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Plant protection products and pollinators: a cross-country study on beekeeper awareness, risk perception, and interactions with farmers

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ABSTRACT

The use of plant protection products (PPPs) in farming systems poses a potential risk to honey bee health, yet beekeepers' awareness and interactions with farmers remain understudied. This study compares the knowledge, perceptions, and PPP risk mitigation practices of amateur and professional beekeepers in Ireland and Greece, based on survey responses from 476 participants. Irish beekeepers were predominantly amateurs, while most Greek beekeepers were professionals. Irish amateurs reported significantly less experience in beekeeping and managed fewer hives compared to the other groups. Across both countries, insecticides were perceived as the most harmful PPPs to honey bees, with Greek beekeepers expressing greater concern than Irish counterparts. Greek beekeepers showed greater confidence in identifying PPP poisoning and were more likely to conduct PPP residue testing. Most beekeepers had limited interaction with farmers and were rarely notified before PPP application, often too late to take protective measures. Risk mitigation practices were minimal among Irish beekeepers, while Greek professionals more actively avoided agricultural areas. Beekeepers strongly agreed that farmers should be better informed on the risks of PPPs and expressed a desire for improved communication, preferably *via* mobile phone applications. Most respondents indicated interest in receiving further education, ideally through beekeeping associations. The findings highlight the need for targeted educational programs, structured beekeeper-farmer communication and collaboration, and accessible tools to mitigate PPP-related risks to honey bees. These insights can support the development of more effective pollinator protection and agro-ecological cooperation strategies.

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Introduction

Pollination is a vital ecosystem service underpinning agricultural productivity and biodiversity, with approximately 75% of major crop species benefiting from animal pollination, with bees playing a central role (Klein et al., 2007). Bees are highly efficient pollinators due to their morphological traits and abundance across ecosystems (Ollerton, 2017), supporting not only crop yields but also ecosystem resilience and human nutrition (Nicole, 2015). Globally, honey bees dominate both natural and agricultural landscapes (Allen-Perkins et al., 2022; Hung et al., 2018) and are often perceived by growers as the primary pollinators (Garbach & Morgan, 2017).

However, both managed and wild pollinators face escalating threats from habitat loss, climate change, disease, and particularly from exposure to plant protection products (PPPs) such as insecticides, fungicides, and herbicides (Goulson et al., 2015). These chemicals can cause acute mortality and sublethal effects, ultimately contributing to colony and population declines (Nicholson et al., 2024; Potts et al., 2016; Rundlöf et al., 2015; Tsvetkov et al., 2017). Although EU regulations (Regulation (EC) No. 1107/2009; Directive 2009/128/EC) aim to mitigate PPP risks, their effectiveness depends heavily on stakeholder engagement in terms of practical implementation (EFSA, 2013). Moreover, current policies often overlook relational and cultural values central to land users' practices (Maderson and Wynne-Jones, 2016), underlining the need for more inclusive, stakeholder-driven risk assessments (Axelman et al., 2024).

Beekeepers are critical stakeholders in this context, offering valuable insights into ecological stressors through local ecological knowledge (Maderson & Wynne-Jones, 2016; Patel et al., 2020). Their participation in honey bee monitoring citizen science projects is mainly motivated by environmental stewardship and can significantly enhance research and apicultural practices (Gratzer & Brodschneider, 2021;

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Maderson & Wynne-Jones, 2016). Notably, beekeeper advocacy contributed to the EU's 2018 outdoor ban on neonicotinoids (Ellis, 2019). Across Europe, conservation strategies that align with personal values (e.g., urban beekeeping and citizen science) have proven effective (Geppert et al., 2024).

Understanding beekeepers' perceptions and practices regarding PPP exposure is thus critical for informing policy (Motta et al., 2018; Woodcock et al., 2017). Traditional beekeeping practices, rooted in social innovation, contribute to sustainable development, yet integrating beekeepers' knowledge into research and governance remains inadequate (Fedoriak et al., 2021). With agricultural intensification threatening pollinators, stronger communication and cooperation between beekeepers and farmers is essential (Breeze et al., 2019; Kahane et al., 2022). Yet relatively few studies have explored how beekeepers' perceptions differ across countries or professional statuses, and how these differences shape responses to PPP risks.

This study addresses these gaps by evaluating the knowledge, perceptions, experiences, and mitigation practices of amateur and professional beekeepers in Greece and Ireland. These countries, with distinct climates, agricultural systems, and beekeeping traditions, offer a meaningful comparative analysis; Greece is characterized by intensive, commercially oriented apiculture, often near PPP-treated crops, while Ireland's amateur-dominated beekeeping operates within more extensive, less chemically intensive landscapes. By exploring how beekeepers understand and respond to PPP risks and how they engage with farmers, this research contributes valuable insights toward enhancing the ongoing efforts into pollinator protection, sustainable agriculture, stakeholder collaboration, and PPP policy development across Europe.

Materials and methods

Survey design and objectives

This study aimed to assess beekeepers' knowledge of PPPs, their perceived impact on honey bee health, and the quality of communication and cooperation with farmers. Differences between professional and amateur beekeepers in Greece and Ireland were explored. Data were collected anonymously through a self-administered, mainly qualitative, online survey designed to encourage honest responses. The survey, developed in English for Irish participants and translated for Greek participants, was available between January and May 2024. It included a total of 43 questions, comprising closed-ended, Likert scale, multiple-choice, and free-text formats.

Questionnaire structure

The questionnaire consisted of five sections designed to capture a comprehensive understanding of beekeepers' knowledge, perceptions, and practices related to PPPs, and their communication with farmers. The beekeeping profile section captured beekeeper status (amateur or professional), primary motivation for beekeeping, number of colonies kept, number of years of beekeeping experience, hive placement, habitat types, and observed foraging sources. Beekeepers were classified as "professional" if beekeeping was their main income source, and "amateurs" if not. In the beekeepers' perception of PPPs section, questions focused on concerns regarding PPP applications near hives, risk perceptions across PPP categories, and the awareness of bee poisoning symptoms based on established handbooks (Hooven et al., 2016; Riedl et al., 2006). Mortality events were also documented with large numbers of dead bees serving as the primary poisoning indicator (Kiljanek et al., 2016). The crop type present in the area during the mortality incident(s), crop distance from colonies, cultivation season, and year of the incident were also recorded. The communication with farmers section investigated beekeeper-farmer communication patterns, including whether contact occurred, who initiated it, experiences with hive placement in agricultural fields, and whether compensation for pollination services was received. The risk mitigation practices section assessed the measures beekeepers use to reduce PPP exposure, including relocation strategies and chemical analyses of hive products (i.e., honey, pollen, wax, propolis, and royal jelly). Practices were informed by Mayer et al. (1999) and Riedl et al. (2006). Questions also covered the adequacy and timing of PPP spray notifications. The filling beekeeper-farmer knowledge gaps section collected beekeeper recommendations for improving communication, collaboration, and wider pollinator protection practices, along with preferred methods for receiving further information and beekeeper association membership.

Survey distribution

The questionnaire was refined through pilot testing with ten stakeholders and five academic reviewers to ensure clarity and contextual relevance. The final version (Supplementary data_Questionnaire) was distributed *via* SurveyMonkey (http://surveymonkey.com/) through beekeeping associations, extension services, newsletters, targeted emails, and social media. Participation was voluntary, anonymous, and conducted without incentives. All data were stored securely, anonymized by unique identifiers, and handled in compliance with EU General Data

Protection Regulation (GDPR) requirements. Ethical approval was obtained from Trinity College Dublin (reference number 3013), and informed consent was secured from all participants.

Data analysis

Only responses from active beekeepers residing in Greece or Ireland were included. Incomplete responses (e.g., survey time <5 min or fewer than three sections completed) were excluded. Data were exported to Excel, statistical analyses were performed using GraphPad Prism version 10 (GraphPad Software, La Jolla, CA), and Microsoft PowerPoint 365 version 2408 was used for the creation of infographics. For the creation of the maps, QGIS (version 3.42.0) was used. For continuous variables (years of beekeeping experience and number of colonies managed), descriptive statistics are reported (median values). Since normality assumptions were not met, non-parametric tests were employed. Kruskal–Wallis H tests were used to assess overall differences among the four independent groups (Greek amateurs, Greek Professionals, Irish Amateurs, and Irish Professionals). When significant differences were detected ($p < 0.05$), *post-hoc* pairwise comparisons were conducted using Mann–Whitney U tests. Multiple comparison correction was applied using the Benjamini–Hochberg false discovery rate (FDR) method. Spearman's rank correlation coefficients were calculated to assess relationships between years of experience and number of hives, both overall and within each group. Statistical significance was set at $\alpha = 0.05$. For all categorical variables (e.g., PPP use concern, worry levels, communication patterns, etc.), Pearson's chi-square tests of independence (χ^2) were performed to examine associations between the four groups and response categories. For variables showing significant omnibus chi-square tests ($p < 0.05$), Bonferroni-corrected pairwise comparisons were conducted to identify specific group differences. With four groups, six possible pairwise comparisons existed. Bonferroni correction was applied by dividing the nominal alpha level by the number of comparisons ($\alpha_{adjusted} = 0.05/6 = 0.0083$). Only pairwise differences with $p < 0.0083$ were considered statistically significant and are presented in the text; results for non-significant comparisons are reported in the corresponding sections of the supplementary material (Supplementary data_Tables). Effect sizes were quantified using Cramér's V and interpreted following Cohen (1988) guidelines: small ($V = 0.06$–0.17), medium ($V = 0.17$–0.29), large ($V > 0.29$). To enhance clarity, when multiple variables were statistically significant, results are presented only for the variables with the largest effect sizes, considering relevance and significance to the results. Descriptive statistics for categorical variables are reported as frequencies with percentages. Open-ended responses underwent thematic content analysis. Spearman's Rank correlation analysis was used to explore associations between beekeeping experience and number of hives.

Results

Beekeeper and apiary characteristics

A total of 476 complete responses were collected, comprising 234 Irish and 242 Greek beekeepers. The largest group was represented by Irish amateurs ($n = 218$, 46%), followed by Greek professionals ($n = 134$, 28%), Greek amateurs ($n = 108$, 23%), and Irish professionals ($n = 16$, 3%). There was a good geographic spread in terms of responses (Figure 1). In Ireland (Figure 1(a)), most of the respondents' hives were placed in Counties Dublin ($n = 134$), Cork ($n = 131$), and Wicklow ($n = 117$). In Greece (Figure 1(b)), the main locations were Euboea ($n = 137$), Ioannina ($n = 95$), and Larissa ($n = 92$). These locations reflect hive placement by surveyed beekeepers who participated in the study but may not represent the respective national distributions.

Beekeeping experience varied significantly across groups ($H = 55.53$, $p < 0.001$) (Figure 2). Greek professionals (median = 13 years; SD ± 8.0) had significantly more experience than Greek amateurs (median = 10 years; SD ± 9.5) ($p_{adjusted} = 0.023$) and Irish amateurs (median = 6 years; SD ± 12.9) ($p_{adjusted} < 0.001$), but no significant difference was observed with Irish professionals (median = 14.5 years; SD ± 11.1) ($p_{adjusted} = 0.292$). Greek amateurs had substantially more years of experience compared to Irish amateurs ($p_{adjusted} < 0.001$), while no significant difference was observed with Irish professionals ($p_{adjusted} = 0.073$). Irish amateur beekeepers had significantly less years of experience compared to Irish professional beekeepers ($p_{adjusted} < 0.005$).

