Basic and Applied Ecology 87 (2025) 11–19

Contents lists available at ScienceDirect

Basic and Applied Ecology

journal homepage: www.elsevier.com/locate/baae

RESEARCH PAPER

Anthropogenic noise can decrease tomato reproductive success by hindering bumblebee-mediated pollination

Zsófia Varga-Szilay [a,*], Gergely Szövényi [b], Gábor Pozsgai [c,*]

[a] Doctoral School of Biology, Institute of Biology, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/C, Budapest 1117, Hungary
[b] Department of Systematic Zoology and Ecology, ELTE Eötvös Loránd University, Pázmány Péter sétány 1/, Budapest 1117, Hungary
[c] Ce3C – Centre for Ecology, Evolution and Environmental Changes, Azorean Biodiversity Group, CHANGE – Global Change and Sustainability Institute, University of the Azores, Faculty of Agricultural Sciences and Environment, Rua Capitão João D'Ávila, 9700-042, Angra do Heroísmo, Terceira, Açores, Portugal

ARTICLE INFO

Keywords:
Anthropogenic disturbances
Bombus terrestris
Plant reproductive success
Traffic noise

ABSTRACT

Anthropogenic noise is a little-studied type of pollution that negatively affects the physiology, nervous function and development of insects. Thereby, it has the potential to disrupt even key ecological services such as pollination. Here, we investigate the effects of anthropogenic noise on the pollination success of tomatoes pollinated by *Bombus terrestris,* under controlled conditions. We hypothesised that bumblebees avoid flowers exposed to noise more than flowers in non-noisy environments, leading to less efficient pollination and lower fruit quality. Three treatments were applied to randomly chosen plants and flowers in polytunnels in Hungary: noisy (with played traffic noise and allowing bumblebees to access the flowers); and two non-noisy, one allowing bumblebees and one excluding them. The flowers were bagged with nets before anthesis to prevent bumblebee visits, opened/unbagged exclusively during treatment, and re-bagged for three more days post-treatment. We recorded the market value of the fruits and the number of seeds they produced. We found no significant differences in the market value of fruits among treatments, but the number of seeds was significantly lower in the noisy treatment, suggesting that anthropogenic noise has substantial effects on bumblebee-mediated pollination. Although these effects may be mitigated by habituation, loud external noise of various machines (e.g. irrigation systems) within polytunnels is still likely to contribute to the everyday noise exposure of bumblebees and could thus potentially lead to hidden economic losses in production. Therefore, further research is needed to understand the behavioural effects of both direct and indirect noise pollution on bumblebees.

Introduction

In human-disturbed environments, multiple anthropogenic stressors threaten biodiversity and the healthy functioning of ecosystems (Wagner et al., 2021; Willmott et al., 2022). Among those, anthropogenic noise is a global phenomenon and an intense form of pollution. Although little studied, it negatively affects the physiology, nervous function and development of many animal taxa, including invertebrates, vertebrates, aquatic and terrestrial species alike (Blickley & Patricelli, 2010; Kight & Swaddle, 2011; Kunc & Schmidt, 2019; Shannon et al., 2016; Slabbekoorn et al., 2018). Anthropogenic noise can cause alterations in physiological responses, such as heightened stress levels, pain, or elevated stress hormone production (Barber et al., 2010; Fakan & McCormick, 2019; Kight & Swaddle, 2011; Shannon et al., 2016).

These physiological effects often lead to increased fitness costs, potentially reducing reproductive success and survival. For instance, studies in birds suggest that adult growth can be impaired and longevity be reduced even when eggs are exposed to traffic noise (Meillère et al., 2024). Moreover, noise disrupts the perception of environmental cues and social interactions of animals that rely on acoustic signals (Brumm & Slabbekoorn, 2005; Classen-Rodríguez et al., 2021; Siemers & Schaub, 2010) (e.g. mating interactions), significantly affecting not only birds (Engel et al., 2024; Halfwerk & Slabbekoorn, 2013) and mammals (Slabbekoorn & Peet, 2003), but also invertebrates, such as molluscs (e. g. Gigot et al., 2024; Serdar et al., 2024) and insects (e.g. Orci et al., 2016; Welsh et al., 2023). The effects of noise pollution are not confined to acoustically oriented animals but extend to organisms with no direct links to the acoustic realm yet exposed to heightened noise (Bunkley et al., 2017; Senzaki et al., 2020). For instance, highway noise induces physiological stress in monarch caterpillars (Davis et al., 2018) and even

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* Corresponding authors.
E-mail addresses: zsofia@vargaszilay.hu (Z. Varga-Szilay), pozsgaig@coleoptera.hu (G. Pozsgai).

https://doi.org/10.1016/j.baae.2025.05.008
Received 10 December 2024; Accepted 26 May 2025

dragonflies without acoustic receptors inhabiting environments adjacent to noisy areas are negatively impacted (Senzaki et al., 2020).

