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REVIEW

How effective are artificial nests in attracting bees? A review

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Abstract

Background: Recent declines in bee populations, along with increasing demand for pollination services in urban, agricultural, and natural environments, have led to strategies to attract wild bees to these areas. One of these strategies is installing artificial nests adjacent to urban gardens and agricultural farms. Bee hotels and nest boxes are among the artificial nests used by gardeners and farmers to attract pollinators. In this paper, we reviewed 50 studies that reported the efficiency of nest boxes and bee hotels in attracting bees. We considered the maximum occupation rate (percentage) as the main index to evaluate the efficiency of artificial nests.

Results: The maximum occupation rate of bee hotels was higher in farms (averaged 44.1%) than in forests (averaged 30.3%) and urban (averaged 38.3%) environments. In the case of nest boxes, most studies reported efficiencies of less than 20%, with an occupation rate of 16% and 5.5% on average in forest and urban environments respectively. However, our meta-analysis results showed that there was no significant relationship between the occupation rate of the nests and their installation place. Regression analysis also showed that the structural features of bee hotels (length and diameter) and nest boxes (volume and entrance size) did not affect their efficiency in attracting bees.

Conclusion: Our data showed that the strategy of installing artificial nests to attract pollinators is successful only concerning bee hotels, and the use of nest boxes has not been very successful.

Keywords: Artificial nests, Bee hotels, Nest boxes, Wild bees, Pollination

Introduction

About 75% of the world's agricultural products, known as human food, are dependent on pollinating insects (Klein et al., 2007). In recent years, there has been global concern about the decline of pollinators around the world (Viana et al., 2012). This concern has led to further studies identifying pollinator threats in agricultural and natural systems. Most of these studies address landscape changes due to habitat loss and fragmentation known as primary threats to pollination (Winfree et al., 2009). Although farmers typically use honeybees to pollinate their crops (Ontiri et al., 2019), the recent decline in their activity and population (Kulhanek et al., 2017; Potts et al., 2010) has led to a greater focus on wild bees and their function in nature. Several studies have shown that wild pollinators enhance the fruit set of crops regardless of honey bee abundance (Garibaldi et al., 2013). For example, for some crops such as blueberries, wild bees are more efficient than honeybees (Kevan et al., 1990). Many wild bees such as bumblebees (*Bombus* spp.), mason bees (*Osmia* spp.), the alfalfa leafcutter bee (*Megachile rotundata*), and stingless bees (*Meliponini* spp.) are reared to pollinate crops (Eeraerts, 2020).

Recent declines in the honeybee population, along with increasing demand for pollination services in urban, agricultural, and natural environments, have led to strategies to increase and attract pollinators to these areas. Bees need two basic resources, food and nesting habitat (Olsson et al., 2015). The proximity of the nesting habitat and floral resources increases the diversity of

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pollinators and consequently pollination (Holzschuh et al., 2012). More pollinators can be attracted to the fields by creating suitable nests. However, there are more than 20,000 bees with different habitat nesting requirements. Therefore, it is difficult to determine the nesting type of different bees in different environments. Identifying the nesting type of bees is critical in attracting these species to urban gardens and agricultural fields by installing artificial nests. For example, bumblebees, honeybees, and stingless bees are eusocial and are among the above-ground nesting bees (Bennett and Lovell, 2019). Stingless bees are the most diverse social bees, and many of them depend on natural cavities to form colonies (Silva et al., 2014). In natural environments such as forests, they nest in tree hollows. About 70% of solitary bees nest in the ground (Frankie et al., 2009).

Many crops that are grown in the city, such as cucumbers, tomatoes, watermelons, strawberries, peppers, and eggplants, require pollinators to produce the crop (Matteson and Langellotto, 2009). Pollination is a vital ecosystem service not only in natural ecosystems but also in cities (Theodorou et al., 2020). In urban environments, bumblebees and honeybees have been identified as dominant species (Bennett and Lovell, 2019; Garbuzov et al., 2017; Giovanetti et al., 2020; MacIvor et al., 2015; Mazzeo and Torretta, 2015). Some studies have reported a higher proportion of solitary bees (Lerman and Milam, 2016), and some have found an equal proportion of the sociality and solidarity of bees (Fetridge et al., 2008) in urban environments. Some studies have claimed that urban farms and gardens are short of pollinators, and to increase agricultural production on urban farms, we need to increase the pollination supply in cities by creating new floral resources around urban farms (Davis et al., 2017). For urban agriculture, the availability of food and nesting habitats around farms is critical to attracting pollinators (Bennett and Lovell, 2019).