Number of hives also varied notably ($H = 360.69$, $p < 0.001$) (Figure 2). Greek professionals (median = 200 hives; SD ± 213.8) managed significantly more hives than Greek amateurs (median = 55; SD ± 74.7) ($p_{adjusted} < 0.001$), Irish amateurs (median = 5 hives; SD ± 14.1) ($p_{adjusted} < 0.001$), and Irish professionals (median = 77 hives; SD ± 77.4) ($p_{adjusted} < 0.001$). Greek amateurs managed significantly higher number of hives than Irish amateurs ($p_{adjusted} < 0.001$), while there was no significant difference with Irish professionals ($p = 0.379$). On the contrary, Irish amateurs managed significantly fewer hives than Irish professional beekeepers ($p_{adjusted} < 0.001$). Across both countries, a positive correlation was observed

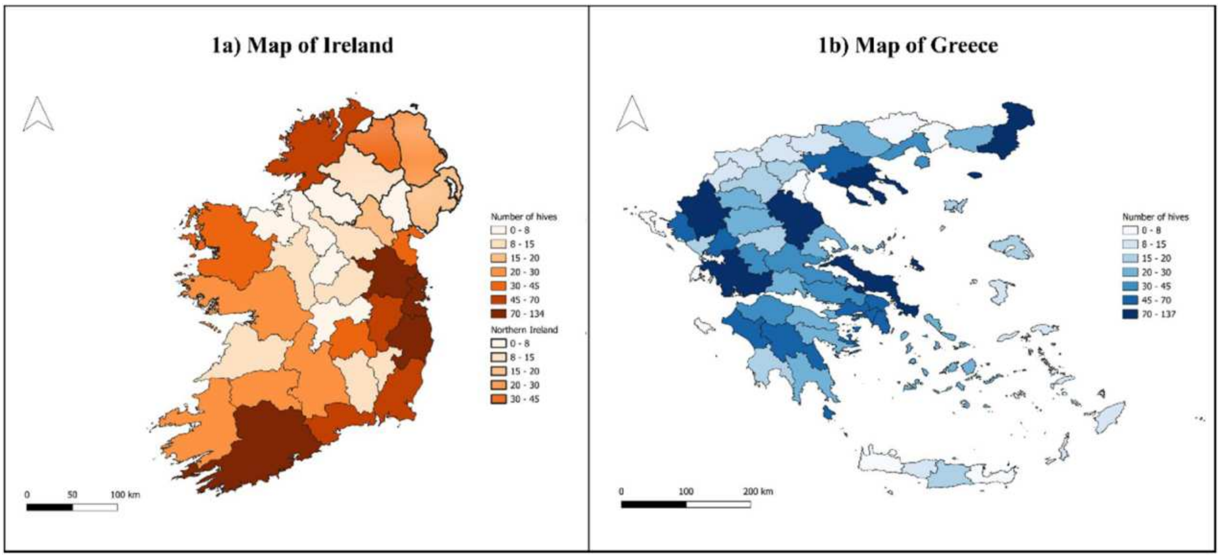

Figure 1. Map of Ireland (1a) and Greece (1b) showing in which regions the beekeepers who participated in the survey placed their hives.

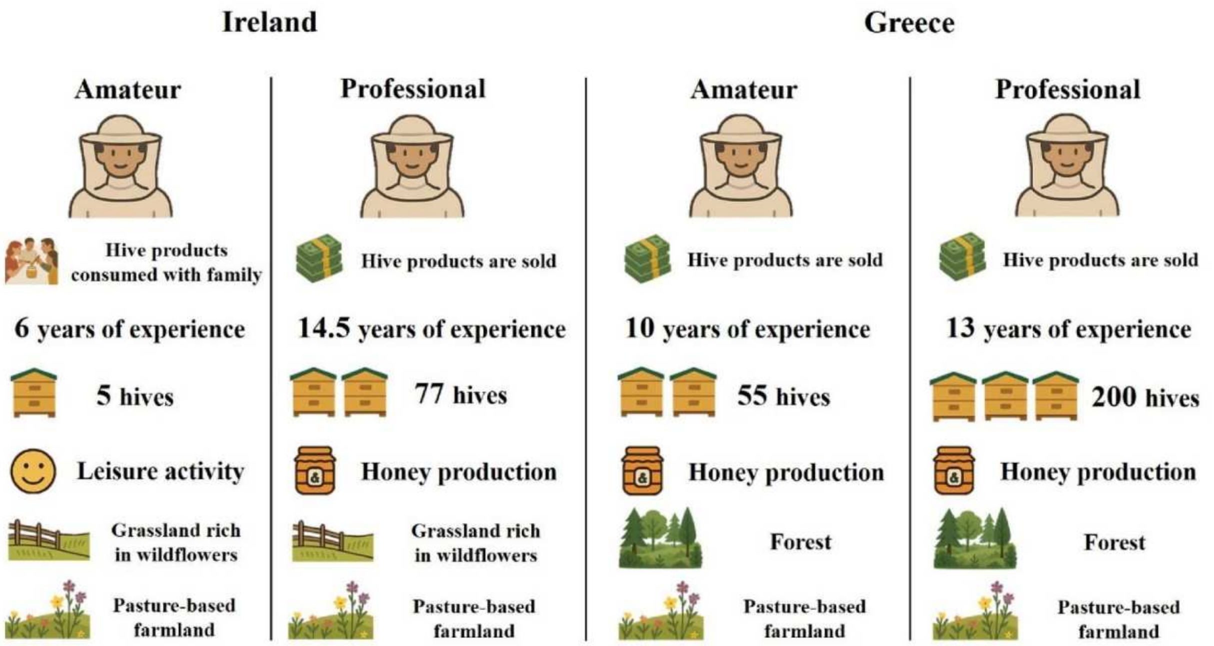

Figure 2. The four different beekeeper profiles based on the use of their hive produce, the median years of experience, the median number of hives, the main motivation for beekeeping and habitat where the apiary is usually placed.

between years of experience and number of hives (Spearman $r_s = 0.494$, $p < 0.001$).

Beekeeping purposes differed significantly across the four groups (Figure 2). All six variables showed significant differences ($p < 0.001$–0.024). Leisure/hobby-oriented beekeeping exhibited the largest effect ($\chi^2 = 171.78$, $p < 0.001$, $V = 0.601$), with Irish amateurs reporting the highest prevalence (87%) compared to Greek professionals (17%, $p < 0.001$), Greek amateurs (58%, $p < 0.001$) and Irish professionals (37%, $p < 0.001$). The difference between the two Greek beekeeper categories was also significant ($p < 0.001$). The production of "Honey bee products" other than honey showed a medium effect ($\chi^2 = 107.91$, $p < 0.001$, $V = 0.476$), with Greek professionals most likely (67%) to produce various other products (e.g., pollen, royal jelly, propolis, wax), followed by Greek amateurs (47%), Irish professionals (37%) and Irish amateurs least likely (14%). Statistically significant differences were observed between Greek amateurs and Greek professionals ($p = 0.003$), Greek amateurs and Irish amateurs ($p < 0.001$) and Greek professionals and Irish amateurs ($p < 0.001$). The production of "Honey" demonstrated the third highest effect ($\chi^2 = 57.91$, $p < 0.001$, $V = 0.349$), with Greek professionals reporting the highest prevalence (95%) followed by Greek amateurs (90%), Irish professionals (87%) and Irish amateurs (64%). Irish amateurs use beekeeping to produce honey significantly less than both groups of Greek beekeepers ($p < 0.001$ for both). Among amateur beekeepers the beekeeping produce use differed significantly between Greece and Ireland; Greek amateurs were more likely than Irish amateurs to sell their produce commercially (77% and 48%, respectively; $\chi^2 = 23.19$, $p < 0.001$, $V = 0.267$), while Irish amateurs used their beekeeping produce more frequently than Greek amateurs for family consumption (85% and 63%, respectively; $\chi^2 = 19.70$, $p < 0.001$, $V = 0.246$) or for giving it to friends (72% and 48%, respectively; $\chi^2 = 16.86$, $p < 0.001$, $V = 0.227$).

Habitat use for the placement of the hives differed significantly across the four groups for 17 of 24 habitat-season combinations. The largest difference occurred for forest habitats in summer ($\chi^2 = 177.55$, $p < 0.001$, $V = 0.611$), where Greek beekeepers reported substantially higher use (amateurs 75% and professionals 81%) compared to Irish beekeepers (amateurs 16% and professionals 44%) (Figure 2). Significant differences were observed among Greek professionals and both Irish amateurs ($p < 0.001$) and Irish professionals ($p = 0.002$), as well as between Greek amateurs and Irish amateurs ($p < 0.001$). The second big difference was observed for forest habitats in autumn ($\chi^2 = 158.87$, $p < 0.001$, $V = 0.578$), where Greek beekeepers reported substantially higher use (amateurs 63% and professionals 82%) compared to Irish beekeepers (amateurs 16% and professionals 44%). Greek professionals had significantly higher percentages than Greek amateurs ($p = 0.001$), Irish amateurs ($p < 0.001$) and Irish professionals ($p < 0.001$). Greek amateurs also significantly differed from Irish amateurs ($p < 0.001$). Conversely, Irish beekeepers showed higher pasture-based farmland use across all seasons, with the strongest difference in summer ($\chi^2 = 54.37$, $p < 0.001$, $V = 0.338$). Values were significantly lower in both Greek amateur and Greek professional beekeepers (23% and 22%, respectively) compared with Irish amateurs (52%) and professionals (81%; all pairwise comparisons, $p < 0.001$).

Forage sources utilized by honey bees according to beekeepers' observations differed significantly across the four groups for 18 of 24 forage-season combinations. The largest difference occurred for tree honeydew in summer ($\chi^2 = 79.20$, $p < 0.001$, $V = 0.408$). Values were highest in Greek professionals (81%), significantly exceeding those of Greek amateurs (58%) and both Irish groups (amateurs 34% and professionals 31%; $p \leq 0.001$). Greek amateurs differed from Irish amateurs ($p < 0.001$) but not from Irish professionals, while no difference was observed between Irish amateurs and professionals. The second bigger difference was in foraging wild plants near cultivated crops in summer ($\chi^2 = 61.90$, $p < 0.001$, $V = 0.361$), where both Greek amateurs (27%) and professionals (23%) showed significantly lower values than Irish amateurs (59%) and professionals (75%; $p < 0.001$). The third was in foraging wild plants near cultivated crops during autumn ($\chi^2 = 58.62$, $p < 0.001$, $V = 0.351$), where both Greek amateurs (23%) and professionals (21%) exhibited significantly lower values than Irish amateurs (54%) and professionals (75%; all $p < 0.001$). It should be noted that in the last two forage-season combinations, no significant differences were detected between statuses within either country.

Perceived risks of PPP use on crops for honey bees

Beekeepers from Ireland and Greece were asked about their perceptions of the necessity of farmers using PPPs to control pests, diseases in crops and weeds in cultivated crops and both demonstrated a generally neutral attitude, with an overall prevalence of 40% (36–44%) of respondents across all groups indicating that such use is "Somewhat necessary." Significant differences among groups were detected for the "Extremely necessary," "Very necessary," and "Not at all necessary" perception levels ($\chi^2 = 9.0$–15.3, $p \leq 0.029$), with small effect sizes ($V = 0.138$–0.179), while no significant differences were observed for the "Somewhat necessary" or "Not so much necessary" categories ($p > 0.06$). Greek professionals (21%) were the most likely to perceive the PPP use as "Extremely necessary" compared with the other groups (Greek amateurs 8%, Irish amateurs 8% and Irish professionals13%), and this proportion was significantly higher than that observed among Irish amateurs ($p < 0.001$). Greek amateurs (24%) showed the highest prevalence in perceiving the PPP use as "Very necessary," followed by Greek professionals (19%) and Irish professionals (19%), with Irish amateurs showing the lowest prevalence (10%). Significant differences were observed only between Greek amateurs and Irish amateurs ($p < 0.001$). Irish amateurs reported the highest prevalence of "Not so much necessary" perception (25%), followed by Greek amateurs (25%), Greek professionals (15%), and Irish professionals (12%). "Not at all necessary" responses were generally low, particularly among Greek amateurs (6%). Irish amateurs showed the highest prevalence (16%), followed by Irish professionals (13%) and Greek professionals (9%).

Despite this overall neutral attitude toward general PPP use on crops, there was strong consensus that PPP application on cultivated crops near hives could negatively impact honey bees (overall 94%) (Figure 3). Specifically, Greek beekeepers showed a significantly stronger agreement, with 81% of Greek

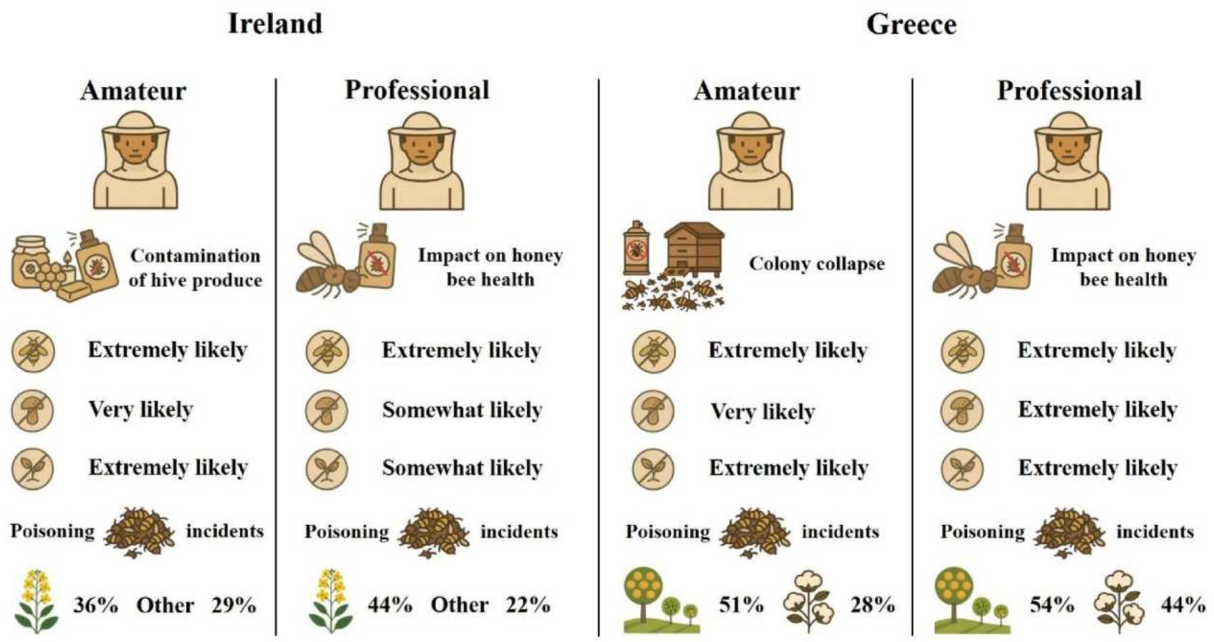

Figure 3. The four different beekeeper profiles based on their perception of the reasons why PPPs may be posing a threat to their apiary, their opinion on the potential hazard of each PPP category (insecticide, fungicide and herbicide), and the flowering crops associated with honey bee poisoning incidents based on the beekeeper's observations.

professionals and 80% of Greek amateurs strongly agreeing, compared to 59% of Irish amateurs and 56% of Irish professionals ($\chi^2 = 26.32$, $p < 0.001$, $V = 0.235$). Conversely, Irish beekeepers (32% amateurs and 38% professionals) were more likely to select "Agree" rather than "Strongly agree" compared to Greek beekeepers (amateurs 19% and professionals 15%) ($\chi^2 = 16.34$, $p = 0.001$, $V = 0.185$). *Post-hoc* pairwise comparisons revealed that both Greek amateur and Greek professional groups differed significantly from Irish amateurs in strongly agreeing with PPP negative impact on honey bees ($p < 0.001$), while Greek professionals differed from Irish amateurs in the "Agree" category ($p < 0.001$).

