, 17 were potential new additions to seed mixes, three were considered to be horticulturally unsuitable for seed mixes, and four were unsuitable due to being considered injurious weeds or invasive species (Figure S2).

3.2 | Comparison of commercially available annual seed mixes (2018)

Four commercially available seed mixes were trialled in 2018, resulting in 2414 visits recorded to 56 plant species (Figure 2). Hoverflies made up most of the visits (46%), followed by bumblebees (28%), honeybees (23%) and solitary bees (3%) (Dataset S1). Visitation differed significantly between seed mix treatments for bumblebees ($\chi^2 = 41.68$, df = 3, $p < 0.001$), hoverflies ($\chi^2 = 40.06$, df = 3, $p < 0.001$) and honeybees ($\chi^2 = 36.10$, df = 3, $p < 0.001$); however, there was no significant difference between seed mix treatments for solitary bee visits ($\chi^2 = 6.88$, df = 3, $p = 0.758$) (Figure 2, Table S4). Species richness differed significantly between seed mix treatments for bumblebees ($\chi^2 = 13.27$, df = 3, $p < 0.049$); however, no significant difference was observed between the seed mix treatments for any of the other pollinator groups for species richness and none for Simpson's diversity (Table S4). Bumblebees visited the seed mix designed for bumblebees (NN_Bumblebee_Commercial) the most (Table S4, mean total visits per plot = 25.3 ± 10.64). The bumblebee seed mix also attracted the greatest number of honeybees. The highest number of hoverfly visits were to the native mix (N_Commercial, Table S4, mean total visits per plot = 43.3 ± 6.98), although more hoverfly species visited the pollinator mix (NN_Pollinator_Commercial, $n = 28$). Solitary bees had a low number of visits for all the seed mixes (Figure 2, $n = 75$). The most visited plant across all seed mixes for Year 1 was *Centaurea cyanus* L. (20% of all visits), followed by *Glebionis segetum* (L.) Fourr. (15%) and *P. tanacetifolia* (10%). *C. cyanus* and *P. tanacetifolia* were used most by bumblebees and honeybees, whereas *G. segetum* was used most frequently by hoverflies. *Linaria maroccana* Hook. f. was the most visited plant for solitary bees making up 17% of solitary bee visits observed, followed by *Anthemis arvensis* L. (Figure S4).

3.3 | Comparison of novel experimental and commercial seed mixes (2019)

3.3.1 | Investigating the overall plant species composition of sown plots

Both novel experimental mixes contained 20 species, of these 15 successfully flowered in the native mix (N_Experimental) and 17 in the non-native mix (NN_Experimental) (Figure S5). For the native novel experimental mix, *A. arvensis* and *G. segetum* flowered most abundantly with *A. arvensis* dominating the flowering display over several months (Figure 3). Flowering amongst the different species was more balanced for the non-native novel experimental mix with 15 plant species representing more than 5% flowering cover. A similar pattern was seen for the commercial mixes, the native commercial mix (N_Commerical) was dominated by *Tripleurospermum inodorum* (L.) Sch. Bip. and *G. segetum* whereas the non-native commercial mix (NN_Pollinator Commercial) had a more balanced floral composition (Figure 3). The peak in percentage cover of flowering plants occurred in August for the native mixes and declined to below 50% cover through late September and October. The non-native mixes had a peak in August; however, overall percentage cover of flowering plants remained over 50% through to October (Figure 3).