One of the strategies to attract pollinators to farms and urban environments is to create artificial nests. These nests are used to study, monitor, and increase bee populations (Leonard and Harmon-Threatt, 2019). These nests differ in design, size, function, and type of materials used for construction. For example, to attract social bees such as honeybees and bumblebees, nest boxes are used that have different dimensions and usually have a big hole as an entrance. The volume of these nest boxes varies from 1 liter to several liters depending on the type of species and the study area. Nest boxes are also used to attract small mammals and birds. Another type of artificial nest that is mostly used to attract solitary bees, especially in urban environments, is bee hotels. Bee hotels also vary in size, design, type of materials used in construction, and function. Bee hotels include nests that have multiple holes or tubes. The diameter of these holes and the length of the tubes vary and affect the efficiency of bee hotels in attracting bees. Today, the use of artificial nests is limited to above-ground, cavity-nesting species, a group that comprises less than 15% of all bee species (Michener, 2000).

So far, various studies have used nest boxes and bee hotels to sample and monitor bees. Another purpose of these studies is to evaluate the efficiency of artificial nests in attracting pollinators to these nests. Understanding the efficiency of these artificial nests determines the success (or lack of it) of the strategy of creating artificial nests on agricultural farms and urban gardens. Therefore, it is necessary to pay more attention to the efficiency of artificial nests in attracting pollinators. To date, various reviews have examined different aspects of artificial nests such as the effects of color, design, and type of materials used to build artificial nests in attracting bees (Leonard and Harmon-Threatt, 2019; MacIvor, 2017; Staab et al., 2018). However, none of these studies has provided a single and straightforward conclusion about the efficiency of these nests in attracting pollinators. Therefore, in this study, we intend to present the results of various studies that have reported the efficiency of artificial nests in augmenting pollinators in a categorized manner. The most important questions that our study will respond to are (1) How effective are artificial nests in attracting pollinators? (2) Do the structural features of bee hotels (length and diameter) and nest boxes (volume and entrance size) affect their occupation rate? (3) Does the installation place (forest, farm, and urban) of artificial nest affects their occupation rate?

Methods

We searched for published studies using the ISI Web of Science. We conducted our search from May 1991 to May 2021 using the following search string: (bee hotel* OR nest box* OR artificial nest*) AND (Bee*). Nearly 316 articles were obtained, leaving 265 unique articles after the duplicate articles were removed. We were only looking for articles that examined the efficiency of artificial nests in attracting bees that would help our knowledge to increase the bee population by installing artificial nests for bees. After reviewing the titles and abstracts of the articles, 50 articles remained that were related to our goals. We recorded the most important results of these articles. We divided the results of these studies into two general sections: bee hotels and nest boxes. In this study, we considered nests that had several tubes or drilled holes as bee hotels and nests having a box shape and one large hole for entrance as nest boxes (Fig. 1).

According to the location of installation, we divided these studies' hotels into three general categories: urban environments, farms, and natural areas such as forests.

Fig. 1 Examples of bee hotels (**A**) and nest boxes (**B**). Bee hotels have hollows or tubes with different lengths and diameters. Nest boxes have only one hole, which is large in diameter

The occupation rate of bee hotels in these studies is reported according to the number of occupied nests or the number of occupied tubes. In some studies, bee hotels have different structural features and have been installed in different locations; therefore, there is a minimum and maximum occupation rate according to different conditions. In this study, we only reported the maximum occupation rate per study. The species column indicates the number or type of species that have been attracted to bee hotels. In some studies, bee hotels have been used for only a predetermined species. The material column represents the materials used in the construction of bee hotels. Bee hotels have several tubes or straws that vary in length and diameter. In Table 1, the length of the tubes is in centimeters and their diameter is in millimeters. In the last column, the key results of each study are reported. In Table 2, the maximum occupation rate, type, and the number of settled species, materials used in construction, volume (liter), and entrance diameter (cm) of nest boxes are reported.