Overall, the most significant reasons of beekeeper concern regarding the use of PPPs near their honey bee colonies ("Extremely worried" and "Very worried") were that PPPs may negatively impact their honey bee health (81%) and eventually make their colonies collapse (76%), followed by the fear of reduction of their apiary production (71%). Specifically, most Greek and Irish professionals were extremely concerned for PPP negative impact on honey bee health (80% and 62%), while most of Greek amateurs were extremely worried that their colonies might collapse (68%), and Irish amateurs feared that their apiary products may be contaminated with PPPs (37%) (Figure 3). Perceived risks regarding the use of PPPs on cultivated crops near beekeepers' honey bee colonies differed significantly across the four groups for 17 of 25 variables, but the largest difference occurred for considerations related to the reduction of the apiary production ($\chi^2 = 92.22$, $p < 0.001$, $V = 0.440$), with Greek professionals showing "Extremely worried" (78%), significantly exceeding Greek amateurs (53%), Irish amateurs (26%) and Irish professionals (38%) (all $p < 0.002$). Greek amateurs significantly exceeded Irish amateurs ($p < 0.001$). Similarly, the second biggest difference was observed in "Extremely worried" about the negative impact of PPPs on honey bee health ($\chi^2 = 77.77$, $p < 0.001$, $V = 0.404$), where Greek professionals (80%) and Greek amateurs (64%) were more worried than Irish amateurs (33%) ($p < 0.001$ for both). The third largest difference was noted in "Extremely worried" about colony collapse ($\chi^2 = 69.12$, $p < 0.001$, $V = 0.381$), with Greek professionals (78%) and Greek amateurs (68%) being significantly more worried than Irish amateurs (36%) ($p < 0.001$ for both).

Unsurprisingly, across all groups and irrespectively of the beekeeping status, the use of insecticides on crops was strongly considered likely to negatively impact honey bee health (91% overall), while herbicides (67%) and fungicides (50%) showed more variable perceptions, with Greek beekeepers consistently rating all PPP types as more harmful than their Irish counterparts (Figure 3). Perceptions of potential negative PPP impacts on honey bee health differed significantly across the four groups for ten of 18 health impact variables with herbicides showing the largest differences ($\chi^2 = 47.80$, $p < 0.001$, $V = 0.317$) for the "Extremely likely" category. Greek professionals perceived herbicides as extremely likely to be harmful most frequently (69%), significantly exceeding Irish amateurs (33%, $p < 0.001$) and Irish professionals (25%, $p = 0.001$). Greek amateurs (54%) also significantly exceeded their Irish counterparts

($p < 0.001$). Insecticides were perceived as "Extremely likely" to be harmful to honey bees by the majority across all groups ($\chi^2 = 38.34$, $p < 0.001$, $V = 0.284$), with Greek professionals showing highest concern (88%) followed by Greek amateurs (80%), Irish professionals (69%), and Irish amateurs (59%). Irish amateurs considered insecticides being "Extremely likely" to be harmful to honey bees significantly less than Greek amateurs and professionals ($p < 0.001$ for both). Fungicides showed the most distributed perceptions across the various potential harm levels.

Confidence in identifying the symptoms of PPP poisoning in honey bee colonies was higher among Greek beekeepers (89%) compared to Irish beekeepers (71%). Results differed significantly across the four groups for all three response categories ("Yes", $\chi^2 = 50.50$, $p < 0.001$, $V = 0.326$; "No", $\chi^2 = 43.33$, $p < 0.001$, $V = 0.302$ and "Unsure", $\chi^2 = 15.09$, $p < 0.002$, $V = 0.178$; all $p < 0.002$). Greek professionals reported the highest confidence rate (94%), significantly exceeding Irish amateurs (64%, $p < 0.001$) and Greek amateurs (84%) significantly exceeded their Irish counterparts. Irish professionals had an equally high confidence level of symptom recognition with their Greek counterparts (94%). Notably, 16% of Irish amateurs reported that they could not identify any symptoms, significantly higher than both Greek beekeeper categories ($p < 0.001$ for both), representing the only group under this answer category. Irish amateurs also showed the significantly highest uncertainty in symptom identification (21%), compared to Greek professionals (6%, $p < 0.001$).

Among beekeepers who felt confident in identifying honey bee poisoning symptoms attributed to PPPs ($n = 414$, 87% of the total sample), identification methods differed significantly for six of nine symptoms. Overall, noticing "Many dead honey bees near the hive entrance or at foraging sites" was the most reported indicator (89%), followed by "Lack of foraging honey bees, forager disorientation, reduced foraging efficiency" (77%) and "Honey bees exhibiting physical symptoms such as trembling, twitching, showing lack of movement coordination, or are unable to move" (71%). The observation of many dead bees showed the largest effect ($\chi^2 = 38.67$, $p < 0.001$, $V = 0.306$), with Greek beekeepers reporting near-universal use (97% amateur and 97% professional) compared to Irish amateurs (77%, $p < 0.001$ for both) and Irish professionals also demonstrating a very high percentage (93%).

Field observations of many dead adult honey bees (>200 bees) in front of the hives or at foraging sites in a single instance also differed substantially ($\chi^2 = 145.19$, $p < 0.001$, $V = 0.552$); 38% of Irish beekeepers had never observed mass mortality events, whereas 75% of Greek beekeepers had. Greek professionals reported the highest rate of incident observations (83%), significantly exceeding Greek amateurs (67%, $p = 0.006$) and Irish amateurs (21%, $p < 0.001$). Irish amateurs reported the lowest incident numbers (21%), significantly lower than Greek amateurs ($p < 0.001$) and Irish professionals (56%, $p = 0.003$).

Among beekeepers reporting field observations of many dead adult honey bees ($n = 237$, 50% of the total sample), most Irish incidents were linked to the presence of oilseed rape within a proximity of 1 km from the hives (amateurs 36% and professionals 44%) and other crops (e.g., field beans) (29%). Greek cases were predominantly associated with the presence of fruit trees (e.g., olive, orange and almond) (amateurs 51% and professionals 54%) and cotton (amateurs 28% and professionals 44%) also within 1 km. The distance of incidents to specific crops differed significantly for six of 23 crop-distance combinations. Cotton crops within 1 km showed the largest difference ($\chi^2 = 34.39$, $p < 0.001$, $V = 0.381$), with Greek professionals (44%) and Greek amateurs (28%) reporting incidents, while no Irish beekeepers did, as cotton is not grown in Ireland. Fruit crops within 1 km also showed substantial differences ($\chi^2 = 33.05$, $p < 0.001$, $V = 0.373$), with Greek beekeepers reporting high incident rates (amateurs 51% and professionals 54%) compared to Irish beekeepers (amateurs 11% and professionals 0%). The percentage of Greek professionals was significantly higher than that of both Irish groups ($p \leq 0.005$), and the percentage of Greek amateurs significantly higher than that of Irish amateurs ($p < 0.001$). Conversely, oilseed rape within 1 km was related to higher Irish incident rates (amateurs 36 and professionals 44%) compared to Greeks (amateurs 10% and professionals 20%) ($\chi^2 = 14.49$, $p = 0.002$, $V = 0.247$), with the percentage of Irish amateurs being significantly higher than that of Greek amateurs ($p = 0.001$).

In terms of seasonal pattern, most Irish incidents linked to oilseed rape took place in spring (amateurs 31% and professionals 56%) and for other crops the reported incidents for Irish amateurs took place in summer (22%), while most incidents reported by Irish professionals took place in spring (22%). In Greece, cases linked to fruit trees were predominantly recorded in spring (amateurs 64% and professionals 69%) and those linked to cotton crops mostly took place during summer (amateurs 31% and professionals 45%). The seasonal timing of incidents by crop type differed significantly for seven of 30 crop-season combinations. Fruit crops in spring showed the largest difference ($\chi^2 = 43.84$, $p < 0.001$, $V = 0.430$), with Greek beekeepers reporting high incident rates compared to Irish beekeepers (amateurs 16% and professionals 22%). Cotton in summer also showed substantial differences ($\chi^2 = 34.85$, $p < 0.001$, $V = 0.383$), with Greeks reporting 31–45% incident rates while no Irish beekeepers did (cotton is not grown in Ireland). Greek professionals and Greek amateurs differed significantly from Irish amateurs for fruit crops in spring (both $p < 0.001$) and for cotton crops in summer (both $p < 0.001$). Of particular concern is that most reported incidents in both countries were recorded in 2022 and 2023.

The attitude toward PPP residue analyses in apiary produce differed significantly across the four groups ($\chi^2 = 126.59$, $p < 0.001$, $V = 0.516$). Greek professionals reported the highest testing rate (58%), significantly exceeding Greek amateurs (26%, $p < 0.001$) and Irish amateurs (5%, $p < 0.001$). Irish amateurs reported the lowest testing rate (5%), significantly lower than all other groups ($p < 0.01$). Also, 25% of Irish professionals reported performing PPP analyses. Overall, only 25% of beekeepers had conducted PPP residue testing, with a clear professional bias (professionals 50% and amateurs 12% across countries) and substantial country difference (Greece 39% and Ireland 6%). Greek professionals were the only group with a majority having tested (58%), while Irish amateurs showed minimal testing engagement (5%).

Among beekeepers who had conducted PPP residue analysis ($n = 120$, 25% of the total sample), preferred testing frequency differed significantly for only one of five frequency options. The answer "If I suspect that my honey bees have been exposed to PPPs" showed the largest difference ($\chi^2 = 12.51$, $p = 0.006$, $V = 0.323$), with all Irish professionals selecting this option (100%) compared to Greek professionals (27%), Greek amateurs (39%), and Irish amateurs (10%). However, *post-hoc* comparisons revealed no significant pairwise differences ($p > 0.0083$). The frequency of "Once per year" was the most common preference overall (52%), favored by Irish amateurs (70%), Greek professionals (55%), and Greek amateurs (43%), while no Irish professionals selected this option. The option "More than once per year" was chosen exclusively by Greeks (18% amateurs, 23% professionals), with no Irish respondents selecting frequent PPP analysis.

When beekeepers were asked about which product of their apiary is contaminated with most different PPP residues, only the option "All are contaminated with similar numbers of PPPs" showed significant differences ($\chi^2 = 9.78$, $p = 0.021$, $V = 0.286$), with Irish amateurs more likely to select this (20%) compared to Greeks (amateurs 4% and professionals 1%), while no Irish professionals voted for this option. However, *post-hoc* comparisons revealed no significant pairwise differences, likely due to small sample sizes, particularly among Irish respondents ($n = 14$ total). The most striking finding was the dominant preference for "All are free of PPPs" (56% overall). Among specific products, "Honey" (16%) and "Pollen" (15%) were most prioritized, while "Wax" (6%), "Propolis" (2%), and "Royal jelly" (0%) received minimal attention.

Perceptions of which honey bee products carry the highest concentration of residues showed no significant differences across groups for any of the six product categories analyzed (all $p > 0.097$). The dominant response was "All are free of PPPs" (58% overall), selected across all groups (Greek amateurs 61%, Greek professionals 58%, Irish amateurs and professionals 50% each). Among the contaminated matrices, "Pollen" was most frequently identified as the product with highest concentrations of PPPs (16%), particularly by Greek professionals (19%), followed by "Honey" (12%), "Wax" (6%), and least by the option "All are contaminated with similar concentrations" (4%). "Propolis" and "Royal jelly" received minimal or no votes (0% and 1%). No pairwise comparisons were significant, reflecting both small sample sizes and a genuine lack of consensus.