To mitigate the effects of noise pollution, animals may either avoid noisy environments or develop compensatory strategies. For instance, some species modify their acoustic signals by increasing the amplitude (Lombard effect) (Brumm & Todt, 2002; Katti & Warren, 2004; Nemeth & Brumm, 2010) or shifting frequencies to higher ranges in noisy environments (Gil & Brumm, 2014; Lampe et al., 2012; Nemeth et al., 2013; Shieh et al., 2012). Others alter their temporal activity patterns, or, ultimately, they might move to quieter places (Brumm, 2013; Warren et al., 2006). However, both compensation and avoidance can lead to significant behavioural changes, such as altering movement, habitat use (Duarte et al., 2011), foraging patterns and foraging efficiency (e.g. Luo et al., 2015; Siemers & Schaub, 2010), or communication patterns (e.g. Brumm & Slabbekoorn, 2005; Naguib, 2013). These behavioural shifts come with energy costs, which, similarly to physiological effects, can negatively affect survival and reproductive success (Kight & Swaddle, 2011). Additionally, bumblebee workers reared by stressed individuals may develop physiologically into poorer quality workers (Jones et al., 2013). However, in some cases, like in crickets, plasticity can, at least partially, buffer against these fitness costs if noise exposure is constant (Welsh et al., 2023).

Behavioural changes can also have cascading effects at the community level (Barber et al., 2010; Senzaki et al., 2020) and can indirectly influence species interactions (Barton et al., 2018), through which they can hamper key ecosystem services such as pollination (Francis et al., 2012; Phillips et al., 2021). For instance, Phillips et al. (2021) found that while road noise does not affect the density of bumblebees (*Bombus* spp.), the number of flower visits and the time bees spend on flowers were significantly higher at sites farther from roads. Additionally, noise pollution could impact short-range acoustic communication between individuals and species (Bunkley et al., 2017), which may further affect the success of vibration-based buzz pollination. Another study found that noise ultimately disrupts the effectiveness of pollination and can therefore lower the reproductive success of both wild plants and crops (Guenat & Dallimer, 2023).

Pollinators increase production and yields of fruits (Greenleaf & Kremen, 2006), while they also enhance the commercial value by improving characteristics such as weight, size, and sugar content (Hogendoorn et al., 2006; Toni et al., 2021). Since the 1980s, commercial bumblebees (e.g., *Bombus terrestris* in Europe) have been widely used in both glasshouse and open-field cultivation (De Ruijter, 1997; Velthuis & Doorn, 2006), as they are among the most efficient pollinators for a wide variety of popular crops like tomatoes (Cooley & Vallejo-Marín, 2021; De Luca & Vallejo-Marín, 2013), eggplants (Mondal et al., 2022), and strawberries (Gudowska et al., 2024). Even crops capable of self-fertilization, such as tomatoes (Zhang et al., 2022), sweet peppers (Roldán Serrano & Guerra-Sanz, 2006), almond (Sáez et al., 2024) and cape gooseberry (Chautá-Mellizo et al., 2012), are well-known to produce larger, heavier, and better quality fruits when bumblebees and/or other bees transport the pollen to the stigma.

One key advantage of bumblebees in pollinating plants over other bees, such as honey bees, lies in their ability to use specific frequency vibration of their thoracic muscles to shake out the pollen from the anthers of some plants (termed ‘buzz pollination‘) (De Luca & Vallejo-Marín, 2013; Vallejo-Marín, 2021). Therefore, crops relying on buzz pollination are likely to be disproportionately impacted by noise-induced decline in pollination activity, and decline in fruit quality in the presence of noise. Despite the well-documented impacts of anthropogenic noise pollution on birds (e.g. Halfwerk & Slabbekoorn, 2013) and marine mammals (e.g. Hastie et al., 2021; Sørensen et al., 2023) there remains a significant knowledge gap regarding to invertebrates (Guenat & Dallimer, 2023; Jerem & Mathews, 2021; Morley et al., 2014; Shannon et al., 2016; Sordello et al., 2020), and particularly on the effects of noise on pollinator behaviour. Previous experiments have focused on the effect of acoustic vibrations of bumblebees on pollination (e.g. Vallejo-Marín, 2021; Woodrow et al., 2024), but how pollination success is altered in noisy environments has not yet been examined. Our understanding on how noise affects these vital pollinators of cultivated plants remains incomplete. Additionally, it is still unknown to what extent bumblebees avoid highly noise-polluted areas, how sound influence plants, and it remains uncertain whether these effects impact crop pollination success and yield quality.

In addition to affecting pollinators, sound waves may also have direct cellular, physiological and molecular effects on plants (Jung et al., 2018). Exposure to daily traffic noise has been associated with disrupted hormonal balance and increased oxidative stress in plants, potentially impairing their growth and development (Kafash et al., 2022). In tomatoes, for example, sound wave treatment can delay the ripening of tomato fruits (Kim et al., 2015). It has been reported that sound waves around 90 dB enhance mung bean (*Vigna radiata* (L.) R.Wilczek) growth (Cai et al., 2014) and certain acoustic frequencies can increase plant growth and crop quality, as well as promote fruit production (Hou et al., 2009; Hou & Mooneyham, 1999). Thus, in contrast to hampering pollinations, exposure to certain noises may increase the market value. Thereby, the net effect of anthropogenic noise on plant quality, along with pollination success is yet to be determined.