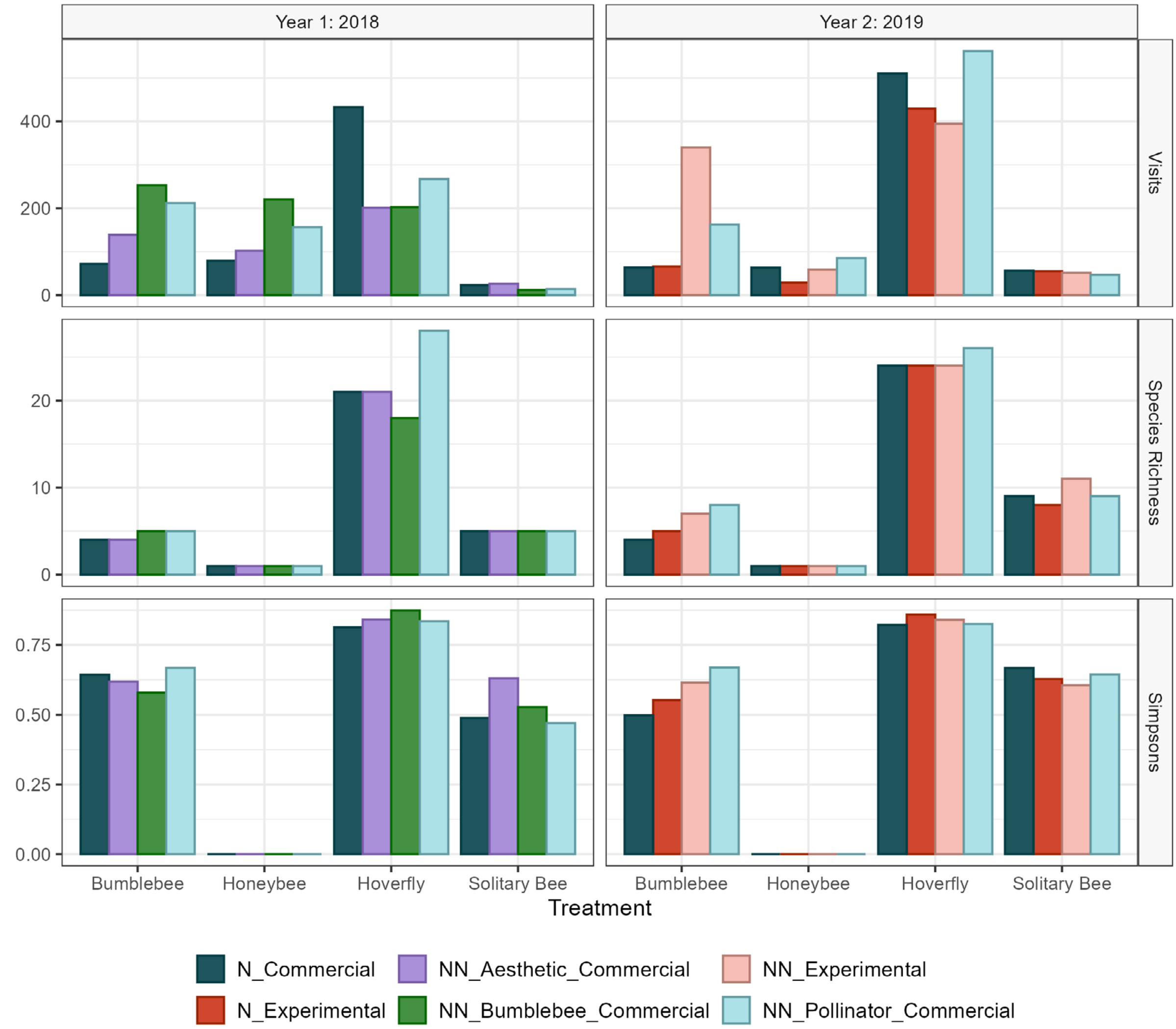

FIGURE 2 Results of field trials in 2018 and 2019. 2018 compared four commercially available seed mixes. 2019 compared two commercial mixes from 2018 with two novel experimental mixes designed as part of this study. The total number of pollinator visits, total number of unique species (species richness) and the diversity (Simpsons) across all plots are presented for each seed mix and pollinator group.

3.3.2 | Comparing insect species visits, richness and diversity in each seed mix treatment

In total, 2977 insect visits were recorded across all the seed mixes through the 2019 survey season. Most visits were from hoverfly species, which made up 64% of visits (23 species), followed by bumblebees with 21% (8 species), honeybees with 8% and solitary bees with 7% (12 species) (Figure 2, Dataset S1). Visitation differed significantly between seed mix treatments for bumblebees ($\chi^2 = 42.52$, df $= 3$, $p < 0.001$), hoverflies ($\chi^2 = 14.22$, df $= 3$, $p = 0.039$) and honeybees ($\chi^2 = 13.47$, df $= 3$, $p = 0.048$); however, there was no significant difference between the seed mix treatments for solitary bee visits ($\chi^2 = 0.35$, df $= 3$, $p = 1$). Species richness differed between the seed mix treatments for bumblebees ($\chi^2 = 32.78$, df $= 3$, $p < 0.001$) and hoverflies ($\chi^2 = 14.22$, df $= 3$, $p = 0.039$) but not for solitary bees (Table S4). There was no significant difference between the seed mix treatments for any of the pollinator groups for Simpson's diversity (Figure 2, Table S4). The most visited seed mix treatment for bumblebees was the non-native novel experimental mix (NN_Experimental) with a mean total visits per plot of $\bar{x} = 34 \pm 10.47$), whereas hoverflies and honeybees were recorded most on the non-native commercial pollinator mix (NN_Pollinator_Commercial) hoverflies $\bar{x} = 55.8 \pm 11.42$, honeybees $\bar{x} = 8.4 \pm 5.08$ (Table S4). Number of solitary bee visits was once again low, although higher than in commercial seed mix trials in 2018 (Figure 2) (2018 $n = 75$ and 2019 $n = 209$).

All seed mix treatments showed a similar pattern of seasonal progression (Figure 4), and month was found to be a significant predictor for visits and richness observed for all pollinator groups, except for bumblebee richness. Bumblebee visits and species richness increased from early July and then were relatively level, until decreasing in October. Bumblebee diversity, however, peaked in August and then declined sharply in September. Hoverfly visits and species richness increased from July and remained high until the end of September. The