Communication patterns with farmers

Farmer-beekeeper communication differed significantly across the four groups for all three communication categories (all $p < 0.001$) (Figure 4). The option "Never communicated" showed strongest differences ($\chi^2 = 49.09$, $p < 0.001$, $V = 0.321$), followed by "Currently in communication" ($\chi^2 = 28.13$, $p < 0.001$, $V = 0.243$) and "Communicated in past" ($\chi^2 = 19.34$, $p < 0.001$, $V = 0.202$). Irish professionals reported the highest rate of current communication (62%), significantly exceeding Irish amateurs (18%, $p < 0.001$) and Greek amateurs (25%, $p = 0.006$), while Greek professionals also differed from Irish amateurs ($p < 0.001$). Conversely, Irish amateurs reported the highest rate of never having communication (61%), significantly exceeding Greek amateurs (37%, $p < 0.001$) and Greek professionals (25%, $p < 0.001$). Past communication was reported similarly by both Greek groups (amateurs 38% and professionals 37%), both significantly exceeding Irish amateurs (21%, $p = 0.001$), while no significant difference was observed compared to Irish professionals (6%). Overall, only 27% currently communicate with farmers, while 44% never have and 29% did in the past.

Among beekeepers who never communicated with farmers ($n = 211$, 44% of the total sample), barriers varied by country and beekeeper type. Greek amateurs (32%) favored the answer "I wanted, but did not know how," Greek professionals (42%) "I

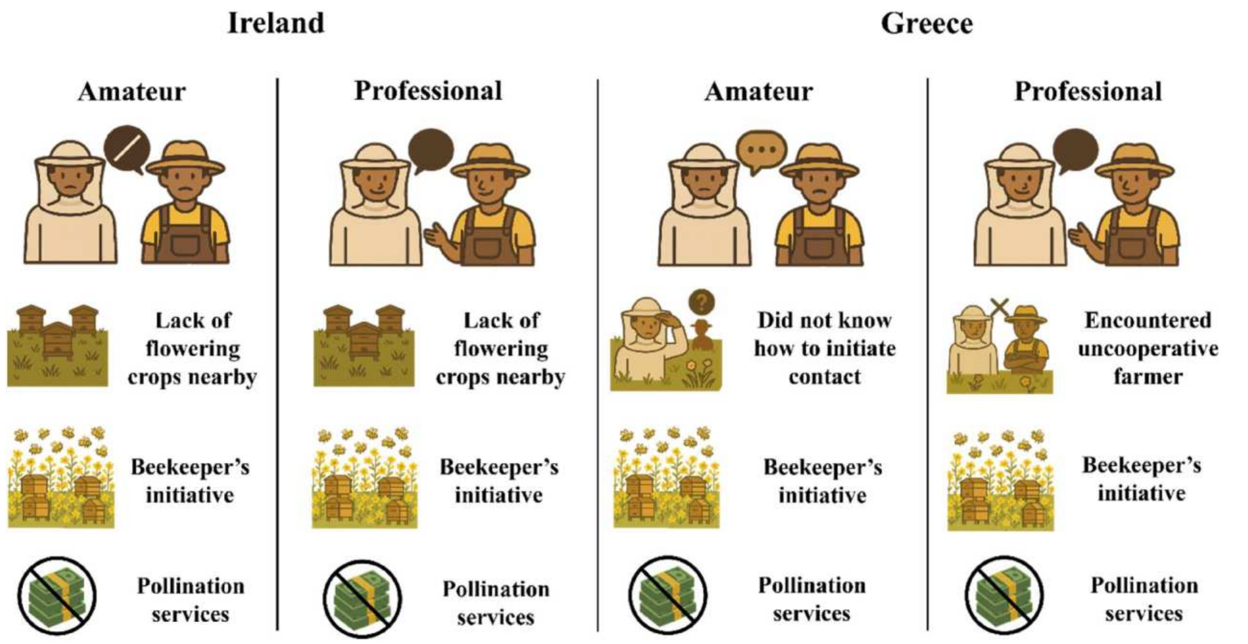

Figure 4. The four different beekeeper profiles based on their communication experiences and interactions with farmers growing flowering crops.

tried, but the farmer was negative,", Irish amateurs and Irish professionals preferred the option "Other" (42% and 60%, respectively). Reasons for non-communication differed significantly for two of the four categories. The option "I tried, but the farmer was negative" showed the largest difference ($\chi^2 = 39.70$, $p < 0.001$, $V = 0.434$), with Greek professionals reporting the highest rate (42%), significantly exceeding Irish amateurs (3%, $p < 0.001$) and Greek amateurs (22%) significantly exceeding Irish amateurs ($p < 0.001$). The answer "Never thought about it" also differed significantly ($\chi^2 = 17.97$, $p < 0.001$, $V = 0.292$), with Irish amateurs reporting highest rates (38%), significantly more than Greek professionals (3%, $p < 0.001$). Irish beekeepers most frequently cited the absence of nearby flowering crops as the main reason for non-engagement, suggesting a structural limitation to the perceived need for dialogue.

Among beekeepers who currently or previously communicated with farmers ($n = 265$, 56% of the total sample), the party initiating communication differed significantly across groups for all three initiation routes (all $p < 0.028$). Beekeepers overwhelmingly initiated communication (91% overall, $\chi^2 = 15.49$, $p = 0.001$, $V = 0.242$) indicating a lack of structured and continuous dialogue from the farmers' side and placing disproportionate responsibility on beekeepers for risk mitigation, with Greeks reporting higher rates (amateurs 97% and professionals 95%) than Irish (amateurs 81% and professionals 82%). Greek amateurs and Greek professionals significantly exceeded Irish amateurs (both $p = 0.006$), while Irish groups did not differ from each other. Farmer-initiated communication was rare overall (6%, $\chi^2 = 14.66$, $p = 0.002$, $V = 0.235$), occurring most among Irish amateurs (14%) compared to Greeks (amateurs 1% and professionals 3%), though no pairwise comparisons were significant. Third-party initiation was minimal (3%, $\chi^2 = 9.16$, $p = 0.027$, $V = 0.186$), highest among Irish professionals (18%) but with no significant *post-hoc* differences.

Perceptions of communication quality also differed; Most Irish amateurs rated it as "Very good" (40%), Irish professionals as "Good" (55%), and Greek beekeepers as "Neither good nor bad" (40% for both). Communication quality ratings differed significantly for only one of the five rating categories. "Very good" showed significant differences ($\chi^2 = 16.35$, $p < 0.001$, $V = 0.248$), with Irish amateurs rating quality highest (39%), significantly exceeding Greek amateurs (13%, $p < 0.001$) and Greek professionals (19%, $p = 0.004$). Overall, 52% rated communication quality positively ("Very good" and "Good"), 35% neutrally ("Neither good nor bad"), and 13% negatively ("Bad" and "Very bad"). Irish beekeepers (amateurs 66% and professionals 73% positive) reported higher satisfaction ("Very good" and "Good") compared to Greeks (amateurs 46% and 42% professionals), while Greeks showed more neutral (40% and 41%, respectively) and negative ratings (amateurs 15% and professionals 18%) compared to Irish (amateurs 8% and professionals 0%).

Among beekeepers who currently or previously communicated with farmers about PPP application ($n = 265$, 56% of the total sample), suggestions for improving communication differed significantly across groups for 3 of 5 improvement categories. "Farmers should be more informed on the honey bee-PPPs issue so as to understand the need for communication" was the dominant suggestion (87% overall, $\chi^2 = 20.80$, $p < 0.001$, $V = 0.280$), with Greeks reporting near-universal agreement (94% both amateur and professional), significantly exceeding Irish amateurs (74%, $p < 0.003$ for both). "Beekeepers should be more informed on the honey bee-PPPs issue so as to have better arguments and convince farmers that they need to communicate" also differed significantly (33% overall, $\chi^2 = 12.74$, $p = 0.005$, $V = 0.219$), with Irish reporting higher rates (amateurs 47% and professionals 45%) compared to Greeks (amateurs 26% and professionals 25%) and Irish amateurs significantly higher than Greek professionals ($p < 0.003$). "Don't want something to be improved" showed significant differences ($\chi^2 = 13.00$, $p = 0.005$, $V = 0.221$), reported only by Irish amateurs (7%).

Hive placement within agricultural fields followed similar patterns ($n = 265$, 56% of the total sample). Overall, most beekeepers (61%) had placed their hives within the limits of an agricultural field of a flowering cultivated crop following prior communication with farmers. However, answers differed significantly across groups for both response categories ($\chi^2 = 26.74$, $p < 0.001$, $V = 0.318$). Greek professionals reported the highest rates in having placed their hives within the limits of an agricultural field of a flowering cultivated crop after communicating with the farmer (76%), significantly exceeding Irish amateurs (40%, $p < 0.001$), while Greek amateurs also showed higher positive responses (65%) than Irish amateurs ($p = 0.004$). No significant difference was observed for Irish professionals who answered 73% positively. Conversely, Irish amateurs reported the highest rate of negative replies (60%), significantly more than Greek professionals (24%, $p < 0.001$) and Greek amateurs (35%, $p = 0.004$). No significant difference was identified for Irish professionals who answered 27% negatively.

Among beekeepers who answered negatively in having placed their hives in agricultural fields ($n = 102$, 21% of the total sample), motivations differed significantly only regarding the concern that the use of PPPs will impact honey bees ($\chi^2 = 9.88$, $p = 0.020$, $V = 0.311$). Greek beekeepers reported the highest rates (54% amateurs and 58% professionals) compared to Irish (25% amateurs and 33% professionals), though no pairwise comparisons were significant. Irish amateurs gave the highest response of "Never thought about it" (39%; 27% overall).

Among beekeepers who replied positively ($n = 163$, 34% of the total sample), responsibility for taking the initiative to start the conversation on hive placement differed significantly only for the category of "Other" ($\chi^2 = 11.60$, $p = 0.009$, $V = 0.267$), reported only by Irish amateurs (9%) with no other groups selecting this option, though no pairwise comparisons were significant after Bonferroni correction (all $p > 0.045$). Most answers provided by beekeepers under this category were related to the fact that some beekeepers were not interested in placing their hives within a crop field, either because they had their own land or because they could place their hives adjacent to the field, so they would not require permission. The greatest percentage of beekeepers took the initiative to start the conversation (68% overall), with Irish professionals (87%) and Greek amateurs (70%) being more proactive than Greek professionals (69%) and Irish amateurs (59%). It seems uncommon for a farmer to initiate the conversations (30% overall), especially for Irish professionals (12%), followed by Greek amateurs (29%), Greek professionals (31%) and Irish amateurs (32%).

Beekeepers generally rated their experiences with placing hives in agricultural fields positively ($n = 163$) and no significant differences were identified across response categories. Overall, 64% rated the experience positively ("Very good" and "Good"), 28% neutrally ("Neither good nor bad"), and 8% negatively ("Bad" and "Very bad"). While no *post-hoc* comparisons were conducted due to lack of significant omnibus tests, descriptive patterns showed Irish amateurs (74%), Greek professionals (62%) and Greek amateurs (64%) most satisfied ("Very good" and "Good"), while Irish professionals were most divided between 50% positive and 50% neutral.

Notably, the overwhelming majority of beekeepers who placed their hives within the limits of an agricultural field of a flowering cultivated crop after communicating the farmer ($n = 163$, 34% of the total sample) did not receive money for their contribution to the pollination of the cultivated crop (98%), highlighting the informal nature of such arrangements and the undervaluation of pollination services.