We investigated the effects of anthropogenic noise on the pollination success of tomatoes (*Solanum lycopersicum* L., Solanales: Solanaceae) visited by *Bombus terrestris* (Linnaeus, 1758) and their fruit production in a polytunnel setting in Hungary. We used tomatoes as they are a key crop and a representative of nightshade crops which, although self-compatible, still require buzz pollination for high yields and high-quality fruits (Picken, 1984; Toni et al., 2021). They are also the best-studied buzz-pollinated plant species (Cooley & Vallejo-Marín, 2021). Since we expect that bumblebees spend less time on flowers exposed to noise, or avoid them completely, we predict less efficient pollination and lower fruit quality in noisy environments than in non-noisy ones. In line with this, we formulated the following hypotheses:

H1: Traffic noise is expected to deter bumblebees from flowers, and thus negatively affect the presence of bumblebees’ bite marks (so-called ‘brown patches’) on the anther cone, which is an indicator of bumblebee flower visitation and the initial fruit set.

H2: Exposure to traffic noise results in a decrease in the number of tomato seeds, which is a reliable measure of pollination success and an important indicator of the plant’s reproductive success.

H3: Traffic noise negatively impacts the market value of fruits, thereby affecting their saleability and, consequently, their economic value for the local producer.

Material and methods

Study sites

The experiment was conducted in Szentes (46°39′09.2″ N 20°13′58.4″ E), located in the Southern Great Plain region of Hungary (Fig. 1), under controlled conditions within a polytunnel, between May 18 and 28, 2023. The polytunnel measured 10×70×5 m, covering an area of 700 m^2, and was heated with thermal water. The cultivation followed integrated pest management (IPM) practices and the ‘Aruba’ tomato cultivar was grown. The tomato plants, which were planted in September of the previous year, were approximately three meters tall and at the 25th truss stage during the experiment (SM Fig. 1). Ten rows of plants were arranged in the polytunnel, with a total of twelve bumblebee nests (exclusively *Bombus terrestris*) placed in the middle of the fifth row (the very centre of the polytunnel). The experiment was conducted in the first, second, and fourth rows from the right side of the polytunnel (SM Fig. 2). In the first row, 35 flowers (from 25 plants), in the second row, 17 flowers (from 14 plants), and in the third row, 10 flowers (from 9 plants) were chosen for the study. Both plants and flowers were randomly selected (therefore, the number of plants and flowers included

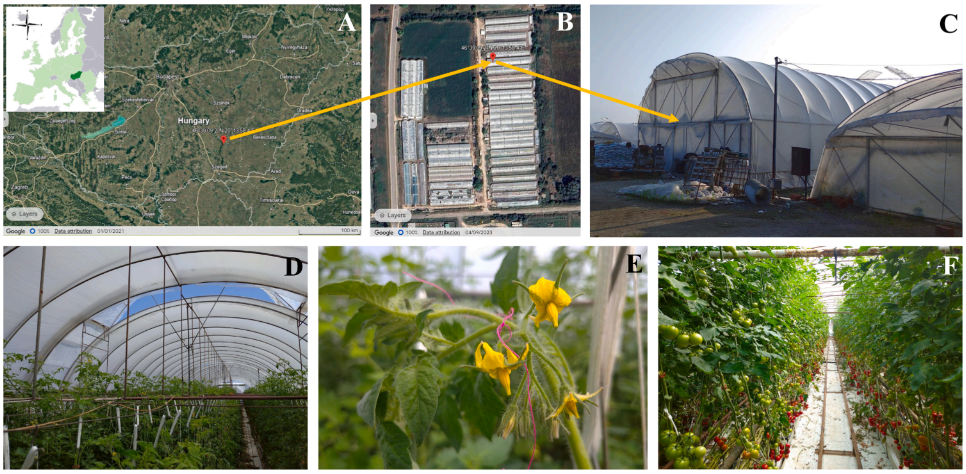

Fig. 1. The study site location in Szentes, Hungary (A), the aerial view and the exterior (B, C), and the interior of the polytunnel where the experiment took place (D-F).

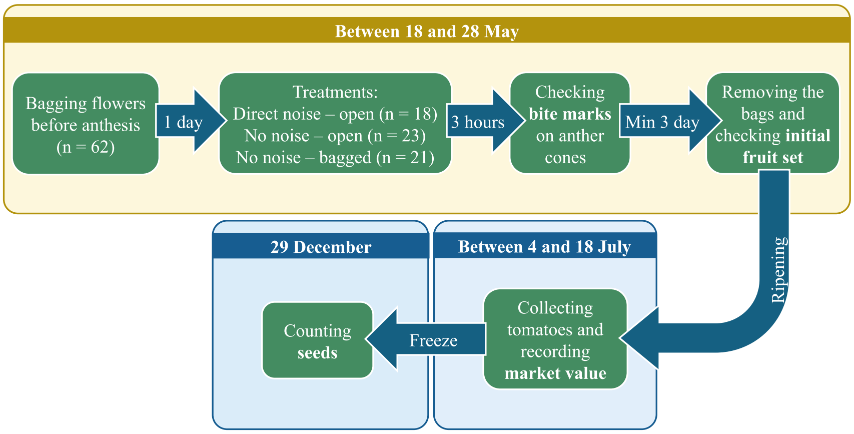

Fig. 2. The experimental and data collection process. The yellow frame indicates the onsite processes and data collection, while the blue frames indicate post-experiment data collection.

in the experiment varied between rows) within each set and spaced as far apart as it was possible (with a minimum distance of 4–5 m, SM Fig. 3) to ensure treatment independence and to prevent any interference between the treatments.