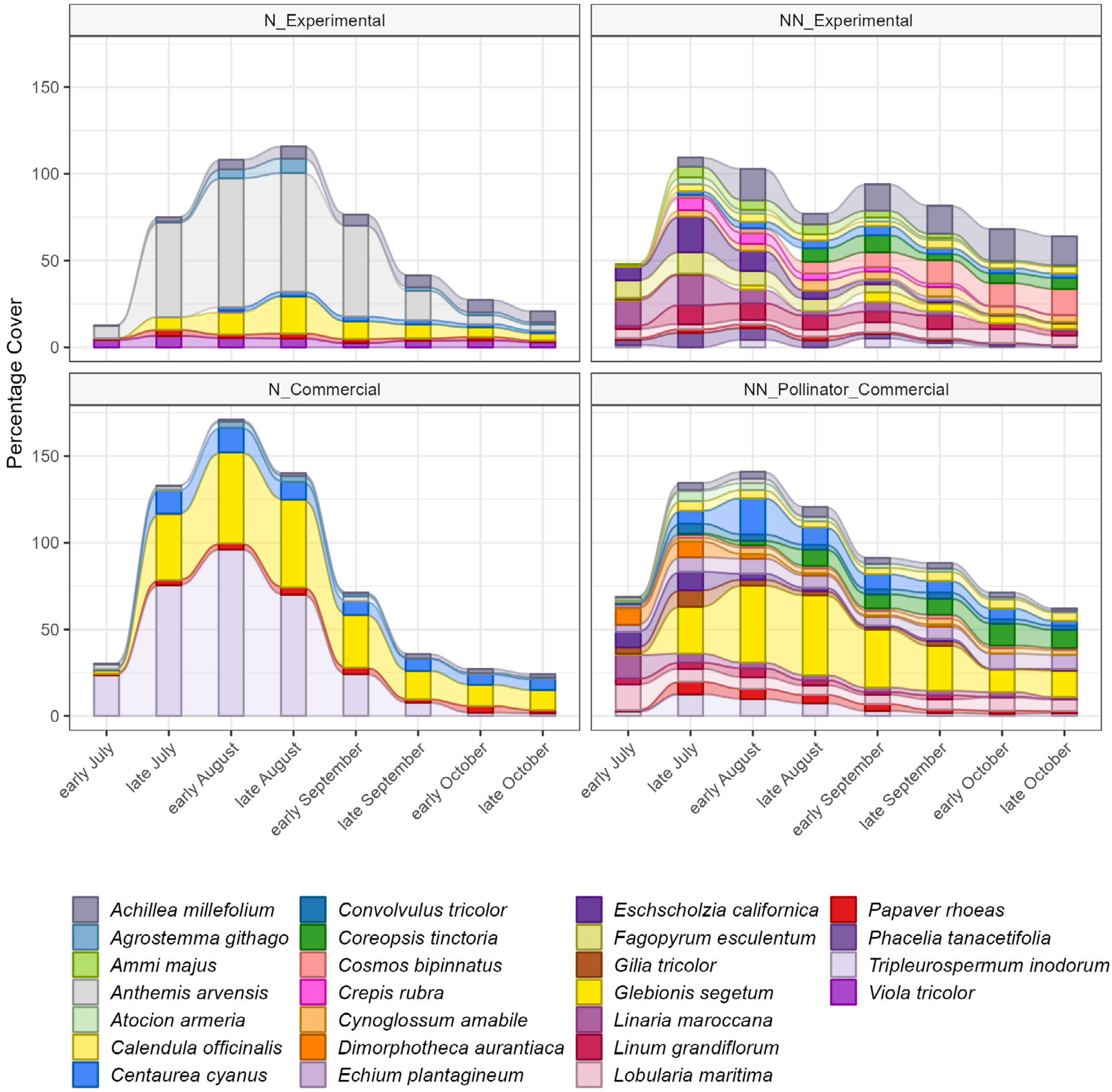

FIGURE 3 Mean percentage cover of plant species recorded flowering across novel experimental and commercial seed mixes (2019). Plants representing >5% percentage cover in any 1 month in any seed mix treatment are shown.

number of hoverfly species observed visiting the seed mixes remained high through all the months until October where the novel experimental mixes still have high diversity whereas the commercial mixes decreased. Solitary bee visits were much lower overall when compared to the other pollinator groups, with a small peak in number of species and visits in late July. Diversity was very variable across the months and the seed mix treatments with no clear seasonal patterns (Figure 4).

3.3.3 | Aesthetic survey

The aesthetics trial conducted in 2019 showed that members of the public visiting the Botanic Garden had a clear preference for the non-native seed mixes with the non-native novel experimental and commercial pollinator mix both representing 45% of votes ($\chi^2 = 218.17$, df $= 3$, $p < 0.001$, $n = 236$) (Figure S6).

3.3.4 | Plant species visited most by pollinators within the seed mixes

In total, 65 plant taxa were visited across all seed mix treatments in 2019 (Dataset S1). *G. segetum* was visited the most, representing 35% of all recorded visits, this was followed by *A. arvensis* and *Cosmos bipinnatus* Cav. *G. segetum* was visited most by hoverflies, accounting for 50% of their visits. *A. arvensis*, *Achillea millefolium* L., *T. inodorum* and *S. arvensis* were also important plants for hoverflies (Figure 5). The plant used most by bumblebees was *C. bipinnatus* (24%), followed