Practices to mitigate PPP impact in beekeeping

The greatest percentage of Irish beekeepers (amateurs 41% and professionals 37%) reported being unable to take any practical steps to protect their colonies from nearby PPP use, in contrast to most Greek beekeepers (amateurs 73% and professionals 65%), who stated they actively avoid placing hives near agricultural areas (Figure 5). The various precautionary measures taken for minimizing PPP exposure differed significantly across the four groups for four of six strategies (all $p < 0.001$). The option "Avoid placing the hives near agricultural areas" showed the largest difference ($\chi^2 = 100.81$, $p < 0.001$, $V = 0.460$), with Greek beekeepers reporting substantially higher percentages (amateurs 73% and

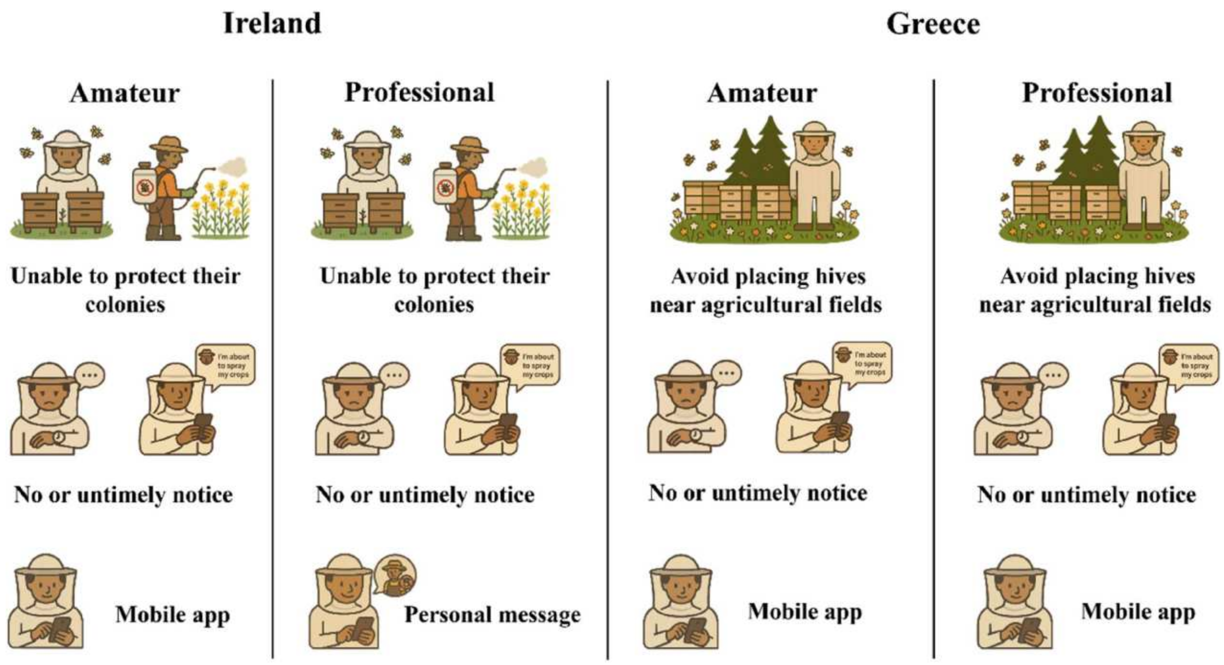

Figure 5. The four different beekeeper profiles based on measures taken by beekeepers for PPP risk management, their communication experiences with farmers regarding timely notifications about PPP applications on crops near their apiaries and their preferred contact method.

professionals 65%) compared to Irish beekeepers (amateurs 23% and 25% professionals). *Post-hoc* comparisons confirmed both Greek groups differed significantly from both Irish groups (all $p \leq 0.005$). The answer "No, I do not take any step" had the second biggest effect ($\chi^2 = 43.88$, $p < 0.001$, $V = 0.304$ for both), indicating that Irish amateurs reported higher rates of taking no protective steps (23%) compared to Greeks amateurs (4%) and Greek professionals (2%) ($p < 0.001$). No significant difference was observed for Irish professionals (12%). Notably, even though the answer "Practically, I cannot take any step" was more popular among Irish beekeepers (amateurs 41% and professionals 37%) compared to Greek (amateurs 33% and professionals 37%), showed no group differences ($p = 0.623$), representing a unanimous constraint.

Current notification frequency before PPP application differed significantly across groups for four of five frequency categories. "Never" was the most common response overall (55%, $\chi^2 = 28.25$, $p < 0.001$, $V = 0.244$), with Irish amateurs reporting the highest rate (68%), statistically exceeding both Greek groups (amateurs 46% and professionals 42%, $p < 0.001$ for both), though this difference should be interpreted cautiously given that the majority of all groups report never receiving notification (42–68%), indicating a universal system failure rather than group-specific problems. "Rarely" also differed significantly (17% overall, $\chi^2 = 28.06$, $p < 0.001$, $V = 0.243$), with Greeks reporting higher rates (30% amateurs, 22% professionals) than Irish amateurs (8%, both $p < 0.001$). "Sometimes" showed differences (15% overall, $\chi^2 = 12.34$, $p = 0.006$, $V = 0.161$), with Greek professionals highest (23%) compared to Irish amateurs (10%, $p = 0.002$). "Always" (6% overall, $\chi^2 = 9.81$, $p = 0.020$, $V = 0.144$) and "Often" (7% overall, $p = 0.235$) were rare across all groups. The critical finding is not the statistical differences between groups, but rather the universal failure across all contexts: only 13% receive regular notification ("Always" plus "Often"), 32% receive inconsistent notification ("Sometimes" and "Rarely"), and 55% never receive notification.

When beekeepers were asked if farmers notified them timely to take the necessary measures for protecting honey bees from PPPs applied on crops, their answers differed across groups for four out of five timeliness categories, but with small or negligible effects. "Never" was the most common response (59% overall, $\chi^2 = 20.70$, $p < 0.001$, $V = 0.209$), with Irish amateurs reporting highest rates (70%), significantly exceeding both Greek groups (amateurs 49% and professionals 50%, $p < 0.001$ for both), though this represents universal failure (44–70% across all groups) rather than group-specific differences (Figure 5). "Rarely" also differed significantly (15% overall, $\chi^2 = 31.03$, $p < 0.001$, $V = 0.255$), with Greeks highest (30% amateurs, 18% professionals) versus Irish amateurs (7%, both $p \leq 0.002$). "Sometimes" showed differences (14% overall, $\chi^2 = 14.52$, $p = 0.002$, $V = 0.175$), with Greek professionals highest (22%), significantly exceeding Irish amateurs (9%, $p < 0.001$). "Always" differed (6% overall, $\chi^2 = 16.29$, $p < 0.001$, $V = 0.185$), with Irish professionals highest (19%) and Irish amateurs (10%), significantly exceeding Greek professionals (1%, $p < 0.004$ and $p < 0.006$, respectively). “Often” showed no differences (6% overall, $p = 0.677$). Overall, only 12% receive consistently timely notification (“Always” and “Often”), 29% receive unreliable timing (“Sometimes” and “Rarely”), and 59% report notifications are never timely.

Among all beekeepers surveyed, the desire for advance notification before farmers apply PPPs near honey bee hives showed no significant differences across groups ($\chi^2 = 7.58$, $p = 0.056$, $V = 0.126$). Overall, 96% of the beekeepers wanted notification, while only 4% did not. Demand ranged from 93% among Irish amateurs to 100% among Irish professionals, with Greek amateurs at 97% and Greek professionals at 98%. The minimal opposition (4%) came primarily from Irish amateurs.

Among beekeepers who wanted to be notified before PPP application ($n = 456$, 96% of the total sample), preferred notification methods showed no significant differences across groups for any of the four method categories (Figure 5); “Mobile phone application” (71% overall, $\chi^2 = 5.42$, $p = 0.143$, $V = 0.109$), “Personal message from the farmer/PPP applicator” (64% overall, $\chi^2 = 4.18$, $p = 0.243$, $V = 0.096$), “Online website” (34% overall, $\chi^2 = 5.24$, $p = 0.155$, $V = 0.107$), and “Other” (2% overall, $\chi^2 = 3.24$, $p = 0.356$, $V = 0.084$). No *post-hoc* comparisons were conducted due to the lack of significant omnibus tests. The pattern reveals a clear preference hierarchy; mobile application (71%) as primary method, personal contact (64%) as important secondary channel, and website portal (34%) as supplemental option, with minimal other methods (2%). Greeks showed slightly higher digital preference (amateurs 72% and professionals 78%) compared to Irish (amateurs 67% and professionals 63%), while Irish professionals showed the highest personal contact preference (87%), though differences were not statistically significant. Other notification channels proposed were contact by email or by a central notification system, but these were not very popular suggestions among participants.

Collaboration with farmers for PPP management and information needs

Among all beekeepers surveyed, beliefs about farmers’ ability to minimize PPP impact on bees differed significantly across groups for two of three response categories (Figure 6). The positive reply showed significant differences (88% overall, $\chi^2 = 17.98$, $p < 0.001$, $V = 0.194$), with Greeks reporting highest confidence toward farmers contribution (amateurs 93% and professionals 95%), significantly exceeding Irish amateurs (82%, $p = 0.007$ and $p < 0.001$, respectively). Irish professionals answered 81%, but no significant difference was observed compared to other groups. Beekeepers who were uncertain about farmers’ contribution to minimise PPP impacts also differed significantly (10% overall, $\chi^2 = 19.93$, $p < 0.001$, $V = 0.205$), with Irish amateurs being more unsure (16%), significantly exceeding Greek professionals (3%, $p < 0.001$). The negative answer showed no significant differences (2% overall, $p = 0.429$), representing a negligible minority across all groups (0.9–6.2%).

Suggestions for improving honey bee protection from PPP use differed significantly across groups for four of six suggested categories. “Farmers could understand that we need to communicate and cooperate” was the dominant suggestion (70% overall, $\chi^2 = 36.32$, $p < 0.001$, $V = 0.276$), with Greeks reporting the highest rates (amateurs 85% and professionals 81%), significantly exceeding Irish amateurs (57%, both $p < 0.001$). Irish professionals’ results showed no significant difference (62%). “Farmers could be easier to reach” also differed significantly (21% overall, $\chi^2 = 25.19$, $p < 0.001$, $V = 0.230$), with Greeks highest (amateurs 27% and professionals 33%) compared to Irish amateurs (12%, $p < 0.001$). Irish professionals’ results showed no significant difference (6%).

Among beekeepers who believe farmers could minimize PPP impact ($n = 468$, 98% of the total sample), strong majorities across all groups supported three complementary interventions (Figure 6); Most beekeepers (79%) selected the option “Farmers could be more informed on the importance of honey bees, their role in pollination, and the potential risks associated with PPP use’ (Greek amateurs 88%, Greek professionals 79%, Irish amateurs 75% and Irish professionals 87%), slightly fewer (77%) selected “Farmers could choose PPPs that are less harmful to honey bees, whenever possible” (Greek amateurs 77%, Greek professionals 70%, Irish amateurs 80% and Irish professionals 93%), and 76% of beekeepers chose “Farmers could notify beekeepers before spraying” (Greek amateurs 76%, Greek professionals 75%, Irish amateurs 75% and Irish professionals at 87%). Only the option “They could be more informed on the importance of honey bees, their role in pollination, and the potential risks associated with PPP use” showed significant differences (79% overall, $\chi^2 = 7.85$, $p = 0.049$, $V = 0.129$), with Greek amateurs highest (88%), though no pairwise comparisons were significant after Bonferroni correction (all $p > 0.009$).

Beekeepers’ desire for more information on how to protect honey bees from the use of PPPs on crops differed significantly across groups ($\chi^2 = 18.09$, $p < 0.001$, $V = 0.195$). Overall, 95% wanted more information, while only 5% did not. Greek

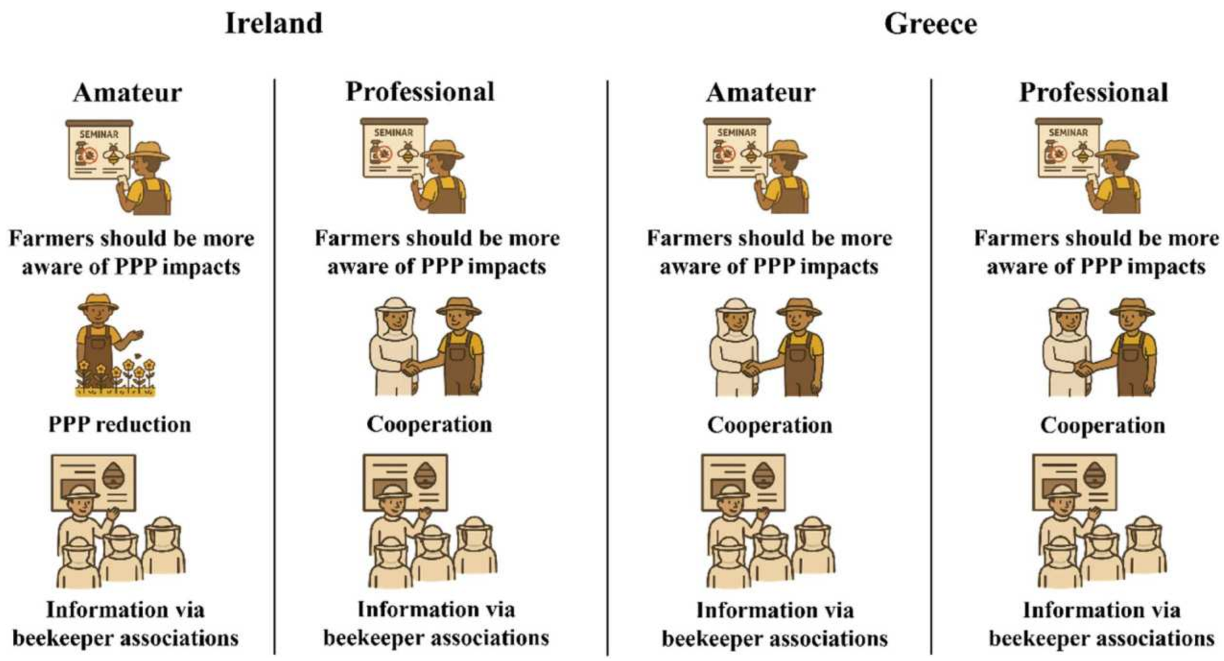

Figure 6. The four different beekeeper profiles based on strengthening beekeeper-farmer knowledge gaps regarding the safe use of PPPs.

professionals showed unanimous interest (100%), significantly exceeding both Irish groups (amateurs 91%, $p = 0.001$; professionals 87%, $p = 0.003$), though the practical difference is modest given that all groups demonstrate overwhelming majority support (88–100%). Greek amateurs also showed near-universal interest (98%).