Experimental design

The experiments were conducted between 7:00 and 18:00 each day. The randomly selected tomato flowers were numbered and enclosed with fine-mesh bags (mesh size: 1 × 1 mm) before anthesis ($n = 62$), released exclusively during treatment, and then re-bagged for three more days when the flowers senesced (Fig. 2). Since flower position within the cluster influences pollination and because it is more difficult to ensure equal noise effect on the entire cluster than on a single flower, to avoid these uncontrollable variables, we chose to use a single flower as the unit of our experiment.

We used 20 repetitions with three types of treatments randomly allocated to flowers (one flower per cluster whose positions within the cluster was known, please see 2.3. Data collection): a noisy (DN-open) with played traffic noise (hereafter noise) from a speaker (see below, Fig. 3A), a non-noisy (NN-open) with a paper dummy speaker (Fig. 3B) matching in size and colour yet not producing sound, and treatment with

Fig. 3. The three types of the study treatment on tomato flowers, (A) noisy with allowed bumblebee visitation (DN-open); (B) non-noisy with allowed bumblebee visitation (NN-open); and (C) the complete exclusion of bumblebees (NN-bagged). No noise was played for the non-noisy (NN-open) and self-fertilisation (NN-bagged) treatments.

the complete exclusion of bumblebees (NN-bagged, Fig. 3C) thereby ensuring self-fertilisation of the flower, without any played noise or dummy speaker. Both the real and the dummy speaker were placed directly next to each of the selected flowers, at a maximum distance of 10 cm (see Fig. 3A, B). For both treatments with bumblebee access (DN-open and NN-open), the bags were removed for 3 h, for the time of treatment, allowing unrestricted visitation of bumblebees. In the noisy treatment, after 5 min of the pre-treatment period, the flowers were exposed to noise.

Environmental conditions, including temperature and humidity, were not modified for the experiment and remained as typically found within the polytunnel, optimised for tomato growth. The temperature at the beginning of the experiments averaged 25.79 °C (± 3.12 °C), while at the end of the experiments, the average temperature was 28.09 °C (± 2.96 °C). The background noise was recorded at the start of each experiment day. For this, we used a VOLTCRAFT SL-10 sound level meter with a sensitivity of 0.1 dB, a frequency range of 31.5 Hz to 8 kHz, and a sound level measurement range of 30 to 130 dB(A). The average of the lowest background noise levels was 43.03 dB(A) (± 3.73 dB(A) SD), and the average of the highest of that was 60.93 dB(A) (± 4.93 dB(A) SD). The traffic noise (the audio source: https://www.zapsplat.com) was played using a LAMAX Sphere2 Mini Bluetooth 5.1 speaker with a frequency range of 150 Hz to 20 kHz. The average of the lowest treatment noise levels was 69.96 dB(A) (± 10.76 dB(A) SD), and that of the highest was 85.96 dB(A) (± 7.11 dB(A) SD). The anthropogenic traffic noise we used in our treatment was significantly louder than the background noise (one-sided Wilcoxon rank sum test, $p = 0.005$).

Data collection

We recorded the total number of flowers on each cluster and noted the position of the flower subjected to the treatment ($n = 62$).

Bite marks and the initial fruit set

Immediately after the treatments, we assessed whether pollination had happened by carefully observing the anther cones (Fig. 4A) on both noisy (DN-open) and non-noisy (NN-open) treatments, looking for the presence of bite marks on the flowers ($n = 41$, because it was not relevant for the self-fertilisation/NN-bagged treatment). These brown discolourations, also known as brown patches and flower bruising, are caused by bumblebee's mandibles on the anther cones, as the bee grasps the anther cones with its mandibles during pollination (Morandin et al., 2001; Woodrow et al., 2024). The intensity and extent of these bite marks serve as strong indicators of bumblebee pollination, closely linked to fruit set and subsequent ripening (Koppert, 2025). As bruising patterns reliably reflect pollination success, they are commonly utilized to assess bumblebee foraging activity and the effectiveness of pollination in tomato (Morandin et al., 2001; Morse et al., 2012). After a minimum of three days (since fertilisation occurs around 24–50 h post-pollination), we permanently removed the bags and, by carefully examining whether there was any structure indicative of early fruit formation beneath the withered or already fallen petals, recorded whether there was any sign of initial fruit set (Fig. 4B).