Meta-analysis

In bee hotels, the length and diameter of the tubes have been reported as factors influencing the efficiency of these nests in attracting bees. In nest boxes, the volume and the entrance size are influential factors. To investigate the statistical relationship between the mentioned factors and the occupation rate of bee hotels and nest boxes, we used Pearson correlation (r) and regression analysis. For this purpose, the occupation rate of the artificial nests was considered as a dependent variable, the diameter, length, and entrance size were considered as independent variables. We used one-way ANOVA test to determine whether the installation place of artificial nests affects their occupancy rate.

Results

Bee hotels

Table 1 shows the details of studies that have applied bee hotels to attract or trap bees. Of the 36 studies we reviewed, 11 were conducted in Brazil (30%), the highest among the countries. After Brazil, the United States is next with eight studies. Most of the reviewed studies have been done in natural environments such as forests and pastures (44.5%), followed by agricultural farms with 35% and urban areas with 19.5% in the next categories. The maximum occupation rate of nests by bees is different depending on the installation location of bee hotels. In agricultural farms, the maximum occupation rate is reported to be between 11 and 100% (on average 42%). In natural areas such as forests and pastures, this rate is reported to be between 3 and 73% (on average 30%). In urban areas, the maximum occupation rate is reported to be between 7 and 75% (on average 38%).

Although some studies have not provided a clear list of identified species, species of the genus *Osmia* or mason bees are reported to be more common (22%) than other species in occupied nests. In addition to wild bees, wasps can also occupy a significant proportion of bee hotels, as 27% of the studies have reported the presence of wasps in bee hotels. Forty-one percent of the studies reported that the bee hotels were made of wood, bamboo, and cardboard are used equally (22%). The length of the tubes used in these studies varies from 1.4 to 28 cm, with an average of 11.3 cm. The diameter of these tubes varies from 2 to 25 mm, with an average of 7.2 mm.

Some of the results of these studies have dealt with the effects of the length of the tubes used for bee hotels. For example, Bosch (1994) found that tubes with a length of 12 cm were less occupied by *Osmia cornuta* than longer ones. Rebouças et al. (2018) also stated that large straws were significantly more occupied than small straws. Others have discussed the effects of tube diameter in the efficiency of bee hotels in attracting bees, for example, Westerfelt et al. (2015) claimed that hole diameter was the most important factor explaining the occupation of a certain aculeate species. Oliveira and Schlindwein (2009) reported that females of *Centris analis* used only tubes with 6-, 7-, and 8-mm diameters. dos Santos et al. (2020) also found that tubes with a 6-mm diameter were mostly occupied by *Megachile zaptlana*. Alvarez et al. (2012) found that *Megachile concinna* showed a preference for cavities of 6- and 5-mm

Table 1 Country, place of installation, maximum occupation rate, type and number of attracted species, materials used in the construction, tube length (cm), diameter (mm), and key results of studies that have used hotels to attract or trap bees