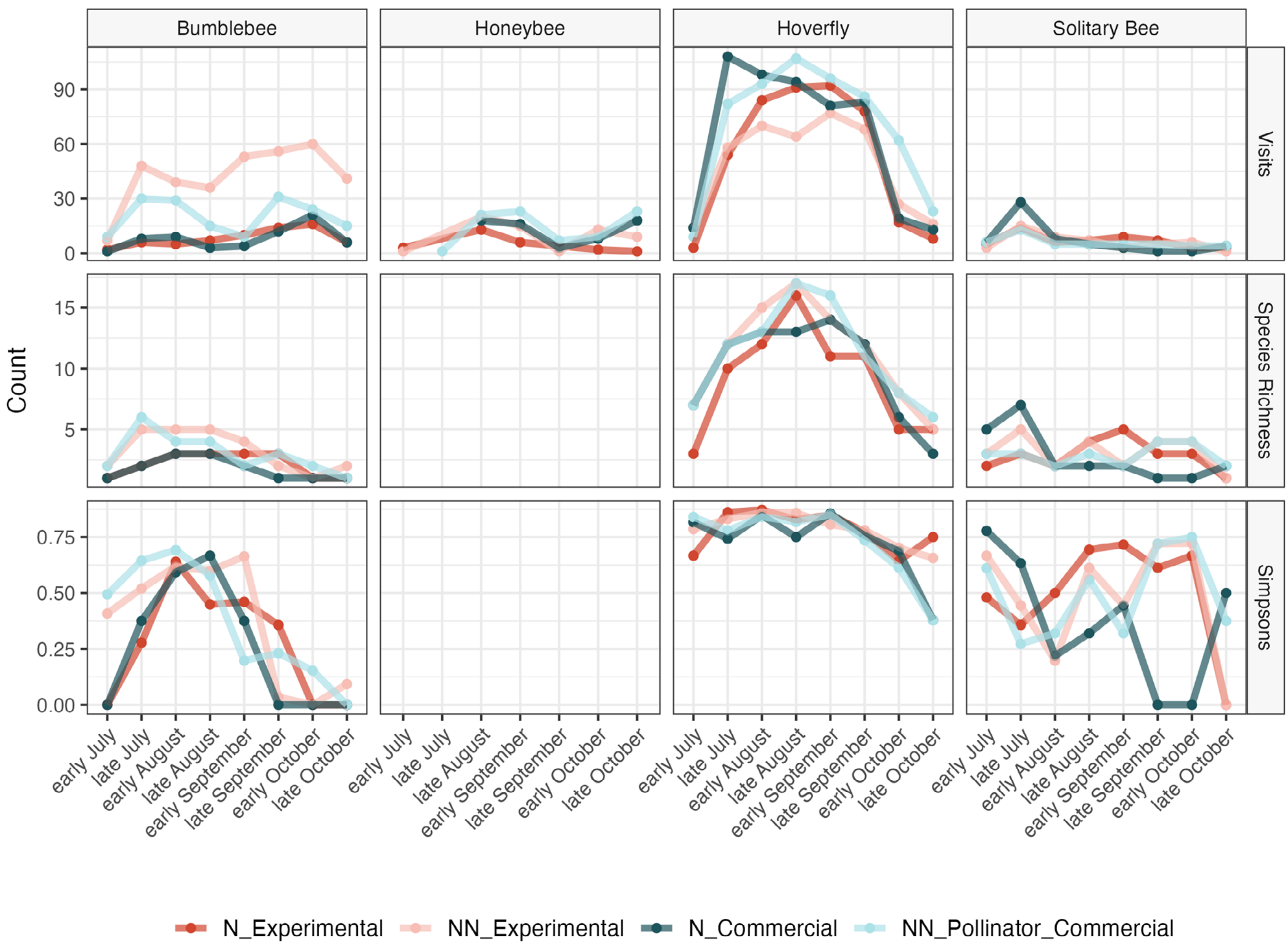

FIGURE 4 Number of visits, species richness and Simpsons diversity for each pollinator group across survey months, visiting each seed mix in 2019. Colour indicates treatment type. N indicates a native mix; NN indicates non-native. Total visits were 2977, from 43 insect species.

by *C. cyanus*, *Echium plantagineum* L., *P. tanacetifolia* and *Papaver rhoeas* L. All these plants except *P. tanacetifolia* were also visited by honeybees. In addition, honeybees also favoured *G. segetum*, *E. plantagineum* and *S. arvensis*. The most visited plants for solitary bees were *G. segetum* (28%), *A. arvensis* and *T. inodorum* (Figure 5).

The results for 2018 were consistent with those seen in 2019, except for *L. maroccana* that had the greatest number of visits from solitary bees in 2018 ($n = 13$) but was visited much less in 2019 ($n = 3$). *S. arvensis* was visited by honeybees, hoverflies and solitary bees in 2019 but does not appear in over 1% of visits in 2018 (Figure 5 and Figure S4). In 2018, it was only found within the native commercial mix and in 2019 was in both native mixes which may explain its higher number of visits (Dataset S1).

Of the plants visited by pollinators, 24 species represented over 1% of visits for at least one pollinator group (Figure 5) and the majority were found growing with over 5% cover in the plots (Figure 3). There were however a few exceptions: *Borago officinalis* L., *E. vulgare*, *S. arvensis* and *Trifolium incarnatum* L. were included within the seed mixes but flowered at less than 5% cover. *Centaurea nigra* L., *Vicia cracca* L. and *Galeopsis tetrahit* L. were not included within the seed mixes and may have grown as 'weeds' in the seed mix treatments.

