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Research Article

Assessing Ecotheological 'Blessing–Cursing' Treatments in Agroecosystems: Chili Pepper Yield Responses and Pollinator Community Metrics

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Abstract
This study examined the association between ecotheological verbal treatments and agroecosystem performance by comparing chili pepper yield and pollinator community metrics across two treatment zones. Employing a field-based stratified purposive design, the study compared a blessing zone, which received prayer and positive verbal expressions, with a cursing zone, which received controlled negative verbal expressions. Pollinator observations were conducted using 18 modified Pollard Walk transects, while microclimatic variables, including temperature, relative humidity, light intensity, wind speed, and altitude, were measured across three daily intervals. Chili pepper yield was assessed through fruit number, average fruit weight, fruit length, and yield per plant, while pollinator communities were analyzed using Shannon diversity, Margalef richness, evenness, dominance, species richness, and abundance indices. The results showed that the blessing zone produced higher chili pepper yield and supported a more diverse, richer, and more abundant pollinator community than the cursing zone, while microclimatic conditions remained relatively comparable. These findings suggest that ecotheological blessing may be understood not as a direct causal mechanism, but as a care-oriented ecological praxis that may encourage attentiveness, responsibility, and more sustainable agroecosystem management. The study implies that integrating ecological science with spiritual-ethical values can offer a culturally meaningful approach to biodiversity-sensitive and sustainable agriculture.

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Introduction

Ecotheology has increasingly become an important conceptual framework for rethinking the relationship between human beings, non-human creation, and ecological responsibility. Rather than viewing nature merely as an exploitable resource, ecotheology positions the natural world as part of a morally and spiritually meaningful creation that demands care, restraint, and ethical accountability. This perspective is consistent with contemporary discussions on creation care, ecological conversion, and ecospirituality, which argue that environmental crises are not only technical or managerial problems but also moral, cultural, and spiritual problems requiring transformation in human values and practices (Beling, 2023; de Diego-Cordero et al., 2024; Messias, 2024). In this sense, religious practices such as prayer, blessing, gratitude, and respectful verbal expressions toward nature may be interpreted not as magical interventions, but as embodied ecological praxis that shapes human attention, responsibility, and care-oriented behavior within agricultural landscapes (Bock, 2024; Mweta et al., 2022; Yulisinta et al., 2024).

Within agroecosystems, such an ecotheological perspective is particularly relevant because farming is not simply a technical process of production but a relational practice involving soil, plants,

insects, water, climate, and human management. Agroecology emphasizes that agricultural productivity is shaped by the interaction between biotic and abiotic components, including crop management, microclimate, habitat structure, and biodiversity-based ecosystem services (Dietrich et al., 2025; Ghersa, 2013; Liang et al., 2025). Among these ecosystem services, pollination plays a crucial role in supporting crop productivity, fruit quality, seed formation, and broader agroecosystem resilience. Previous studies have shown that pollinators contribute substantially to global crop production, food security, and ecosystem stability, while their decline is associated with habitat loss, land-use intensification, pesticide exposure, climate change, and reduced floral resources (Dada et al., 2025; Kitikidou et al., 2024; Liu et al., 2021). Therefore, integrating ecotheological ethics with agroecological monitoring offers a promising interdisciplinary pathway for examining whether spiritually framed practices can be associated with more careful land management and healthier ecological indicators.

Pollinator communities are particularly suitable as ecological indicators because their abundance, richness, evenness, and dominance are sensitive to habitat quality, vegetation structure, disturbance intensity, and microclimatic variation. Diversity indices such as Shannon diversity, Margalef richness, evenness, and dominance are commonly used to evaluate whether a habitat supports a stable and balanced biological community, although their interpretation must always consider sampling intensity, ecological context, and environmental variability (Dada et al., 2025; Magni et al., 2023; Stamin & Cosmulescu, 2025). The Pollard Walk method has been widely adopted in butterfly and pollinator monitoring because it provides a standardized transect-based approach for comparing pollinator presence across habitats, especially when observation time, transect length, observer consistency, and weather conditions are carefully controlled (Barkmann et al., 2023; Isaac et al., 2011; Viliani et al., 2022). In chili pepper agroecosystems, pollinator monitoring is also agronomically meaningful because insect visitation can influence fruit set, fruit size, seed development, and yield-related traits in *Capsicum* species and related pepper crops (Sikorska et al., 2022; Tai et al., 2025; Zhou et al., 2024).