Reference	Country	Place	Occupation rate	Species	Material	Length	Diameter	Key results
(Bosch, 1994)	Spain	Farm	29%	*Osmia cornuta*	Milk cartons	12, 15, 18	8	12-cm straws were less accepted than longer straws.
(Stubbs et al., 1997)	USA	Farm	30%	*Osmia*	Wood	14	8	*Osmia* populations increased in two of the three fields that had trap-nest blocks provided.
(Wilkaniec and Giejdasz, 2003)	Poland	Farm	100%	*Osmia rufa*	Reed, Plastic	8, 22	5,6,9	All tubes made of straw and printer sheeting were occupied.
(Oliveira and Schlindwein, 2009)	Brazil	Farm	22%	*Cenris. analis*	Cardboard	7.5, 8.5	5,6,7,8,12	Females of *Centris analis* used only tubes with 6-, 7-, and 8-mm diameters.
(Junqueira et al., 2012)	Brazil	Farm	21%	Carpenter Bees	Bamboo	25	14,24	Supplying a bee shelter with a combination of suitably sized empty bamboo stalks can increase the population of actively nesting bees by 200%.
(Fabian et al., 2014)	Switzerland	Farm	13%	13 bees and wasps	Plastic	20	2,10	The most abundant bee species was the Red Mason bee.
(Artz et al., 2014)	USA	Farm	31%	*O. lignaria, Apis mellifera*	Cardboard	15	7.5	The color of the nest box that surrounds the bee hotels affect its attractiveness.
(McCallum et al., 2018)	Canada	Farm	71%	61 *O. tersula*, 34 *Megachile*, 10 wasps	Wood, milk carton	8	7,9	Bees nested more in tubes of milk cartons (71%) than wooden nests.
(dos Santos et al., 2020)	Brazil	Farm	20%	*Megachile zaptlana*	Wood	7, 10	4,5,6,8,12	Bees mostly occupied tubes having a 6-mm diameter.
(Martínez-Núñez et al., 2020)	Spain	Farm	33%	Solitary bees	Bamboo, Reed	6, 12, 20	4,7,12	Organic fields had higher colonization rates than their control farms.
(Wilson et al., 2020a)	USA	Farm	100%	*Megachile rotundata*	Plastic	7.8	7	Cavity temperature varied by the direction the cavity faced and by the position of the cavity within the nest box.
(Graham et al., 2020)	Canada	Farm	11%	*Megachile pugnata, Osmia caerulescens*	Reed	8	6	We found significantly greater nesting at farms with wildflower plantings.
(Eeraerts, 2020)	Belgium	Farm	71%	Mason bee	Wood, cardboard	13, 12	8	Cardboard tubes reduce the infestation rate of mites by 81.8%.
(Barthell et al., 1998)	USA	Mixed natural	42%	Bees, wasps, and exotic	Cardboard	10	5,6.5,8	Native species never accounted for >25% of all occupied nesting cavities of either monitoring period of the study.
(Armbrust, 2004)	USA	Mountain	56%	*Megachilidae*	Wood	1.4	8	The nesting rate changed significantly according to the season.
(Jenkins and Matthews, 2004)	USA	Forest	34.7%	*Aculeate Hymenoptera*	Wood	8	6.4,9.5,12.7	Bees (*Osmia. albiventris and Megachile. frigida*) nested early in the season (April–May).
(Buschini, 2006)	Brazil	Forest, Swamp	20%	*Megachilidae, Apidae*	Wood	8	7,10,13	Swamp habitat yielded the greatest abundance and diversity of bee species.
(Kamke et al., 2008)	Brazil	Forest	25%	*Eufriesea smaragdina*	Bamboo	7, 9, 20	5,7,10,25	The activity of *Eufriesea smaragdina* bees was seasonal.
(Taki et al., 2008)	Canada	Forest	35%	12 wasps	Milk carton	15	3,5,7,9	The artificial covering on trap nests improves the colonization of trap-nesting wasps.
(Guisse and Miller, 2011)	USA	Forest	3.2%	*Osmia lignaria*	Cardboard	14	7	Nest number per site was positively correlated with proximity to water, but negatively with elevation
(Dorado	Argentina	Pasture	42%	7 solitary	Wood	15	5,8	Trap nest sampling was good for estimating

Table 1 Country, place of installation, maximum occupation rate, type and number of attracted species, materials used in the construction, tube length (cm), diameter (mm), and key results of studies that have used hotels to attract or trap bees *(Continued)*