4 | DISCUSSION

Global declines in biodiversity (Isbell et al., 2023; Wagner et al., 2021) place decision makers in a juxtaposition of balancing the needs of a growing population (Cena & Labra, 2024; Mouratidis, 2021) along with meeting the resource needs of declining wildlife, including bumblebees, hoverflies and solitary bees, which are important pollinators. Amenity spaces can enhance human health and well-being and increase connectivity with nature (Ajayi & Amole, 2022; Cox et al., 2018). These spaces can also provide important resources for pollinators (Baldock, 2020; Baldock et al., 2019). Through increasing our understanding of how pollinators utilise the floral resources within these spaces and developing tools which can be used to enhance them, our findings can support seed mix manufacturers, urban planners, landscape gardeners and the public in selecting plant species to deliver multiple outcomes for people and pollinators.

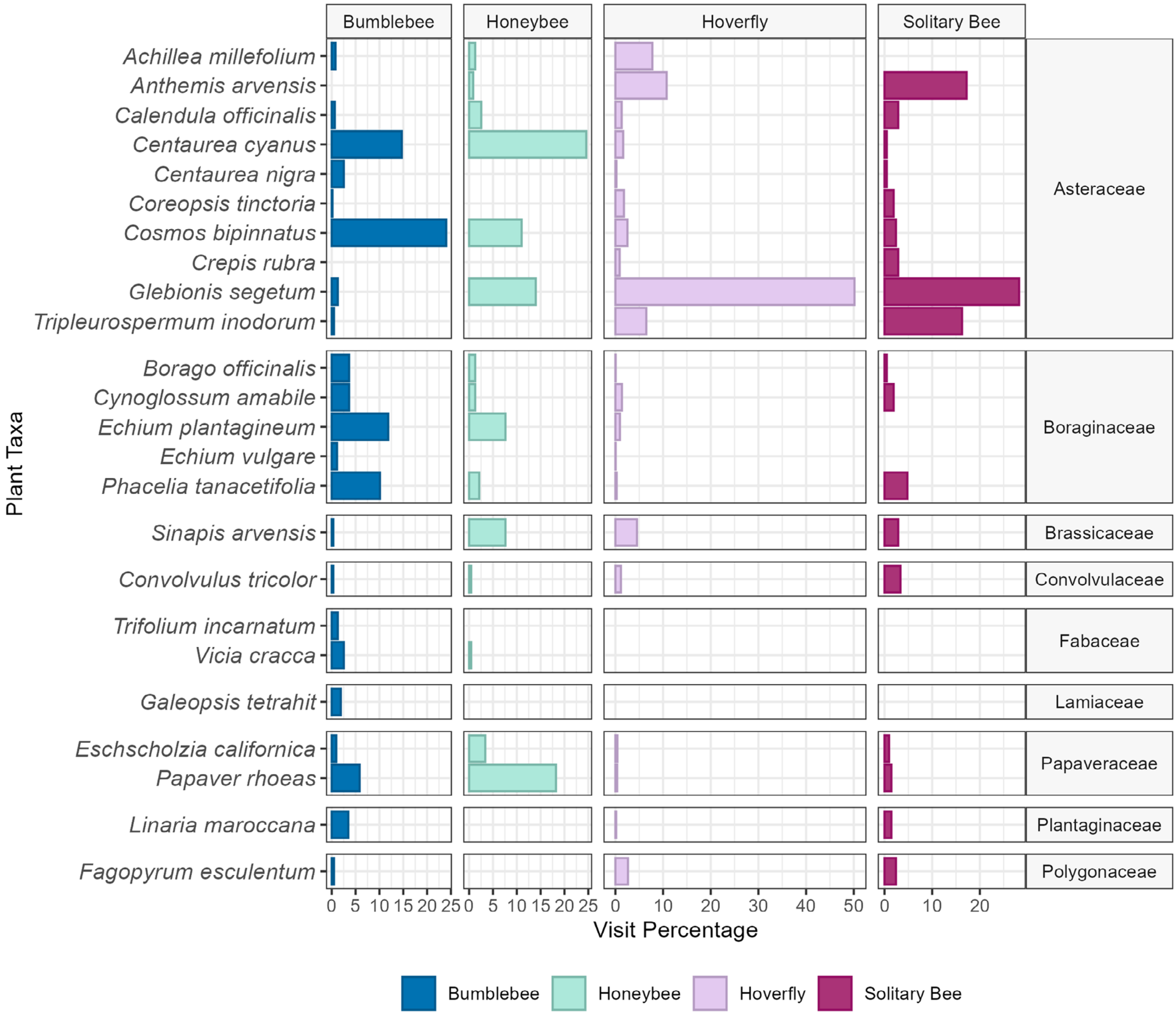

FIGURE 5 Plant species which represented >1% of pollinator visits observed across all seed mix treatments for at least one pollinator group for 2019.