Market value of the fruit

After fruit ripening, the local producers (who were unaware of our applied treatments) harvested the marked tomatoes in their usual manner or made a note if the numbered tags were missing (Fig. 4C). During harvesting, they cut off the fruits from the clusters and classified them individually based on their market value. This categorisation was hypothetical, as the fruits were not actually sold; however, the categorization was based on the price for which local producers could have sold them. Non-developed (aborted) fruits were placed as *Category 0*. Very small, green or lowest value fruits were classified as *Category 1*. Fruits that would have been sold in bulk were classified as *Category 2*, while those that could have been sold in assortments of seven or six (tomatoes arranged in a single row of a box) were classified as *Category 3* and *Category 4* (highest values), respectively. This categorisation is primarily based on fruit size, as, for example, tomatoes sold in assortments of six (*Cat. 4*) were slightly larger than those sold in assortments of seven (*Cat. 3*) and both of them notably larger than tomatoes sold in bulk (*Cat. 2*). Hence, although fruit size was not measured, the categorisation

Fig. 4. Data collection by observing the anther cones (A), checking the sign of initial fruit set (expanding fruit, B), recording the market value (C), and counting the total number of seeds of tomato fruits (D).

served as an indicator for it. After classification, local producers preserved the collected tomatoes, placed them individually in labelled plastic bags along with their labels and freezed them for later seed counting (SM Fig. 4).

Number of seeds

Seed count was selected as a key metric due to its sensitivity to pollination and its reliability in assessing reproductive success (Toni et al., 2021) making it a consistent parameter for evaluating the effects of our treatments. To determine the total seed count per fruit, we first allowed the frozen fruits to thaw completely (SM Fig 4), then the fruits were carefully opened, and all seeds were extracted and counted (Fig. 4D, SM Fig. 4).

Statistical analysis

We applied binomial generalised linear models (GLMs) to analyse the presence of bite marks and the initial fruit set. For bite marks, we compared DN-open and NN-open treatments, excluding the NN-bagged group where this variable was not applicable. For fruit set, all three treatments were included in the model. In both analyses, the response variable was binary (presence/absence), and treatment was included as a categorical predictor. We tested for overdispersion in all binomial GLMs. Whilst we initially attempted to use generalised linear mixed models (GLMMs), including the position of the flower in the cluster and the repetition set, did not improve the models and thus simpler GLMs were applied.

To analyse the market value of the fruit by treatment, first, we converted market value categories to numerical variables and then we used a generalised linear model (GLM) with a Poisson distribution to appropriately handle the integer data. From the analysis, we excluded the flowers with unknown outcomes ($n = 12$) and two cases where the plant died before fruit development. In this case the GLM was also superior to the GLMM in which the position of the flower in the cluster and the repetition set were used as random variables.

For the analysis of the number of seeds by treatment, we utilised a generalised linear mixed model (GLMM, glmer() function in the lmer R package, Bates et al., 2015) with a Poisson distribution. The flower's location within the cluster and the repetition set were included as random effects in the model and flowers that failed to set fruit ($n = 4$) were excluded from this analysis. We ensured that the variances were homogeneous in all occasions with the Breusch-Pagan test, and tested the normality with the Shapiro-Wilk test when the seed numbers were compared.

We used estimated marginal means (EMMs) from the "*emmeans*" R package (Lenth et al., 2024) for pairwise comparisons to examine the differences between treatments. The data analysis and visualization of the results were conducted in the R (R Core Team, 2021).

Results

Bite marks and initial fruit set

The GLM model comparing the presence of bite marks between treatment groups revealed no significant difference between the noisy and non-noisy treatments (Estimate = –0.13, SE = 0.69, $z = -0.19$, $p = 0.85$).

The GLM model for initial fruit set indicated no significant differences among the treatments. The number of initiated fruits did not differ significantly between either NN-open and DN-open or NN-bagged and DN-open treatments (NN-open: Estimate = 0.104, SE = 1.051, $z = 0.099$, $p = 0.921$; NN-bagged: Estimate = −0.626, SE = 0.996, $z = -0.628$, $p = 0.530$).

Market value of the fruits

Of the 62 flowers 71 % ($n = 44$) developed into fruits, 32 % ($n = 14$) in DN-open, 34 % ($n = 15$) in NN-open, and 34 % ($n = 15$) in NN-bagged treatment. The remaining flowers either failed to set fruit ($n = 4$), died before fruit development ($n = 2$), or their outcome is unknown ($n = 12$). For the analysis, we included flowers that produced fruit (*Category 1–4*) and those classified as aborted flowers (*Category 0),* resulting a sample size of 48. Although the market value seemed to be higher in the non-noisy (NN-open) treatment than in the other two groups (Fig. 5), the differences were not significant (analysis of deviance, deviance = 33.327, df = 45, p-value = 0.767). Pairwise comparisons did not show significant differences between the treatments (Table 1).

Number of seeds

The GLMM implied significant differences among treatments in seed numbers (analysis of deviance, $\chi^2 = 23.091$, df = 2, $p < 0.001$). Differences were significant between NN-open and NN-bagged treatments, and between DN-open and NN-open, while the difference between DN-open and NN-bagged was marginally significant (Table 2), Fruits under the NN-open treatment producing the most seeds, and those under DN-open treatment showing the lowest seed counts (Fig. 6).