Reference	Country	Place	Occupation rate	Species	Material	Length	Diameter	Key results
et al., 2011)				bees				rare species degree.
(Torretta et al., 2014)	Argentina	Forest	7%	*Megachlie catamarcensis*	Wood	-	-	*Megachile catamarcensis* uses petals and/or leaf pieces and mud as nest materials.
(Westerfelt et al., 2015)	Sweden	Forest	30%	Bees, Wasp	Wood	4.5, 6.5, 8	3,5,7,10	The hole diameter was the most important factor explaining the occupation of a certain aculeate species.
(Peralta et al., 2017)	Argentina	Pasture	14%	Wood-nesting bees	Wood	15, 28	5,8,11	Trap nests contained pollen from forty five plant species
(Iantas et al., 2017)	Brazil	Forest and farm	73%	6 bees, 12 wasp (91%)	Wood	8	5,7,10,13	The grape organic fields presented the highest number of nests.
(Rebouças et al., 2018)	Brazil	Forest	28%	5 bees	Cardboard; Bamboo	5.8, 10.5, 22	6,8,16	Large straws were significantly more occupied than small straws.
(Guimaraes-Brasil et al., 2020)	Brazil	Forest	18%	6 *Apidae, Megachilidae*	Bamboo, Cardboard	20	3,5	Nesting preference was observed for certain types of substrates with bamboo internodes being preferred by bees to build their nests.
(Araújo et al., 2020)	Brazil	Forest, Pasture	16.7%	14 Solitary bees, 26 wasps	Wood	10	8,12,16,20	All types of reforestation studied were successful in maintaining a greater diversity of bees and wasps.
(Wilson et al., 2020b)	Australia	Forests and orchards	36%	13 bees; 28 wasps (74%)	Wood	10,15	6,8	More species of bees and wasps used hotels in the wet season (spring-summer).
(Gaston et al., 2005)	UK	Urban	45%	Solitary bees	Bamboo	4, 9, 10, 11	4,6,8,10	Bamboo sections and 4mm holes in the wooden blocks were used in more than half of the gardens.
(Loyola and Martins, 2011)	Brazil	Urban forest	16%	7 bees (25%); 4 wasps (75%)	Wood	11	6,9,12	Increase in wasp, but not bee species richness following an increase in sampling unit size (25, 100, and 400 m^2).
(Alvarez et al., 2012)	Argentina	Urban	37%	*Megachlie concinna*	Wood	6	4,5,6	*Megachlie concinna* showed a marked preference for cavities of 6 and 5-mm diameter with 88.2 % compared with only 11.8% of 4 mm.
(MacIvor and Packer, 2015)	Canada	Urban	75%	31 *Megachildae,* Apidae	Cardboard	15	3,5,7	Native wasps were significantly more abundant than both native and introduced bees and occupied almost 3/4 of all bee hotels each year
(von Königslöw et al., 2019)	Germany	Urban	31%	22 Bees (49%), 6 Wasps	Bamboo, Reed	5, 8, 13, 20	4,6,8,9	Cavities with diameters between 4 and 8 mm were occupied most often.
(Geslin et al., 2020)	France	Urban	57%	*Megachile sculpturalis, Osmia*	Trunk, Bamboo	20	6,8,10,12	The most abundant species that emerged from bee hotels was the exotic bee species *Megachile sculpturalis*.
(Boff and Friedel, 2020)	Brazil	Urban	7%	*Centris analis*	Wood	12	6,8	Females preferred to nest in painted nests compared to unpainted nests, with blue nests being the most occupied ones.

diameter with 88.2 % compared with only 11.8% for 4 mm. Gaston et al. (2005) also found that tubes with 4-mm diameter in the wooden blocks were used more. von Königslöw et al. (2019) stated that tubes with diameters between 4 and 8 mm were occupied most often.

The material of the tubes also affects the efficiency of bee hotels in attracting bees. For example, Wilkaniec and Giejdasz (2003) stated that all tubes made of straw and printer sheeting were occupied by *Osmia rufa*, but in plastic straws, the occupation rate was 80%. McCallum et al. (2018) found that nest occupation was significantly affected by nest design, with more bees nesting in tubes of milk cartons (71%) than wooden nests. Guimaraes-Brasil et al. (2020) found that there was a nesting preference for bamboo internodes by bees to build their nests. Gaston et al. (2005) found that bamboo tubes were used in more than materials. Fernandes et al. (2020) also claimed that cardboard tubes reduce the

Table 2 Country, place of installation, maximum occupation rate, type and number of attracted species, materials used in the construction, volume (L), entrance (cm), and key results of studies that have used nest boxes to attract or trap bees