At the same time, claims regarding the direct effects of spoken words, prayer, or negative verbal treatment on plant growth must be approached with scientific caution. Recent plant science has shown that plants may respond to certain acoustic or vibrational stimuli, including pollinator sounds and stress-related airborne signals; however, these studies involve controlled acoustic conditions, measurable frequencies, and specific physiological responses rather than ordinary human speech as a direct causal mechanism (Bugannim et al., 2025; Morales-Luque et al., 2025; Stokes et al., 2019). Consequently, the most scientifically conservative explanation for ecotheological "blessing" practices in agriculture is not that verbal expressions directly alter plant physiology, but that spiritually meaningful practices may mediate human behavior by increasing attentiveness, consistency of care, observational discipline, and ethical sensitivity toward the cultivated environment (Al-Attas Bradford, 2022; Leach, 2013; LeVasseur, 2025). This distinction is essential for maintaining methodological rigor and avoiding unsupported causal claims while still allowing ecotheology to be empirically examined as a value-based framework for sustainable agricultural practice.

Previous studies have extensively examined three related but largely separate areas: ecotheology as a framework for ecological ethics and spiritual transformation, agroecology as a scientific approach to biodiversity-based farming systems, and pollinator ecology as a measurable

indicator of agroecosystem health (Bicksler et al., 2023; Jones et al., 2023; Vikas & Ranjan, 2024). However, limited empirical research has connected ecotheological practices with measurable agronomic and ecological indicators in a field-based crop system. Existing ecotheological studies tend to remain conceptual, theological, or educational, while pollinator and crop-yield studies usually focus on habitat structure, pollinator diversity, pollination services, or management intensity without explicitly considering religiously framed care practices as part of the agroecosystem context (Giovanetti et al., 2021; Jones et al., 2023; Katumo et al., 2022). This leaves an important research gap: whether ecotheological praxis, operationalized through "blessing" and "cursing" verbal treatments, is associated with observable differences in chili pepper yield and pollinator community structure when microclimatic conditions are monitored and compared systematically.

Based on this gap, the present study aims to assess the relationship between ecotheological "blessing–cursing" treatments and agroecosystem outcomes by comparing chili pepper yield, pollinator community metrics, and microclimatic conditions across two treatment zones. Specifically, this study examines whether the zone receiving prayer and positive verbal expressions shows different agronomic performance and pollinator diversity patterns compared with the zone receiving negative verbal expressions. By integrating ecotheological interpretation with field-based agroecological measurement, this study contributes a novel interdisciplinary approach that positions spiritual-ethical practice not as a substitute for scientific agronomy, but as a potential mediator of care-oriented agricultural behavior and ecological attentiveness. Its contribution lies in developing a more empirically grounded model of ecotheological praxis within agroecosystem research, while also offering a cautious framework for future studies that seek to examine the relationship between religious values, sustainable crop management, and biodiversity-sensitive farming.

Method

This study employed a field-based comparative design using a stratified purposive approach to examine the association between ecotheological verbal treatments, chili pepper yield, and pollinator community structure in an agroecosystem. The comparative design was selected because the study sought to observe differences between two treatment zones under relatively similar crop and environmental conditions. The ecotheological dimension was positioned not as a direct metaphysical causal mechanism, but as a value-based ecological praxis that reflects care, relational responsibility, and ethical interaction with the natural environment. This position is consistent with recent ecotheological studies that emphasize environmental stewardship, religious-ethical responsibility, and the moral relationship between humans and ecosystems (Bratton, 2002, 2018). The verbal treatments were also treated as a form of standardized acoustic or verbal exposure, considering that recent plant science literature has discussed sound and vibration as environmental stimuli that may influence plant physiological responses, although such effects must be interpreted cautiously and empirically (Doesborgh et al., 2004; Kozłowski & Młyński, 2014).

The research site was divided into two treatment zones with comparable crop conditions, cultivation practices, and environmental characteristics. Zone A received prayer and positive verbal expressions, hereafter referred to as the "blessing" treatment, whereas Zone B received controlled negative verbal expressions, hereafter referred to as the "cursing" treatment. The negative expressions were formulated in neutral, non-human-directed language to avoid hate speech, psychological harm, or unethical communication toward individuals or groups. Both zones were selected purposively based on accessibility, similarity of planting conditions, and feasibility for

repeated ecological observations. To reduce environmental bias, the same observation protocol, measurement schedule, sampling duration, and field instruments were applied in both zones.