Discussion

In this study, we examined how anthropogenic noise affects the pollination of tomatoes facilitated by *Bombus terrestris* under controlled polytunnel conditions. The noisy treatment did not influence either bumblebee visits (measured as the presence of bite marks) or the initial fruit set (**H1** was not supported). However, our findings confirm that traffic noise has a measurable significant negative effect on seed production (**H2** holds), suggesting an adverse impact on bumblebee pollination behaviour. Furthermore, the seed count in noisy treatment was marginally significantly lower than in the self-fertilisation one, which implies that noise may have a direct negative impact on plants. Indeed, Kafash et al. (2022) showed that traffic noise exposure significantly altered the phytohormone profile and antioxidant metabolism in plants, which may disrupt their natural mechanisms, such as self-fertilization. However, in the absence of noisy treatment with excludes pollinators, this effect is difficult to fully unravel or quantify.

In contrast, noise did not influence the market value of the fruits (**H3** was not supported). This lack of significant difference in market value among treatments suggests that the direct economic impacts of anthropogenic noise may be more nuanced than initially anticipated, at least at the coarse level we used for value characterisation. However, the consistent and relatively loud background noise within the polytunnel where the experiment was conducted may also have masked the differences between treatments. Moreover, the fact that fruits under noisy treatments produced less seeds than self-fertilising flowers suggests a direct negative effect of noise on fruit quality and allows the speculation that consumer value, in some unmeasured parameters important for human consumption, such as taste and flavour of the fruit, may also be negatively affected. Since Zameer et al. (2022) and Zhang et al. (2022) shown the positive effect of pollination by bumblebees on the vitamin C levels and flavour of fruits, it is reasonable to posit that noise, by disrupting bumblebee activity and potentially preventing them from effectively pollinating the plants, impairs fruit properties, such as vitamin content and shelf life. Additionally, for other crops grown outside of polytunnels/greenhouses, seed count decreasing could have important implications for future yield.

Indeed, within greenhouses and polytunnels, daily operations produce a variety of noises from sources such as automated irrigation systems, and human activity, including tasks and conversations, or radios playing music from early morning until the end of the workday. Since continuous noise exposure is likely to accumulate over time (Kok et al.,

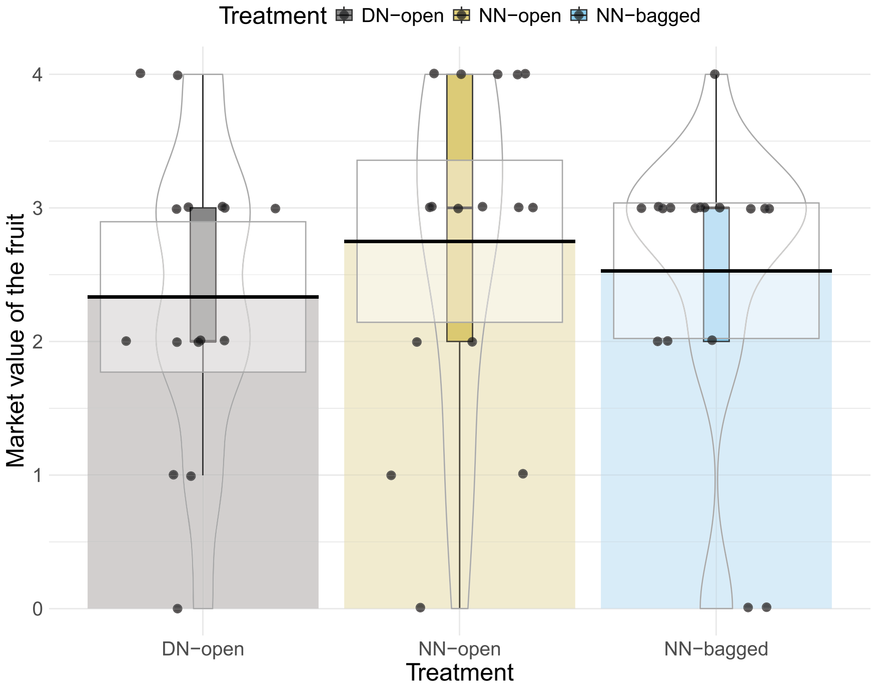

Fig. 5. The market value of the fruit by the three types of treatments, noisy (DN-open, $n = 15$), non-noisy (NN-open, $n = 16$), and self-fertilisation (NN-bagged, $n = 17$). Dots represent the category of the market value of the fruit of individual tomato samples. The categories are defined as follows: 0 – undeveloped/aborted fruit, 1 – very small or green fruit, 2 – fruit sold in bulk, 3 – fruit sold in assortments of seven, and 4 – fruit sold in assortments of six. Box plots display the median and interquartile range, while violins show density, mean, and credible intervals. There were no significant differences among the treatments.

Table 1

Comparisons of market values of tomatoes between treatment pairs with estimated marginal means (no p-value adjustment). Treatments: DN-open: noisy ($n = 15$), NN-open: non-noisy ($n = 16$), NN-bagged: self-fertilisation ($n = 17$). In all cases, degrees of freedoms are estimated by Z-test approximation to infinity.