Reference	Country	Place	Occupation rate	Species	Material	Volume	Entrance	Key results
(Barron et al., 2000)	New Zealand	Farm	13%	Bumblebee	Wood	-	2.5	In the intensive farms, occupation was lower than less disturbed sites.
(Inoue et al., 1993)	Indonesia	Forest	6%	*Trigona minangkabau*	Wood	0.7, 2	-	Arboreal ants occupied one-half of artificial nest sites.
(Coelho and Sullivan, 1994)	USA	Forest	30%	Honeybee	Wood	-	6	The nest boxes were not attractive to bees while the entrances were open.
(Prange and Nelson, 2007)	USA	Forest	10%	Honeybee	Wood	6.7	3.1	Our observations supported the theory that minimum acceptable cavity volume varies geographically.
(Oliveira et al., 2013)	Brazil	Forest	10. 2%	9 Stingless bees	Cardboard, Plastic	0.5, 1, 2, 3	-	Most swarms chose the largest container (3 L).
(Veiga et al., 2013)	Kenya	Forest	31%	Native bee	Wood	3, 7, 15	0.45	Bees were more abundant in forest boxes than savannas.
(Silva et al., 2014)	Brazil	Forest	0.035%	Honeybee and 5 *Meliponini*	Plastic	1, 2, 3	-	The present study suggests the existence of a minimum volume threshold of approximately 1 L for most local species of stingless bees.
(Efstathion et al., 2015)	Brazil	Forest	51%	*Tetragonisca sp*, Honeybee	Wood	2.7	2.5	Trap boxes may be effective at reducing the number of bird nest boxes colonized by invasive Africanized honeybees and wasps.
(Le Roux et al., 2016)	Australia	Forest	12.5%	Honeybee	-	-	2, 3, 5.5, 9.5, 11.5	Nest boxes with small (20 and 35 mm), intermediate (55 and 75 mm), and large (95 and 115 mm) entrance sizes were predominately occupied by *Apis mellifera*.
(Arena et al., 2018b)	Brazil	Forest	5.5%	*Scaptotrigona postica*	Plastic	3	2.5	We suggest reducing the diameter of the PVC pipes (nest entrances).
(Arena et al., 2018a)	Brazil	Forest	5.5%	Stingless bee	Plastic	3	2.5	Bees showed a preference for occupying artificial shelters that were located in the patches' cores.
(Guimaraes-Brasil et al., 2020)	Brazil	Forest	6%	*Apidae, Megachilidae*	Wood	1.5, 6	1,2	Only nest boxes with a volume of 1.5 L were occupied.
(Berris and Barth, 2020)	Australia	Forest	24%	Honeybee	Wood, PVC	-	-	Feral honeybees were less likely to occupy nest boxes made of PVC (5%).
(Gaston et al., 2005)	UK	Urban	0%	Bumblebee	Wood	-	2	No bumblebee nest sites of any of the three designs.
(Lye et al., 2011)	UK	Urban	3.1%	Bumblebee	Wood	6	2, 12, 20	Attempts to use domiciles for conservation or research in the UK are likely to be ineffective.
(Johnson et al., 2019)	Canada	Urban	13.3%	Bumblebee	Wood	3, 6	2	The majority of sites had at least one domicile occupied.

infestation rate of mites by 81.8%. Guimaraes-Brasil et al. (2020) also stated that bees preferred bamboo internodes for nesting.

The color of the nests is also effective in attracting bees, for example, Boff and Friedel (2020) females of *Centris analis* prefer to nest in painted nests compared to unpainted nests. Artz et al. (2014) showed that the color of the box that surrounds the tubes affect the nests' attractiveness. In addition to the design and materials used in the construction of bee hotels, climatic factors also affect the efficiency of these nests in attracting bees, for example, Armbrust (2004) found that the occupation rate changed significantly according to the season. Jenkins and Matthews (2004) found that two species of *Osmia albiventris* and *Megachile frigida* nested early in the season (April–May). Kamke et al. (2008) claimed that the activity of *Eufriesea smaragdina* was seasonal. Wilson et al. (2020a) stated that bee hotels inserted on southwest sides recorded the highest maximum temperatures while the northeast sides recorded the lowest maximum temperatures. Wilson et al. (2020b) showed that more species of bees and wasps used hotels in the wet season (spring-summer).

The landscape around the nests also affects their efficiency in attracting bees. For example, Wilson et al. (2020b) found that distance to forest and forest cover around the nests positively affected the occupation rate. Martínez-Núñez et al. (2020) found that organic fields had higher colonization rates than their control farms. Graham et al. (2020) found that significantly greater nesting at farms with wildflower plantings, with only one out of 236 completed nests at a farm without a planting. Guisse and Miller (2011) found that nest number per site was positively correlated with proximity to water, but negatively with elevation. Iantas et al. (2017) showed that the grape organic fields presented the highest number of occupied nests. On the other hand, the forest fragments presented the lowest number of occupied nests.