Overall, the most popular information channels were the beekeeping associations (71%) followed by beekeeping magazines (58%) (Figure 6). The preferred information channels differed significantly across groups for four of 11 channel categories. "Scientific journals" showed strongest differences (33% overall, $\chi^2 = 57.69$, $p < 0.001$, $V = 0.348$), with Greeks preferences (51% amateurs, 45% professionals), significantly exceeding Irish amateurs (15%, both $p < 0.001$). Irish professionals showed no significant difference to other groups (44%). "Live training seminars" also differed substantially (38% overall, $\chi^2 = 56.11$, $p < 0.001$, $V = 0.343$), with Greeks highest (55% amateurs, 54% professionals), significantly exceeding Irish amateurs (20%, both $p < 0.001$). Irish professionals showed no significant difference to other groups (37%).

Beekeeper association membership differed significantly across groups ($\chi^2 = 67.39$, $p < 0.001$, $V = 0.376$). Overall, 78% were association members, while 22% were not. Irish amateurs showed highest membership (93%), significantly exceeding both Greek groups (54% amateurs and 74% professionals, $p < 0.001$ for both). Greek amateurs had the lowest membership (54%), significantly lower than all other groups ($p < 0.002$), apart from Irish professionals (87%, $p = 0.02$).

Discussion

Beekeeping profile and apiary management

The contrast of differing beekeeper categories reflects differing apicultural traditions and economic structures between the two countries. Across Europe, beekeeping is generally dominated by amateurs (Gratzer & Brodschneider, 2021), though a lack of standardized definition for "professional" beekeepers complicates cross-country comparisons (Breeze et al., 2019; Chauzat et al., 2013). As differences in beekeeper status can influence engagement and sectoral representation (Maderson and Wynne-Jones, 2016), separate analysis of amateurs and professionals is needed.

Beekeepers' experience aligned with previous findings (Abou Nader et al., 2023; Makri et al., 2015). Interestingly, significant between-country differences in experience were found, contrasting with earlier reports of greater consistency across Europe (Breeze et al., 2019). The relatively lower experience among Irish amateurs corresponds with recent findings suggesting a younger, amateur beekeeping sector (Smith et al., 2023).

The number of hives was indicative of wider European patterns of hive density (Breeze et al., 2019; Chauzat et al., 2013). Greece leads Europe in hive density and the number of hives, largely driven by nomadic practices, where hives are routinely moved to follow floral resources (Abou Nader et al., 2023; Jara et al., 2020; Kantartzis et al., 2023; Martínez-López et al., 2022). In line with previous European studies (Abou Nader et al., 2023; Breeze et al., 2019), it is suggested that the operational growth is often experience-driven.

Motivations for beekeeping and the use of hive products varied significantly between Irish and Greek respondents, reflecting structural and cultural differences. These findings align with European trends. Greek beekeepers reported longer experience and larger operations, consistent with Greece's status as one of Europe's most commercially intensive beekeeping sectors (Bacandritsos et al., 2004; Chauzat et al., 2013; Makri et al., 2015). Beekeeping in Greece remains integral to rural economies, especially in southern regions where nomadic practices are common (Kantartzis et al., 2023). In contrast, Ireland's beekeeping sector is predominantly amateur and small-scale, with around 2,000 beekeepers managing relatively few hives (Murphy* et al., 2000; Smith et al., 2023). This hobby-based, non-commercial structure (Chauzat et al., 2013; Smith et al., 2023) helps explain the lower number of hives and shorter experience observed among Irish amateurs.

Unlike in the United States, where professional beekeepers often earn substantial income from pollination services, European beekeepers mainly rely on honey and hive product sales (Suryanarayanan & Kleinman, 2014). For Irish amateurs, beekeeping offers food, recreation, and ecological benefits (Burke & Corrigan, 2024), supporting mental well-being and contributing to pollination services (Moore & Kosut, 2013; Pearson & Craig, 2014). While not primarily profit-driven, amateur beekeeping can provide modest economic returns through local sales (Thoms et al., 2019) alongside social and environmental gains. These structural and motivational differences between professional and amateur beekeepers may influence attitudes toward risk perception and management strategies, including behaviors related to PPP use. Understanding these differences is essential for designing appropriate regulatory frameworks and supporting systems tailored to the socio-economic contexts of different beekeeping communities. Apiary placement is a key management decision influencing foraging efficiency, honey yields, and colony health, typically guided by beekeeper experience, seasonal flowering patterns, space availability, and pollination requests (Komasilova et al., 2020). Our findings revealed differences between Irish and Greek beekeepers, reflecting the contrasting agricultural and ecological landscapes of the two countries. Beekeepers in Greece were primarily focused on forest landscapes that could provide bees with honeydew, while Irish beekeepers were taking advantage of wild flowers growing close to cultivated crops in Irish pastoral settings. All forage types showed significant cross-country differences in autumn, indicating this as a critical period for divergent foraging patterns. Forage utilization strongly reflects landscape ecology and beekeeping context: Greek forest landscapes have a tree honeydew dominance while Irish pastoral landscapes with wild plants are more likely to be close to cultivated crops. Professional beekeepers in both countries optimize for their dominant local resources, while amateurs show similar but less intensive patterns.

These preferences in hive placement mirror national land-use patterns. Ireland's agriculture covers over 60% of the land, dominated by intensively managed grasslands primarily for livestock and dairy production (DAFM, 2020). Landscapes are typically monocultures of perennial ryegrass, maintained through reseeding, fertilization, grazing, and silage harvesting, which reduces floral diversity. Flowering crops, though less common, such as oilseed rape and apples, provide important early-season forage (Bottero et al., 2021). Hedgerows, a characteristic feature of Irish farmland, support biodiversity and offer resources for pollinators throughout most of the year.

Conversely, Greek apiaries are often located in forested areas and wildflower-rich landscapes, driven by both ecological and economic considerations. Pine forests are central to Greek apiculture, accounting for over 60% of national honey production (Gounari et al., 2023). Many Greek beekeepers practice nomadic beekeeping, relocating their hives on an average of three times per year to follow floral resources, with professionals migrating more extensively (Kagiali et al., 2023). This movement reflects a strategic preference for natural forage over cultivated fields, ensuring consistent and high-quality nectar sources (Abou Nader et al., 2023; Kagiali et al., 2023).

Landscape structure further differentiates the two countries. Irish farms, combined with hedgerows, create semi-natural corridors that buffer environmental stressors, whereas Greek agricultural landscapes are more fragmented, with smaller fields and minimal field margins due to land-use intensification (Kati et al., 2021). Field-level data from beekeepers are critical for assessing pollinator risks in such fragmented systems, where overlapping PPP applications and diverse cropping patterns create complex exposure scenarios (Kasiotis et al., 2021).

These differences in landscape structure and apiary placement likely influence not only the diversity of bee diets but also the level and nature of exposure to agrochemicals. Beekeepers' mixed attitudes toward mass-flowering crops reflect a tension between forage benefits and PPP risks, often leading to crop avoidance (Breeze et al., 2019). Longstanding conflicts with the farming sector, particularly over ineffective PPP regulations, have intensified frustrations within the beekeeping community (Maderson and Wynne-Jones, 2016). Beekeepers operating in intensively managed agricultural systems may encounter more frequent interactions with PPPs, while those in forested or semi-natural landscapes may perceive lower levels of PPP-related risk. These contextual factors are essential to understanding cross-country differences in risk perception, foraging behaviour, and the implementation of adaptive management strategies by beekeepers.

Beekeepers' perceptions and experiences with PPPs

The beekeepers' perceptions of the potentially negative health impact of PPP on honey bees show a clear hierarchy where insecticides are unanimously perceived as highly likely to impact honey bee health, whereas there are more variable perceptions for herbicides and fungicides. While research findings on PPP impacts on honey bees vary from negligible to moderate (Holder et al., 2018; IPBES, 2016; Tsvetkov et al., 2017; Woodcock et al., 2017), and a lack of clear guidance compels beekeepers to rely on personal experience and media sources (Breeze et al., 2019), beekeepers' perceptions on PPP risk for honey bees in this study align reasonably well with the scientific findings (Feldhaar & Otti, 2020; Motta et al., 2018; Siviter et al., 2021; Tsvetkov et al., 2017). Insecticides are seen as more likely to negatively impact honey bee health, while herbicides and fungicides are seen as a less certain threat, suggesting good risk perception according to current knowledge, although the potential sub-lethal and indirect effects of herbicides and fungicides are less well understood scientifically (Cullen et al., 2019).

Confidence in recognizing symptoms of potential poisoning attributed to the use of PPPs near the hives showed contextual differences. While most beekeepers declared feeling confident, professional status proved more important than geography for symptom recognition ability; both Greek and Irish professionals showed near-identical high observation rate, while amateur certainty varied substantially. Our research findings suggest that the coherence between perceived exposure, worry levels about PPP use, beliefs around potential negative effects on honey bees, and symptom observations, which validates that beekeeper risk perceptions are grounded in direct experience rather than hypothetical concerns. Acute PPP toxicity can result in immediate bee deaths (Graham et al., 2021; Kadlíková et al., 2021), while sub-lethal effects (e.g., disorientation, reduced learning ability, and behavioral changes etc.) may pose long-term colony risks (Vanengelsdorp & Meixner, 2010). Farmers tend to focus only on the risks of insecticides, overlooking the potential harmful effects of non-insecticide PPPs on pollinators (Zhang et al., 2018), whereas local beekeepers are more aware of and concerned about the PPP impacts (Abou Nader et al., 2023). PPP misuse during application remains a leading cause of bee poisonings globally (Kadlíková et al., 2021; USEPA, 2023), emphasizing the urgent need for precise identification of the cause. Given their extensive foraging ranges and environmental interactions, honey bees and hive products are recognized as bioindicators of PPP contamination (Feketéné Ferenczi et al., 2024) and field observations from experienced beekeepers should be also considered.

The elevated concern for PPP use among Greek beekeepers aligns with previous studies reporting agrochemical use as a major issue in rural Greece (Marnasidis et al., 2021; Tampakis et al., 2019) likely reflecting their greater proximity to intensive agriculture and economic dependence on hive productivity. Field studies from Greece confirmed PPP contamination in 73% of bee mortality cases (Kasiotis et al., 2014), illustrating the central role of PPPs in bee health decline. This percentage may have been higher, if nomadic practices in Greece did not further complicate residue analysis, as delayed reporting and sample pooling reduce data reliability (e.g., in the case of evaluating PPP residue levels in dead honey bees) (Kasiotis et al., 2021). Furthermore, Greek beekeepers and especially professionals reported the highest rate of mass dead honey bee observations, significantly exceeding both Greek and Irish amateur groups, indicating potentially increased exposure intensity in intensive agricultural contexts and reflecting greater training and experience. Moreover, Greek beekeepers' higher testing rates suggest stronger commercial pressures. On the other hand, Irish beekeepers show more moderate perceptions in the potential negative PPP impact risk for all categories, but still, the majority are concerned about insecticides. This is consistent with potentially lower perceived exposure and the pastoral context of Ireland. Differences in perceived risks support previous research suggesting that perceptions of PPP risk are influenced by professional status, geographical context, and floral resource availability (Feketéné Ferenczi et al., 2024; López-I-Gelats et al., 2025; Marnasidis et al., 2021).

PPP residue testing of apiary produce revealed stark disparities, with only a very low percentage of beekeepers having ever tested their apiary produce for contamination, indicating a substantial diagnostic gap despite exposure concerns. Professional status demonstrated a strong influence, while country differences were even more pronounced, with Greek professionals leading and Irish amateurs at the lowest, a 12.6-fold difference between extremes reflecting the different exposure contexts. Greek professionals' higher testing engagement stems from commercial stakes justifying laboratory costs, EU honey quality standards requiring residue monitoring, and high-exposure contexts creating diagnostic necessity. Conversely, Irish amateurs face multiple barriers: prohibitive costs for hobby operations with no economic return, low perceived need in pastoral low-exposure contexts, limited procedural knowledge, and less market or regulatory testing pressures.