Treatments	Estimate	SE	z ratio	p-value
DN-open – NN-open	−0.164	0.226	−0.725	0.468
DN-open – NN-bagged	−0.081	0.228	−0.354	0.723
NN-open – NN-bagged	0.084	0.214	0.390	0.697

Table 2

Comparisons of the number of seeds between treatment pairs with estimated marginal means (no p-value adjustment). Treatment: DN-open: noisy ($n = 14$), NN-open: non-noisy ($n = 15$), NN-bagged: self-fertilisation ($n = 15$). In all cases, degrees of freedoms are estimated by Z-test approximation to infinity.

Treatments	Estimate	SE	z ratio	p-value
DN-open – NN-open	−0.246	0.052	−4.767	< 0.001
DN-open – NN-bagged	−0.100	0.054	−1.851	0.064
NN-open – NN-bagged	0.146	0.053	2.756	0.006

2023), common noise sources – beyond traffic or industrial activities – could also affect bumblebee-mediated pollination. These, in turn, can potentially lead to substantial disruptions in flower-visitation activity and pollination success and can have broader implications for yield quantity and quality.

Moreover, these continuous background noises may also negatively affect brood size and quality in bumblebee nests, which may have a measurable economic cost in bumblebee production facilities.

Behavioural flexibility, or the ability to exhibit plastic responses (e.g. bird song plasticity, Slabbekoorn, 2013) to stable but intrusive sounds, could help buffer some effects of noise, allowing animals to function (survive and reproduce) in high-noise urbanised or agricultural environments. Studies on invertebrates (e.g. grasshoppers, Lampe et al., 2014) also suggest that the capacity to 'tune out' uniform stimuli may help maintain essential behaviours even under anthropogenic noise pollution. Thus, in polytunnels, the continuous exposure to repeated stimuli of background noise may lead bumblebees to habituate to these sounds, reducing immediate stress responses. Yet, this adaptation may only apply when noise remains relatively constant, as more variable noise is likely to impose higher physiological and behavioural costs (Naguib, 2013). Thus, non-constant noise of machinery or radio is still likely to affect bumblebees' behaviour and diminish pollination efficiency.

Beyond its impact on foraging behaviour, research on field crickets and scallops has shown that larval or juvenile exposure to noise can disrupt the normal development of invertebrates, potentially impairing adult behaviours related to survival and reproduction (de Soto et al., 2013; Welsh et al., 2023). While similar effects in bumblebee larvae are currently speculative, such impacts could potentially affect colony success rates and reproductive output, highlighting an area open for further investigation.

Indeed, it is plausible to expect that noise pollution also influences various stages of bumblebees' lifecycle, including the hibernation ability of queens and the reproductive success of colonies, such as larval development rates and the number of reproductive offspring. However, developmental noise exposure may also contribute to habituation and noise tolerance in adult bumblebees. Nevertheless, if managed bumblebee colonies are raised in noisy environments which reduces their sensitivity to noise and potentially limits their observable behavioural responses, they still undergo early-life stress that may negatively influence growth and can have oblique deleterious effects on physiology which ultimately decrease pollination efficiency. These also raise animal welfare concerns, as studies have shown that bumblebee workers raised under such conditions may not only experience direct physiological stress but could also be affected by being reared by already stressed individuals (Jones et al., 2013). This can potentially lead to the development of poorer-quality workers, further compromising colony health and reproductive success, which further implies that commercial bumblebee producers could benefit from controlling the environmental noise in their facilities and improve both colony health and welfare.

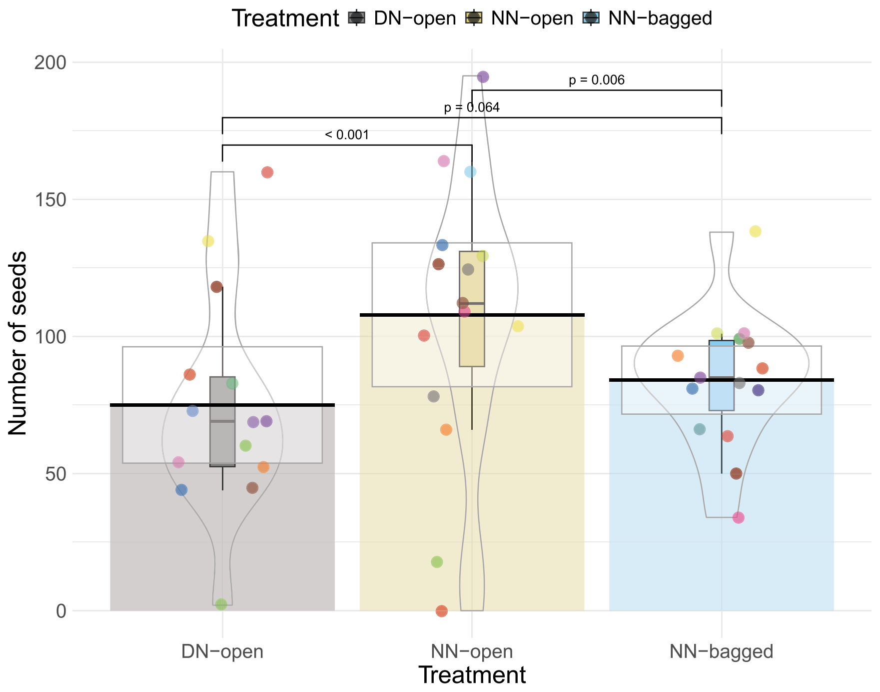

Fig. 6. The number of tomato seeds separated by treatments, noisy (DN-open, $n = 14$), non-noisy (NN-open, $n = 15$), and self-fertilization (NN-bagged, $n = 15$). Dots represent the seed number of individual tomato samples, with repetitions indicated by separate colours. Box plots display the median and interquartile range, while violins show density, mean, and credible intervals. The p-values show the comparisons between treatment pairs based on estimated marginal means.