One of the problems with bee hotels is the presence of non-native species and wasps as competitors for native bees, which sometimes occupy a significant proportion of tubes. For example, Inoue et al. (1993) reported that 50% of the bee hotels were occupied by ants. Barthell et al. (1998) found that native species (including bees and wasps) never accounted for >25% of all occupied nesting cavities. Taki et al. (2008) found 12 species of wasps in bee hotels, while no pollinating bees were observed. Oliveira et al. (2013) also found that 19% of plastic nests and 5% of cardboard nests were occupied by spiders and ants, implying competition for nesting. MacIvor and Packer (2015) also reported that native wasps were significantly more abundant than both native and introduced bees and occupied almost 3/4 of all bee hotels. Geslin et al. (2020) found that the most abundant species that emerged from bee hotels was the exotic *Megachile sculpturalis*, representing 40% of all individuals. von Königslöw et al. (2019) found 22 species of bees and wasps, of which 51% were bees and 49% were wasps. In another study, 31 species of pollinators were observed that 47% of them were non-native (Maclvor, 2016). Wilson et al. (2020b) observed 41 species of bees and wasp in bee hotels, of which 13 species were bees and 28 were wasps.

Nest boxes

Table 2 shows details of studies that have used nest boxes to attract or trap bees. Six of these studies were conducted in Brazil (37%), more than in other countries. We found only one study that used nest boxes on farms that had a 13% occupation rate of nest boxes. In contrast, 75% of these studies are conducted in natural areas such as forests and 3% of the studies are conducted in urban areas. The maximum occupation rate of nest boxes in natural areas is reported to be between 0.03 and 51%, with an average of 27%. This rate is 5.5% on average in urban areas. Nest boxes are used for species that live socially. Hence, they need more nest space to survive and reproduce. Bumblebees, honeybees, and stingless bees fall into the category of social bees. Table 2 shows that honeybees and bumblebees are more frequent than other species in nest boxes. Similar to bee hotels, nest boxes are sometimes occupied by non-native and non-pollinating insects. For example, Inoue et al. (1993) claimed that arboreal ants occupied 50% of artificial nest sites as competitors for native bees.

Table 2 shows that most studies have used wood to make nest boxes (68%). Berris and Barth (2020) found that feral honey bees were less likely to occupy nest boxes made of PVC (5%) compared with wooden nest boxes (24%). Some studies have not reported the volume of nest boxes; however, the volume of these nests in these studies varies from 0.5 to 15 l, with an average of 3.6. The volume of nest boxes affects their efficiency in attracting bees, for example, For honeybees, the optimum entrance size in nest boxes is 20 to 30 cm^2 (Coelho and Sullivan, 1994). Oliveira et al. (2013) stated that most swarms chose nest boxes with a volume of 3L. Silva et al. (2014) also suggested a minimum volume threshold of approximately 1 L for most local species of stingless bees. Guimaraes-Brasil et al. (2020) stated that only nest boxes with a volume of 1.5 liters were occupied. Prange and Nelson (2007) also found that the minimum acceptable nest volume varies geographically.

According to Table 2, the nest box entrance hole also varies from 0.45 to 20 cm on average 4.6. The inlet diameter of the nest boxes has a significant effect on their colonization by bees. For example, Coelho and Sullivan (1994) found that nest boxes were not attractive to bees while the entrances were open because the entrance holes were too large. Le Roux et al. (2016) also found that nest boxes with small (20 and 35 mm), intermediate (55 and 75 mm), and large (95 and 115 mm) entrance sizes were predominately occupied by *Apis mellifera.* Arena et al. (2018a) suggested reducing the diameter of the PVC pipes (nest entrances) in the next studies.