4.1 | Empirical plant–insect interaction data can support the development of seed mixes designed for pollinators

Our systematic review highlights plant species that could provide important resources for flower-visiting insects in the United Kingdom and Northern Europe. The list in this review can be used as a source of information to guide the selection of annual plant species to attract flower-visiting insects and support the development of plant recommendation lists. In addition, it indicates that the success of the seed mixture for a given insect group may reflect the availability of data for that group. For example, the review returned more data on interactions between plants and more commonly studied groups such as honeybees and bumblebees, compared with solitary bees and hoverflies. The difference in data availability could therefore influence the effectiveness of chosen plants for attracting the less-studied groups. Further research into the floral resource preferences, ecology and resource requirements of these understudied insect groups has the potential to improve future seed mixtures designed for pollinators.

The review also provides an open access resource that can be used to support future research into plant–insect interactions. For example, the interaction data could be assessed alongside pre-existing databases such as the TRY Plant Trait Database (TRY, 2022) or Biol-Flor Database (BiolFlor, 2024) to gain greater insight into the mechanisms behind these plant–insect interactions, such as floral morphology and nutritional content (Fornoff et al., 2017; Moerman et al., 2017). These databases could be used to further refine seed mixtures in future work by incorporating these additional traits into the plant species selection criteria. Our decision framework (Figure 1) highlights that plant species selection is an iterative process, being frequently refined alongside developments from field trials and emerging literature. In addition to plant–pollinator interactions, there are multiple factors that must be considered when developing a seed mixture (Bretzel et al., 2024). For example, horticultural suitability is also important which includes the availability and cost of seed (Williams & Lonsdorf, 2018), whether the plant is easy to cultivate and whether it is aesthetically pleasing to people (Scheper et al., 2021); Schueller et al. (2023).

Furthermore, we emphasise the importance of excluding non-native invasive and injurious weeds from use in seed mixtures and a regular review of the most up to date information, to ensure that any plants that are newly identified as invasive or injurious are excluded (Roy et al., 2024). Using interaction data from the literature also has biases that should be considered; in particular, some species and habitats, particularly those most common in anthropogenic landscapes, are subject to more research than others (Caldwell et al., 2024; Reverté et al., 2023). Examining the literature on plant–pollinator interactions revealed over 1000 bumblebee interactions, the highest compared with other insect groups, providing a greater breadth of information for selecting plant species for bumblebees in seed mixtures compared to solitary bees and hoverflies. Similarly, there is more extensive literature on agricultural landscapes than native landscapes, leading to a disproportionate amount of interaction data in the review including crops and other plants associated with agriculture.

4.2 | Novel experimental seed mixes work well for bumblebees but are less effective for solitary bees and hoverflies

Four different commercially available mixes were compared in 2018, one mix containing native and archaeophyte plant species and three containing native, archaeophyte and neophyte species. One of these mixes was designed for bumblebees, one designed for pollinators generally and one for aesthetic appeal. The seed mixes performed well compared to their descriptions. The bumblebee mix attracted the greatest number of visits and species of bumblebees compared with the other mixes. The pollinator mix also performed well with a high number of pollinator visits across a diverse suite of species. This is a reassuring result compared to other studies that have found that seed mixes designed for pollinators were less effective than expected (Barry & Hodge, 2023).

The aim of the novel experimental seed mixes trialled in 2019, was to create mixes that were attractive to bumblebees, hoverflies and solitary bees, providing consistent seasonal floral resources for all key pollinator groups. Our research demonstrates that this was effective for bumblebees with the non-native novel experimental mix performing very well through the year for a range of bumblebee species. Solitary bee abundance across all seed mixtures was lower in comparison to bumblebees and hoverflies across both years, apart from a small peak in July. This may be due to differences in foraging behaviour and ecology between the pollinator groups. Solitary bees experience landscapes at smaller spatial scales than social bees, requiring suitable nesting and floral resources in close proximity. Their foraging preferences are often more specialised and variable between different species (Gathmann & Tscharntke, 2002; Persson et al., 2018). Research using seed mixes in agricultural settings have shown that solitary bees are less likely to use these resources, instead depending on native plants in the surrounding area (Sydenham et al., 2023; Wood et al., 2016). Targeted research is required on solitary bees to understand how to better support their needs in gardens and amenity spaces. However, it is important to note that since the abundance of solitary bees in the wider landscape was not assessed in this study, the low numbers may be a result of low abundance and diversity of solitary bees in the local landscape, rather than a reflection of the attractiveness of the seed mixture.

For hoverflies, the novel experimental seed mixtures sown in 2019 were found to be less attractive to hoverflies compared to the commercial seed mixtures. As plant–insect interaction data available for hoverflies were the lowest across all insect groups, this may explain why novel experimental seed mixtures were less attractive to this insect group and highlights the need for further research to build upon the evidence available at the time of the review. Indeed, since the systematic review was completed, three additional plant–pollinator interaction databases have been published: DoPI (Balfour et al., 2022), CPC pollinators of rare plants database (CPC, 2024) and EuPPolNet (Lanuza et al., 2025). These can be used as additional evidence when informing decisions for plant species selection.