Among those conducting testing, frequency preferences clustered around moderate annual schedules or event-driven approaches (e.g., when suspecting contamination or observing massive bee deaths), with more frequent testing exclusively adopted by Greek beekeepers, reflecting cost-benefit optimization across operational contexts. Greek professionals favored scheduled annual testing as commercial quality control aligned with harvest cycles, while Irish professionals unanimously preferred event-driven testing only when suspecting contamination, demonstrating a cost-conscious reactive approach for smaller operations, and/or reflecting the paucity of professional testing widely available in Ireland. The consensus for annual testing represents a manageable cost-frequency balance – not too expensive (single annual cost) yet adequate for quality assurance and trend monitoring – while the complete absence of frequent testing among Irish beekeepers reflects prohibitive costs or inaccessibility for hobby operations in low-exposure pastoral contexts without commercial quality requirements. The high overall non-testing rate, despite potential honey bee poisoning incidents, represents a critical diagnostic gap preventing contamination confirmation, exposure quantification, and evidence-based risk management. Policy interventions should prioritize subsidized testing programs, expanded regional laboratory services, simplified procedures, and education campaigns emphasizing diagnostic value, with annual testing as an achievable standard with majority support and event-driven diagnostic testing subsidized for incident investigation, enabling cost-effective expansion from the current 25% testing participation to broader coverage supporting both routine monitoring and responsive problem diagnosis across diverse beekeeping operations.

Of particular concern is that most reported potential poisoning incidents in both countries occurred within 1 km of apiaries and were recorded even in recent years of 2022 and 2023, immediately preceding our survey. Suspected poisoning incidents were taking place when flowering crops were within 1 km, declining at 1–3 and 3–10 km, demonstrating a potential relationship between hive-crop distance and potential honey bee poisoning occurrence incidents. Overall, fruit crops within 1 km represented the highest risk of poisoning incidents, followed by cotton (in Greece) and oilseed rape, with incident patterns reflecting local agricultural practices: Mediterranean crops (cotton, fruits) dominated Greek incidents, while temperate crops (oilseed rape) were more prevalent in Irish incidents. Crops such as citrus, cotton, and sunflower are recognized as important forage sources, yet also present substantial PPP exposure risks. In Greece, about 90% of these crops are treated with PPPs (Balayiannis & Balayiannis, 2008), and crops like cotton, olives, and sunflowers were most frequently avoided by beekeepers due to perceived PPP risks (Abou Nader et al., 2023). Similarly, oilseed rape and sunflower have been both sought and avoided by UK beekeepers based on PPP concerns (Breeze et al., 2019). The 3- to 8-fold decline in incident rates beyond 1 km scientifically validates buffer zone recommendations and supports spatial management as a critical PPP risk mitigation strategy. Geographic specificity was evident, with Greek professionals experiencing the highest cotton-related incidents, reflecting proximity to intensive agriculture, while Irish amateurs showed higher oilseed rape exposure, demonstrating that local crop cultivation patterns rather than universal crop hazards drive context-dependent risk, necessitating regionally adapted protective distance requirements and crop-specific risk assessments in policy frameworks.

Strong seasonal concentration of potential poisoning incidents reinforced these spatial patterns, with spring and summer accounting for most of all cases, while autumn and winter showed sharp declines. Spring represented the peak risk period, dominated by fruit crop incidents reflecting bloom-period PPP applications, with Greek beekeepers experiencing significantly higher exposure. Summer maintained high activity with cotton incidents reflecting intensive treatment periods, again with geographic specificity, since cotton is not cultivated in Ireland. Crop phenology appears to be driving temporal risk patterns: recorded poisoning incidents with fruit orchards in the honey bee foraging area peaked in spring bloom, cotton in summer growth cycles, and oilseed rape during spring flowering. The temporal clustering indicates approximately 80% of incidents occur during two critical windows (spring fruit bloom and summer multi-crop treatments), validating seasonal management strategies and supporting targeted regulatory restrictions during high-risk periods. These patterns demonstrate that effective protection requires both spatial management (distance-based buffers) and temporal management (phenology-based application restrictions), with seasonal hive relocation and bloom-period coordination emerging as essential risk mitigation strategies tailored to regional agricultural calendars and crop cultivation patterns.

Communication and interaction with farmers

Farmer-beekeeper communication revealed widespread failure, with the majority lacking active information exchange. Communication barriers included addressable issues (e.g., never considering communication, lacking approach knowledge etc.) and structural challenges requiring regulatory enforcement, particularly hostile farmer rejection experienced by Greek professionals. Among communicators, profound burden asymmetry emerged with beekeepers overwhelmingly initiating contact. Communication quality showed moderate satisfaction, with only a minority achieving satisfactory coordination. Greek beekeepers' previously established systems deteriorated under agricultural intensification, while Irish amateurs showed the highest isolation due to hobby-scale operations and low perceived risk. Professional status strongly influenced communication success, potentially driven by economic necessity and agricultural networks. Our results indicated a higher level of coordination among professionals and a lower engagement among amateurs, with a preference for non-intensive landscapes. This demonstrates how professional status may influence not only the likelihood of collaboration but also strategic land use for apiary placement. Moreover, these differences likely reflect agricultural intensity and hive placement proximity, with Greek professional beekeepers often needing to negotiate access to agricultural land and PPP application practices with farmers near intensively managed crops (Abou Nader et al., 2023).

The fact that Irish beekeepers did not communicate with farmers in the absence of flowering crops may imply that they do not see a threat from PPP use in cereals or grassland crops, but only when there are flowering crops. However, recent research in Ireland and Europe has demonstrated widespread contamination of flowering resources beyond flowering crops, on sub-lethal levels (Nicholson et al., 2024; Zioga et al., 2022, 2023a, 2023b). In Greece, the primary reasons for the lack of communication were uncertainty about initiating contact and uncooperative farmers. These results suggest that outreach and awareness campaigns could be more effective in Ireland, while conflict resolution and farmer education might be prioritized in Greece.

Among beekeepers who placed their hives in agricultural fields after communicating with the farmer, quality ratings showed no significant differences across groups, with overall moderate positive ratings, substantial neutral responses, and minimal negative ratings, indicating universal moderate satisfaction pattern regardless of country or professional status and leaving room for improvement. Although many Greek beekeepers report good relationships with farmers, ongoing issues persist, such as unclear hive placement arrangements and limited farmer understanding of pollinator roles (Marnasidis et al., 2021). A recurring atmosphere of mistrust has previously been noted, with beekeepers expressing concerns about farmers' PPP practices (Abou Nader et al., 2023), while farmers often believe their precautions are adequate, underestimating PPP risks to non-target organisms. Such disconnects are consistent with broader European patterns where beekeepers avoid certain crops due to PPP concerns, even as farmers express a desire for increased pollination services (Abou Nader et al., 2023; Breeze et al., 2019).

Managed honey bees remain vital to EU agricultural production, complementing the services from wild pollinators (Abou Nader et al., 2023; Potts et al., 2016), but despite their central role, formal pollination service arrangements between farmers and beekeepers remain rare in Europe (Breeze et al., 2014). Most beekeepers in this study received no compensation for pollination services. This corresponds with European trends, where only 2.4% of Greek farmers currently pay for hive rentals (Faure et al., 2023; Marnasidis et al., 2021). Unlike the U.S., where pollination services form a major income source for commercial beekeepers (Suryanarayanan & Kleinman, 2013), European beekeepers are rarely compensated despite their critical contributions to crop production (European Parliament, 2019). In Greece, pollination services are emerging informally, especially in intensive monocultures (Abou Nader et al., 2023). However, most arrangements lack formal contracts, and dissatisfaction persists regarding unclear agreements on responsibilities and PPP management (Abou Nader et al., 2023).

Beekeepers may benefit from increased forage and honey yields of monocultures, but our results mirror other surveys indicating that especially professional beekeepers prioritize reduced PPP exposure, better quality of forage availability, and formal compensation mechanisms (Breeze et al., 2019; Feketéné Ferenczi et al., 2023). Amateur beekeepers, with less hive mobility, particularly advocate for PPP reductions and increased local forage (Breeze et al., 2019). While farmers increasingly recognize the importance of pollination (Breeze et al., 2019), engagement with beekeepers remains limited (Maderson, 2023; Marnasidis et al., 2021) as economic arrangements, liability concerns, and trust issues continue to limit formal partnerships (Abou Nader et al., 2023).

PPP use continues to pose a major barrier, and pollination markets must be carefully regulated to safeguard wild pollinators, who synergistically enhance yields alongside honey bees (Abou Nader et al., 2023; Klein et al., 2003). Disorganization, especially among migratory beekeepers, often limits pollination service potential. Strengthening hive placement systems, enhancing farmer education, and introducing financial incentives like payments for ecosystem services or agri-environmental schemes could support market development (Abou Nader et al., 2023; Marnasidis et al., 2021). Interest in agri-environmental programs is high among both farmers and beekeepers, though motivations differ. Farmers are more willing to participate without subsidies, whereas beekeepers prioritize clear compensation and reduced PPP use (Marnasidis et al., 2021). In Ireland, crops like apples and oilseed rape could greatly benefit from better pollination, yet few farmers actively adapt PPP practices for pollinator safety (Breeze et al., 2019; Burns & Stanley, 2022; Stanley et al., 2013). Addressing these concerns requires systemic reforms that incorporate beekeeper experiential knowledge alongside scientific data (Faure et al., 2023; Maderson & Wynne-Jones, 2016). Long-term sustainability will depend on inclusive governance, institutional innovation, and equitable stakeholder engagement. By breaking down knowledge hierarchies and recognizing beekeepers' critical role, agricultural systems can better align productivity with pollinator conservation.

Managing PPP risk in beekeeping

PPP exposure emerged as a critical concern across all beekeeper groups, reaffirming findings from earlier European research where PPPs were widely rated as a highly relevant threat to honey bee health, particularly in PPP-intensive agricultural regions (Perichon et al., 2024). Our results reveal a difference in the capacity of beekeepers to implement protective measures, shaped by landscape structure, agricultural intensity, and beekeeper mobility.

The different strategies regarding the reduction of PPP exposure between the two countries reflect structural constraints in Ireland, where intensively managed grasslands offer few spatial options for hive isolation in combination with flower rich areas, whereas Greek beekeepers benefit from access to semi-natural landscapes and a tradition of nomadic beekeeping, allowing strategic relocation to reduce PPP exposure. On the other hand, migratory beekeeping systems may further complicate PPP exposure dynamics. Colonies moved between crops are exposed to varying PPP regimes depending on crop type and timing, increasing their risk (Traynor et al., 2016).

However, hive relocation is not always feasible and this may lead beekeepers to take other measures. For example, Greek beekeepers, especially in Thessaly, have publicly urged farmers to avoid daytime PPP spraying to protect bees (Eleftheria Newspaper, 2021). In regions with monoculture and intensive farming, incidents of acute PPP poisoning have fostered distrust and social conflict between farmers and beekeepers (Perichon et al., 2024). Such events, often linked to spring spraying, were perceived as avoidable and highlight beekeepers' feelings of helplessness regarding PPP applications beyond their control (Perichon et al., 2024). These findings emphasize the importance of informed placement strategies and proactive risk management, particularly for commercial operations.

While Greek beekeepers displayed a more proactive, landscape-responsive approach facilitated by hive mobility, Irish beekeepers reported greater limitations in flexibility, emphasizing the need for alternative mitigation strategies such as strengthened beekeeper-farmer communication, timely PPP spray notifications, and regulatory protections in intensive landscapes.

Beekeepers' PPP concerns also drive crop selection behaviors. Consistent with prior studies (Breeze et al., 2019), many beekeepers prioritize crops perceived as safer and avoid those linked to intensive PPP use, although such decisions are often based on personal experience rather than scientific evidence (Abou Nader et al., 2023; Breeze et al., 2019). This reinforces the need for clearer, evidence-based guidance on low-risk farming practices. Risk perceptions also vary with experience, with professional beekeepers relying heavily on personal judgment due to a lack of accessible data (Abou Nader et al., 2023; Breeze et al., 2019). Targeted research and the development of trust-building tools are therefore crucial to support collaborative risk management between beekeepers and farmers.

Widespread concern about PPP risks to bee health was evident across all groups. Notably, many beekeepers in European surveys advocated for stricter limitations on PPP use to protect pollinators (Perichon et al., 2024). These findings underscore the urgent need for improved communication, cooperative planning, and systemic changes to safeguard pollinators in agricultural landscapes.

A key theme emerging from this study is the critical need for timely and reliable communication between farmers and beekeepers regarding PPP applications. Advance notification before PPP applications demonstrated near-universal consensus, representing the strongest agreement observed across the entire survey, indicating notification is universally recognized as fundamental baseline requirement regardless of country, professional status, or agricultural context. This overwhelming demand contrasts starkly with current delivery failures, with the majority reporting notifications never arrive timely enough for protective action across all groups and even when notification occurs, it arrives too late for protective responses like hive relocation or entrance closure. This communication gap significantly increases honey bee exposure risk, emphasizing the need for formalized notification systems. Technology solutions may enable addressing this gap simultaneously through systems where farmers register PPP application plans days ahead, triggering automated instant notifications, solving frequency through mandatory participation and timing through structured advance planning, establishing advance warning as non-negotiable baseline protection measure and transforming the current reality where only a minority receive actionable warnings to universal coverage enabling effective protective coordination. Despite the common need for timely notifications, our results indicate that outreach efforts must be tailored since some beekeeper categories favored digital notifications, while others preferred personal contact, highlighting the need for diversified communication strategies.