Meta-analysis

Table 3 shows the average occupation rates in bee hotels and nest boxes in different land covers. According to this table, the occupation rate of bee hotels on farms (44.1%) is higher than in forests (30.3%) pastures (28%) and urban (38.3%). The average occupation rate in the 38 cases that have used bee hotels to attract bees is 37%. Unlike bee hotels, the average occupation rate of nest boxes in the forest (16%) is higher than in the farms

Table 3 The average occupation of bee hotels and nest boxes in different land covers

	Land cover	Average occupation rate	No. case
Bee hotel		37.1%	38
	Forest	30.3%	14
	Farm	44.1%	15
	Pasture	28%	2
	Urban	38.3%	7
Nest box		13.8%	16
	Forest	16%	12
	Farm	13%	1
	Urban	5.5%	3

Table 5 One-way ANOVA results for determining the differences between group means

	Source	DF	Adj SS	Adj MS	*F*-value	*R*-Sq	*P*-value
Bee hotel							
	Factor	2	0.1148	0.05738	0.94	5.38%	0.401
	Error	33	2.0172	0.06113			
	Total	35	2.1319				
Nest box							
	Factor	2	0.02659	0.01329	0.67	9.40%	0.527
	Error	13	0.25641	0.01972			
	Total	15	0.28300				

(13%) and urban (5.5%) environments. The average occupation rate of nest boxes in the 16 studies that have used these nests is 13.8%, which is significantly lower than that of bee hotels.

Table 4 shows the statistical relationships between nest occupation rates and the length, diameter, volume, and entrance size of the artificial nests. According to this table, the length and diameter of the tubes did not have a significant effect on the occupation rate of bee hotels. The volume and entrance size of the nest boxes did not show a significant relationship with the occupation rate of these nests either.

OR occupation rate, *DI* diameter, *LE* length, *VO* volume, *EN* entrance

Table 5 shows the results of the one-way ANOVA test, which was used to determine whether the installation place of bee hotels and nest boxes affect their occupancy rate. The null hypothesis of this test states that the group means are all equal. According to the *P*-value (more than 0.05), there was no significant relationship between the occupation rate and their installation place, implying that the installation place did not affect the efficiency of artificial nests in attracting bees.

Conclusion

Our data showed that (1) the average occupation rate of bee hotels and nest boxes are 37.1% and 13.8%. (2) The structural features of bee hotels (length and diameter) and nest boxes (volume and entrance size) did not affect their efficiency in attracting bees. (3) The installation place of bee hotels and nest boxes did not affect their occupancy rate. Bee hotels are built and installed to attract solitary bees, but nest boxes are for social bees such as bumblebees and honeybees (Gaston et al., 2005). The behavioral ecology of solitary and social bees in nesting is different. For example, social bees need more nest space than solitary bees. Concerning bee hotels in urban environments, various studies have reported occupation rates from 7 to 75%. This result is consistent with studies that identify urban gardens as pollinator hotspots (Baldock et al., 2019; Theodorou et al., 2020). In agricultural farms, various studies have shown that bee hotels have an efficiency from 11 to 100% in attracting bees, which varies depending on the type of bee hotels and their location. In natural environments such as forests, bee hotels showed efficiencies from 3 and 73%. Concerning nest boxes, in forest environments, various studies reported occupation rates from 0.03 to 51%%. It is noteworthy that most studies reported an efficiency of less than 20%. In urban environments, the efficiency of nest boxes was reported to be very low, as in one study, the occupation rate was reported to be zero (Gaston et al., 2005), and in another study, the authors stated that attempts to use domiciles for conservation or research in the UK are ineffective.

Table 4 The statistical relationship between occupation rate and length, diameter, volume, and entrance size of artificial nests

	Regression equation	R-Sq	*P*-value		*r*
Bee hotel					
	OR = − 132.4 + 49.49 DI − 4.434 DI^2 + 0.1196 DI^3	13.1%	0.23	LE	−0.2
	OR= 61.33 − 5.206 LE + 0.3961 LE^2 − 0.01057 LE^3	5.7%	0.60	DI	−0.11
Nest box					
	OR = − 29.70 + 37.77 VO − 9.686 VO^2 + 0.7249 VO^3	25%	0.53	VO	0.18
	OR = 30.39 − 13.66 EN + 3.172 EN^2 −0.1928 EN^3	14.5%	0.72	EN	−0.11

Abbreviations
OR: Occupation rate; DI: Diameter; LE: Length; VO: Volume; EN: Entrance; r: Pearson correlation coefficient

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Code availability
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Authors' contributions
ER has written the paper and has presented the articles in summary form in tables. ShB has reviewed the paper, helped to write, and interpreted the results. PD has reviewed the paper, edited the grammar, and helped to interpret the results. The authors read and approved the final manuscript.

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