4.3 | Mixes containing non-native, along with native species, have better establishment, provide sufficient floral resources from early July until late October and are considered more aesthetically pleasing to the public

In the seed mix trials, the mixes containing both non-native and native species flowered over a longer period, compared with those containing only native species. They provided a good diversity of flowers from early July until late October and received many pollinator visits, particularly from bumblebees. One of the native mixes performed best for hoverfly visits, but this pattern was driven strongly by the high number of visits to *G. segetum*, a species that is considered an archaeophyte in the UK flora and is now frequently seen due to its addition in seed mixes (Stroh et al., 2023). There is emerging evidence to suggest that non-native species can be attractive to a diversity of pollinators and can extend the flowering season, providing a source of much needed pollen and nectar later in the year (Jones et al., 2022; Lowe et al., 2022; Poole et al., 2025; Salisbury et al., 2015; Seitz et al., 2020).

Furthermore, the results of the aesthetic survey clearly show that people preferred the seed mixes containing non-native along with native species. This may relate to the higher number of species successfully flowering within the non-native mixes creating a much greater diversity of colour and floral form. However, the reasons associated with aesthetic preferences are diverse and subjective, with evidence to suggest that these may also be driven by social environment (Kendal et al., 2012). Indeed, the non-native species included in these mixes are frequently grown within horticulture so are likely to be preselected for horticultural suitability and may already be familiar to the public (Schueller et al., 2023). An additional consideration is that the time of year at which the aesthetic survey was carried out (1 August to 5 September 2019) may have influenced the results. The composition of floral resources varies through the season, with some species peaking earlier than others, which may also influence visual aesthetic preferences (Xu et al., 2022). For example, seed mixtures with species that peak during August may have been perceived as more visually appealing during the survey, whereas those that contained species with peak flowering time later in the season may have been less visually appealing during this time.

Our results indicate that the seed mixtures that were preferred by pollinators were also those that were the most appealing to the public. This suggests that it may be possible to develop seed mixtures that are both aesthetically appealing to the public and attractive to pollinators and indicates that there may not need to be a trade-off between ecological and social value. This is also supported by research that highlighted that the public had greater appeal for a seed mixture when they knew that it was the most attractive to pollinators (Wei et al., 2024).

Within gardens and amenity spaces, non-native plant species can fill important resource gaps and extend the flowering season (Poole et al., 2025; Rollings & Goulson, 2019; Salisbury et al., 2015). However, the use of non-native species may have unintended consequences for pollinator communities. Comparison of pollinators between native and non-native seed mixes have shown significant differences in pollinator assemblages with more specialised plant–bee visitation networks seen with native mixes (Seitz et al., 2020). In addition, there is evidence to suggest that non-native species may alter community level phenology of plants and pollinators (Harrison & Winfree, 2015). Furthermore, the pollination of non-native plants may have unintended consequences for native plant communities, such as the erosion of genetic diversity through hybridisation (Johnson et al., 2016).

Our research indicates that a combination of both native and non-native species can provide a continued availability of resources for pollinators within our gardens and amenity spaces. Native species have an important role, and space should be made for these. Indeed, native plant species have an important ecosystem function within gardens and amenity spaces, such as through food and habitat provision for wildlife (Karimi et al., 2021; Tartaglia & Aronson, 2024) In addition, non-native species, which have been shown to be attractive to pollinators and are commonly grown within horticulture, can supplement native plants and extend the flowering season (Lowe et al., 2022; Poole et al., 2025; Rollings & Goulson, 2019; Salisbury et al., 2015). It is important to note that these annual seed mixes should only be used in anthropogenic landscapes, such as in a horticultural context and planted in gardens or amenity areas. The use of annual seed mixes in these areas must first consider the existing plant communities already present on the site to ensure that plant communities that are important components of urban biodiversity are not lost (Schueller et al., 2023).

4.4 | A small number of key plant species are visited frequently in seed mixes, and these differ between pollinator groups

A relatively small number of plant species were used frequently within the seed mixes, suggesting that the attractiveness of seed mixes to pollinators may be dependent on a few key plant species (Warzecha et al., 2017). This is particularly evident in our study with *G.* segetum, which was visited at high levels by hoverflies and used by solitary bees and honeybees. Differences are seen between the flowering plants visited most by the different pollinator groups. Bumblebees show preferences for *C. cyanus* and *C. bipinnatus* in the Asteraceae, *E. plantagineum* and *P. tanacetifolia* in the Boraginceae and *P. rhoeas* in the Papaveraceae. Hoverflies show a particular preference for *G. segetum* and to a lesser extent *A. arvensis*, *T. inodorum* and *A. millefolium*, all in the Asteraceae. They also showed relatively high visitation rates for *S. arvensis* in the Brassicaceae. The Asteraceae are often visited by the solitary bees with *G. segetum*, *A. arvensis* and *T. inodorum* being the most visited flowers. In the first year, *L. maroccana* in the Plantaginaceae also had high visitation. As expected, the flowers visited most by pollinators also represent species with greater percentage cover that flower over a long period within the seed mix. This is particularly noticeable for *G. segetum*, *T. inodorum* and *A. arvensis*.