Effective collaboration requires coordinated stakeholder practices, such as aligning hive placement and PPP scheduling (Faure et al., 2023). However, relying solely on voluntary farmer notifications has been criticized as ineffective, with many beekeepers noting that notifications are often missing or delayed (Maderson & Wynne-Jones, 2016). Challenges such as unpredictable PPP application schedules and competition for PPP-free sites further undermine informal risk mitigation efforts (Maderson, 2023). Although general recommendations for reducing PPP exposure exist, systematic evaluations of new mitigation techniques are limited (Zhang et al., 2023). While relocating or sealing hives during PPP applications are recommended strategies, they are logistically challenging due to factors like weather variability, changing spray schedules, and high operational costs (Zhang et al., 2023). Successful protective measures depend fundamentally on timely, reliable communication.

Formalized notification systems, such as SMS alerts, web-based platforms, or hive location registries, have been recommended as best management practices (NASDA, 2015). Beekeeping associations and agricultural extension services could facilitate these efforts, encouraging farmers to notify beekeepers before spraying and prompting beekeepers to share hive placement plans to support coordinated actions. Examples of successful collaboration already exist. In the UK, the voluntary "BeeConnected" scheme (BeeConnected, 2025) alerts nearby beekeepers of planned spray events. In Ireland, the All-Ireland Pollinator Plan promotes best practices for grower-beekeeper cooperation, integrating diverse stakeholders into national conservation efforts (All-Ireland Pollinator Plan, 2025).

Despite these initiatives, many beekeepers still rely on informal relationships for information, underscoring the importance of trust-building and regular stakeholder engagement. European studies show that farmers and beekeepers are willing to increase dialogue about pollination services and PPP use, reinforcing the collaborative opportunities highlighted in our findings (Breeze et al., 2019). Nonetheless, tension persists between conventional scientific assessments and beekeepers' lived experiences. Beekeepers often detect subtle, sub-lethal impacts not captured by traditional risk models, reinforcing the need to integrate experiential knowledge into regulatory frameworks (Maderson and Wynne-Jones, 2016).

Farmer awareness gaps also persist. Many farmers underestimate the risks that insecticides, fungicides, and herbicides pose to pollinators, revealing a critical disconnect in risk perception (Marnasidis et al., 2021). Currently, beekeepers optimistically believe farmers can help, yet continue experiencing preventable harm. Capability recognition without knowledge and motivation fails to generate protective action. However, the connection between beekeepers' beliefs and their education requests is revealing. Most beekeepers believe farmers can minimize PPP negative impacts, and most also desire farmer education. This suggests the problem is that farmers do not understand rather than cannot help. Education therefore represents a solution that unlocks existing potential rather than creating new capabilities. The overwhelming confidence in farmer capability, combined with near-universal education requests, creates a clear policy mandate. Interventions should focus on addressing knowledge and motivation barriers rather than technical impossibility. This validates investment in comprehensive mandatory training covering honey bee biology, pollination ecosystem services, PPP impact mitigation, and best management practices. Such training would transform recognized capability into obligated performance.

Among beekeepers who believe farmers could minimize PPP impacts, three suggested methods received remarkably similar support: farmer education, use of less harmful products, and advance notification. This three-way tie indicates recognition that comprehensive protection requires multiple integrated interventions rather than single-solution approaches. Greeks emphasized education most strongly, aligning with their protection improvement requests. This reflects direct experience with farmer knowledge gaps in intensive agriculture contexts. Irish beekeepers showed slightly higher support for safer products, consistent with a chemical reform focus addressing root causes. The three-tier solution pattern mirrors protection priorities. It demonstrates consistent recognition that effective bee protection requires farmer knowledge transformation, chemical regulatory reform, and mandatory communication systems working synergistically. No single measure alone has proven sufficient. Voluntary frameworks have failed to deliver protection at the scale needed by beekeepers who demand advance warning from farmers who currently rarely initiate communication.

Desire for additional information about PPP-bee interactions revealed near-universal appetite for education. Greek professionals' unanimous information seeking reflects economic necessity driven by high exposure contexts. Commercial stakes require evidence-based practice, and agricultural integration demands PPP knowledge for operational survival. This finding complements earlier results where substantial proportions requested farmer education. It demonstrates that beekeepers recognize dual knowledge needs (their own and farmers'), creating a comprehensive mandate for bidirectional educational interventions. The present survey findings combine to provide a complete implementation pathway; Beekeepers have documented problems through universal observations, they have identified solutions including notification systems and communication frameworks, they have demonstrated engagement readiness and specified preferred delivery mechanisms such as beekeeper associations, beekeeping magazines, and social media. These elements validate that policy interventions will encounter a receptive audience. Information-seeking stakeholders are ready to transform knowledge into protective action. This supports a systemic shift from current protection failures to effective farmer-beekeeper coordination that minimizes agricultural PPP impacts on pollinator populations.

The relationship between beekeeping and PPPs has evolved from early conflicts (e.g., the oilseed rape-related bee deaths in Britain during the 1970s) to more collaborative models like the "BeeConnected" platform (BeeConnected, 2025; Carreck, 2017). Effective communication remains central to pollinator protection, and, as our findings suggest, expanding structured notification systems, strengthening education, and fostering inclusive engagement hold significant promise for advancing collaboration and safeguarding pollinator health.

Filling beekeeper-farmer knowledge gaps

Protecting pollinators in modern agriculture requires bridging communication gaps, addressing regulatory shortcomings, and fostering collaborative, landscape-scale strategies. Beekeepers in both Greece and Ireland strongly emphasized the need for improved communication with farmers, particularly regarding PPP application timing and pollinator risks.

Both in our study and at a European context, beekeepers advocate for PPP reduction rather than outright bans (Breeze et al., 2019). Nevertheless, barriers to effective PPP risk mitigation persist, particularly due to inconsistent or vague application guidelines. Although regulations recommend applying insecticides during non-foraging hours, many PPP labels neglect fungicide and herbicide risks and fail to account for regional agricultural conditions (Karbassioon & Stanley, 2023; Straw et al., 2021). Fungicides and herbicides, long considered harmless, also contribute to sub-lethal effects on pollinators (Belsky & Joshi, 2020; Farina et al., 2019; Straw & Brown, 2021). While Irish farmers generally comply with EU standards for PPP use, adherence to bee-specific guidelines remains inconsistent (Straw et al., 2023). In Greece, compliance challenges are greater since 37% of farmers disregard label instructions, and many rarely follow pollinator protection measures (Hellenic Ministry of Rural Development & Food, 2018; Marnasidis et al., 2021). These findings align with global patterns of PPP misuse and unsafe practices (Fikadu, 2020; Shegaw et al., 2022; Teshome et al., 2023), underlining the need for stronger regulation, clearer labels and targeted farmer training (Decourtye et al., 2023).

Importantly, beekeepers' experiential knowledge remains underutilized. Beekeepers often detect PPP risks and forage deficits before formal scientific monitoring (Maderson, 2023). Initiatives like INSIGNIA show that beekeepers can successfully collect environmental data, motivated by stewardship (Gratzer & Brodschneider, 2021). However, beekeepers' knowledge is often marginalized in policymaking (Maderson and Wynne-Jones, 2016; Durant, 2020). Many criticize agricultural policies for prioritizing economic intensification over ecological health and perceive conservation efforts as superficial when broader systemic drivers, like habitat loss, remain unaddressed (Maderson and Wynne-Jones, 2016). This exclusion risks undermining trust, particularly when PPP enforcement is weak or non-existent (Johnston et al., 2014; Perichon et al., 2024).

Nonetheless, beekeepers consistently identified opportunities for improved cooperation with farmers, advocating for better education, reduced PPP use, and structured communication channels. Their high rates of association membership present an opportunity for building capacity and driving change. The alignment between three findings creates a complete implementation pathway. The vast majority want information, most prefer beekeeping associations as the delivery channel, and a substantial majority are members of such organizations. This enables immediate education program deployment through trusted community networks. Regional strategies should be tailored to existing infrastructure. Irish associations have near-universal coverage, allowing immediate implementation. Greek association infrastructure requires strengthening through new chapter development and targeted recruitment. These approaches will maximize the reach of educational interventions that support mandatory notification compliance, farmer-beekeeper coordination, and comprehensive PPP risk management. Success requires multi-channel, culturally-adapted information dissemination across diverse beekeeping contexts.

To foster inclusivity, local pollinator protection guidelines should be co-developed by beekeepers, farmers, and advisors. The All-Ireland Pollinator Plan serves as a strong model for stakeholder collaboration (All-Ireland Pollinator Plan, 2025), while Greek beekeeping unions have called for a national pollinator action plan (Johnston et al., 2014). Practical steps such as advance PPP application notifications, strategies like Integrated Pest and Pollinator Management, and rewarding pollinator-friendly practices through agri-environment schemes and co-designed pollinator protection plans could bridge current gaps (Cass et al., 2022; Kleftodimos et al., 2021; Zhang et al., 2018). Both Ireland and Greece are bound by EU mandates to increase integrated pest management adoption, but localized education and demonstration projects are needed to make this goal actionable (European Commission, 2023).

Looking ahead, several key research priorities emerge to support more sustainable and pollinator-friendly agricultural systems. First, there is a need to evaluate the effectiveness of communication tools (e.g., mobile apps, liaison committees, and notification platforms) in reducing PPP-related bee mortality and enhancing pollination outcomes. Second, research should explore market models for pollination services across a broader spectrum of crops to better understand their economic viability and potential for scaling. Third, expanding field studies on landscape-scale PPP impacts is essential, particularly those examining how managed and wild pollinators can be jointly leveraged to optimize crop yields while maintaining biodiversity (Potts et al., 2016; Zhang et al., 2023). Lastly, greater investment in beekeeper-led citizen science initiatives could generate valuable, large-scale data on environmental contaminants and pollinator health, strengthening both local decision-making and evidence-based policy development.

Our cross-country analysis reaffirms the tight interdependence of agriculture and apiculture. Achieving sustainable farming and pollinator conservation requires synergistic efforts combining scientific evidence, regulatory reform, and local ecological knowledge. Promising initiatives, such as Ireland's cross-jurisdictional strategy (the All-Ireland Pollinator Plan) and Greek beekeeper advocacy, alongside broader EU PPP reduction goals (Perichon et al., 2024), demonstrate that inclusive, informed collaboration is the most effective path forward. While national contexts differ, the fundamental solution is universal: partnerships between farmers, beekeepers, scientists, and policymakers are essential for creating resilient agricultural ecosystems where pollinator protection and crop productivity can thrive together.

Conclusions

This study provides a comparative overview of beekeeping practices, PPP risk perceptions, and mitigation behaviors among Irish and Greek beekeepers, highlighting differences shaped by professional status, national context, and environmental conditions. Greek beekeepers, particularly professionals, managed larger operations and employed more proactive risk management, while Irish beekeepers – mostly amateurs – reported less engagement with farmers and more challenges in mitigating PPP risks. Nevertheless, broad consensus emerged across both countries on the harmful effects of PPPs, with insecticides perceived as the greatest threat. The findings emphasize the need to improve beekeeper-farmer communication, ensure timely notification of PPP applications, and promote education on pollinator-friendly practices. Targeted interventions, particularly for amateurs, could enhance residue testing, hive placement decisions, and collaboration with farmers. Beekeeping associations have a key role in supporting these efforts by facilitating information exchange and advocating for policies that prioritize pollinator health. While this study advances understanding of local context in shaping PPP risk management, certain limitations exist. The online survey format may have introduced selection bias, favoring digitally active beekeepers, and findings may not fully represent national trends, especially regarding geographic hive distribution. Regardless, strengthening beekeeper-farmer collaboration, increasing awareness of PPP risks, and supporting amateur and small-scale beekeepers through education and infrastructure could significantly support pollinator protection efforts in both countries. Future research should focus on evaluating the effectiveness of communication tools and real-world mitigation strategies, as well as identifying regulatory and cultural barriers to cooperation within agro-ecosystems. Overall, enhancing the sustainability of beekeeping in agricultural landscapes requires integrated efforts that combine scientific knowledge, practical tools, and inclusive stakeholder engagement. Building partnerships across the food production system is essential to ensure honey bees, wild pollinators, and agriculture thrive together under increasing environmental pressures.

Disclosure statement

E. Zioga is currently employed by the European Food Safety Authority. However, the work described here was conducted independently at Trinity College Dublin, prior to employment with EFSA. J. Stout declares no conflicts of interest.

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Data availability statement

The dataset associated with this study are not publicly accessible due to confidentiality concerns, as they contain information that could potentially compromise participant consent agreements. Informed consent was obtained from all participants.

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