Limitations

Our sample size was constrained by the setup of the polytunnel, where only three out of the ten rows had plants lowered to a height (ca, 3 m) that allowed access to the flowers. Though we examined the presence of bite marks on the anther cones as an indicator of flower visitation immediately after treatments (DN-open and NN-open), in fact, it can take up to four hours for these brown marks to become fully visible (Koppert, 2025). Therefore, the presence or absence of these marks immediately after the relatively short duration of our treatments could not be considered a completely reliable indicator for flower visitation by bumblebees, thus it must be interpreted with caution. Since our original aim was to study bumblebee pollination, we did not include a noisy treatment with bumblebee exclusion, which prevents the disentangling of the potential impact of noise on self-pollination. Lastly, we did not directly measure bumblebee activity during the treatment, which may have provided additional insights into the impact of noise on their foraging behaviour. However, this also allowed us to minimize human disturbance during the experiment, ensuring that pollination occurred under as natural conditions as possible in the polytunnel.

Conclusion and future perspectives

With this study, we laid the foundations of how bumblebee-mediated pollination efficiency is impacted by noise. As a proof-of-concept, even in our relatively small-scale study, we found deleterious negative effects of noise on tomato pollination. This, from an economic perspective, underlines that noise pollution can diminish pollination efficiency which could lead to unforeseen losses in crop yields, particularly near to urban infrastructure. Our study underscores the importance of identifying and managing noise sources within agricultural systems, such as polytunnels and greenhouses, where bumblebees are necessary for high-quality production. Yet, currently, there is a lack of information on how anthropogenic noise affects entire bumblebee colonies, creating a significant gap in our understanding. Addressing this is essential, as understanding these potential effects is crucial for developing strategies to mitigate noise-related disruptions and to ensure the sustainability of pollination services. Further research is needed to understand how different types of anthropogenic noise can alter the behaviour of both wild and commercially reared pollinators, ultimately affecting pollination efficiency. We recommend using video-based observations to study bumblebee foraging activity and behaviour (Varga-Szilay et al., 2024), as this would enable detailed data collection on the impact of noise on flower-visitation events while minimizing human disturbance.

In addition, to better understand the direct effect of noise on tomato plants, and particularly on self pollination, future studies should include a treatment where bumblebees are excluded but additional noise is imposed. To fully elucidate the nuanced impacts of noise and provide a more comprehensive picture of how noise impacts pollination systems, future experiments should involve a broader variety of crops, such as strawberry or pepper. Moreover, since parameters like the characteristics of the vibration (Arroyo-Correa et al., 2019) vary among bumblebee species and subspecies, future studies should include different commercially reared bumblebee species (like *Bombus impatiens)* and subspecies (such as *Bombus terrestris* spp. *audax*).

Noise may have other, yet unforeseen, effects as well. Efforts to utilise acoustic signals to estimate bumblebee activity (e.g. Miller-Struttmann et al., 2017) and the use of artificial-sound-assisted pollination for crops like tomatoes or strawberries that respond to sonication to replicate natural pollination (Dingley et al., 2022) are in the rise. However environmental noise may disrupt the necessary signals and hamper the further development of these methods. Thus, focusing research on the effects of noise on pollination is inevitable from this perspective as well.

Ultimately, gaining a comprehensive understanding of the ecological effects of noise pollution on bumblebees' and other pollinators' behaviour has a high potential for developing practices that better support pollinator health and well-being, ensuring the sustainability of pollination-dependent agriculture in a rapidly urbanising world.

Data availability

Data and the underlying computer code are available in the GitHub repository https://github.com/zsvargaszilay/buzz_amidst_noise/

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT-4 Turbo and Grammarly solely to improve the readability and language of the manuscript. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Zsófia Varga-Szilay: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gergely Szövényi:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Gábor Pozsgai:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful to Gábor Deák (Szentes-Bio Kft.) for choosing the experimental site and for helping us with the organization throughout the experiment. We also thank the Szentesi Pa-ri Kft. for providing the experimental site and for contributing to the follow-up data collection. Last but not least, we thank the Talent Support Council of ELTE Eötvös Loránd University for supporting the experiment.

Funding

GP was supported by the contract FCT-UIDP/00329/2020-2024 (Thematic Line 1 – integrated ecological assessment of environmental change on biodiversity, https://doi.org/10.54499/UIDB/00329/2020) and by the Azores DRCT Pluriannual Funding (M1.1.A/FUNC.UI&D/010/2021-2024).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.baae.2025.05.008.

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