Many of the most visited species are considered as archaeophytes in the UK flora, often originally found as weeds within arable crops (Stroh et al., 2023). Agricultural intensification has caused substantial declines in arable weeds throughout Europe (Richner et al., 2015); annual seed mixes share similarities with this habitat and could potentially be used to ensure that these species are able to persist in the United Kingdom. Similarly, gardens in residential areas act as hotspots for pollinator diversity, and there is significant potential to increase the value of urban amenity areas for both plant and pollinator conservation (Baldock, 2020; Baldock et al., 2019).

4.5 | Pollinating insects need adequate floral resources alongside suitable resources for nesting and larval requirements

It is important to note that providing a seed mix should not replace the need for diverse and abundant flowering plants within the surrounding area (Scheper et al., 2015; Wood et al., 2016), instead they should be seen as an attractive supplement to these essential floral resources (Erickson et al., 2020; Scheper et al., 2015; Wood et al., 2016). Similarly, diverse and abundant floral resources are just one of the requirements that pollinators need in urban and amenity areas (Ayers & Rehan, 2021). In addition, it is important to provide adequate resources for nesting bees and the larval stages of hoverflies (Schueller et al., 2023). For example, bare soil can support ground-nesting bees (Tsiolis et al., 2022) whereas aerial nesters often require hollow cavities (Fortel et al., 2016). Considering the larval diets of hoverflies is also important, as these ecological traits determine how effectively a habitat can support their populations (Moquet et al., 2018). Egg laying in hoverflies can be encouraged by providing aquatic habitats and decaying wood to support the diversity of larval requirements (Lowe et al., 2022). Pesticides should not be used if the aim is to create an amenity space or garden that is pollinator-friendly. It has been shown that pesticides applied to plants labelled as pollinator-friendly can have levels of pesticide residue that are harmful to insects (Lentola et al., 2017), thus ensuring a pesticide-free environment is as essential for pollinators as providing floral resources.

5 | CONCLUSIONS AND RECOMMENDATIONS

This research highlights plant species that have the potential to attract a diversity of pollinators and indicates that selecting plant species with high visitation from specific insect groups could be used to develop targeted seed mixtures to attract different pollinator groups. In addition, it indicates the importance of using both native and non-native plant species, to extend the flowering season and provide a continued availability of floral resources for pollinators. Following an iterative approach, to further refine these novel experimental mixtures, it would be beneficial to build upon these results and consider the wider resource requirements of pollinators. Indeed, trialling these mixtures at scale, across different soil types and in the context of different pollinator assemblages and with more detailed modelling of commercial costs would be beneficial next steps. In addition, future studies should also look to investigate how native annual seed mixtures can be enhanced to ensure greater seed emergence and flowering success within annual seed mixtures. Furthermore, additional research of pollinator ecological requirements is needed to gain a better understanding of how lesser known groups including solitary bees and hoverflies can be supported within gardens and amenity spaces. Building upon this research, these findings could be used by horticulturalists or urban planners to deliver targeted outcomes for conservation projects in anthropogenic landscapes.

5.1 | Recommendations

- The systematic review assembled here provides an open access resource of plant–pollinator interactions that can be used, alongside other emerging databases, to help design seed mixes in addition to other ecological studies. The systematic review should be used in combination with the decision flowchart to ensure that all important factors are considered in seed mix design.
- It is valuable to include non-native species alongside native species in seed mixes designed for horticultural plantings to extend the flowering season, which in turn increases the number of pollinator visits and enhances aesthetic impact. Further research is required however to understand the impact of non-native plant species on plant–pollinator network structure and wider biodiversity.
- Although some flowering plants are valuable to all pollinator groups, others are preferred by one group. Selecting plant species in a seed mixture that include both plants attractive to all pollinators and including those species preferred by specific groups ensure a seed mix that can be used by a diversity of pollinators. Conversely, selecting plant species, which are more attractive to one pollinator group, will alter the assemblage of species visiting the seed mixture.
- Solitary bees are an understudied group and had the smallest number of visits to the seed mixes trialled here. More work is required to understand the floral resources used by solitary bees.
- Based on visitation by pollinators, successful establishment, availability and aesthetic appearance, we recommend the following species as key components of 'pollinator-friendly' seed mixes. Native species to the United Kingdom: *A. millefolium*. Archaeophytes: *A. arvensis*, *C. cyanus*, *E. plantagineum*, *G. segetum*, *P. rhoeas*, *S. arvensis*, *Tripleurospermum inordorum*. Neophytes: *C. bipinnatus*, *L. maroccana* and *P. tanacetifolia*.

AUTHOR CONTRIBUTIONS

Natasha de Vere and Lucy Witter conceived the study with suggestions from Peter Dennis, Gemma Beatty, Laura Jones and Abigail Lowe. Lucy Witter carried out the review screening process. Laura Jones, Abigail Lowe and Lucy Witter carried out the data analysis, with suggestions from Natasha de Vere. Laura Jones created the figures, Will Ritchie provided expert horticultural advice on the horticultural suitability of novel seed mixtures and managed the preparation and establishment of the seed mix trial plots. Lucy Witter, Natasha de Vere, Abigail Lowe and Laura Jones wrote the article, and all authors contributed to the discussion on the content and edited the manuscript before submission.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest to disclose.

DATA AVAILABILITY STATEMENT

This dataset is available as an open access resource within the supplementary information.

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SUPPORTING INFORMATION

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