The crop observed in this study was chili pepper (*Capsicum annuum* L.), cultivated under field conditions. Chili pepper was selected because it is an economically important horticultural crop and its productivity can be assessed through clear agronomic indicators, including fruit number, fruit weight, fruit length, and total yield per plant. Previous studies have shown that pollinator activity can contribute to chili pepper fruit set and productivity, making chili pepper a relevant crop for studying the relationship between plant performance and pollinator community dynamics (Pereira et al., 2015; Reddy et al., 2022). The use of chili plants also allowed the study to examine both agronomic outcomes and ecological indicators within the same agroecosystem setting.

The ecotheological verbal treatments were applied consistently throughout the observation period using standardized verbal scripts, fixed treatment duration, and similar distance from the plants. In the blessing zone, the verbal treatment consisted of prayer, gratitude, and positive expressions emphasizing care, growth, ecological harmony, and appreciation for life. In the cursing zone, the verbal treatment consisted of controlled negative expressions directed only toward the plant condition in a non-offensive and non-discriminatory manner. This procedure was intended to ensure that the comparison between zones was based on treatment consistency rather than uncontrolled differences in researcher attention, emotional expression, or interaction intensity. All verbal treatments were delivered at comparable times and under comparable field conditions to maintain procedural consistency.

Pollinator observation was conducted using a modified Pollard Walk transect method (Barkmann et al., 2023; Walpole & Sheldon, 1999). This approach was selected because transect-based observation is widely used in pollinator monitoring and allows systematic recording of pollinator diversity and abundance under field conditions (Bruschini et al., 2026; Zhang et al., 2026). A total of 18 transects were established, consisting of nine transects in the blessing zone and nine transects in the cursing zone. Each transect was 50 m in length with a 5 m observation belt, extending 2.5 m on each side of the transect line. The minimum distance between transects was maintained at approximately 100 m to reduce the possibility of repeated observations of the same pollinator individuals. During each transect walk, all visible pollinators visiting chili flowers or moving within the observation belt were recorded.

Pollinators were identified to the lowest possible taxonomic level based on direct field observation, photographic documentation, and available identification references. Only active pollinators observed during standardized walking periods were included in the analysis. Individuals flying outside the observation belt, not interacting with the crop area, or not clearly identifiable were excluded from the final count. This procedure was used to improve the accuracy and consistency of pollinator data. Pollinator observation was considered important because both bee and non-bee pollinators can contribute to crop pollination services and agroecosystem stability (Giovanetti et al., 2021; Seddik & Ali, 2025).

Microclimatic variables were measured simultaneously with pollinator observation to control for possible environmental variation between zones. The measured variables included air temperature, relative humidity, light intensity, wind speed, and altitude. These variables were included because pollinator activity, foraging behavior, and visitation frequency may be affected by weather and field-level environmental conditions (Prado et al., 2021). Measurements were

conducted at each transect during three daily observation intervals: morning from 07.00 to 09.00, midday from 11.00 to 13.00, and afternoon from 15.00 to 17.00. These intervals were selected to capture daily variation in pollinator activity and microclimatic conditions. Observations were not conducted during heavy rain, extreme wind, or very low visibility to maintain comparability across observation sessions.

Chili pepper yield was assessed using systematic plant sampling within each transect belt. In each transect, a fixed number of chili plants was selected using a systematic sampling interval to avoid subjective selection bias. The observed yield variables included the number of fruits per plant, average fruit weight, fruit length, and total yield per plant expressed in grams. Fruit number was counted directly from each sampled plant, while fruit weight was measured using a digital scale. Fruit length was measured using a ruler or caliper from the base to the tip of the fruit. Total yield per plant was calculated by summing the fruit weight obtained from each sampled plant. These variables were selected because they represent both quantitative productivity and fruit quality indicators relevant to chili pepper cultivation.

Pollinator community structure was analyzed using several ecological indices, including Shannon diversity index, Margalef richness index, evenness index, dominance index, species richness, and total abundance. The Shannon index was used to evaluate overall diversity by considering both richness and relative abundance. The Margalef index was used to estimate species richness in relation to the total number of individuals recorded. Evenness was calculated to determine whether individuals were distributed proportionally among taxa, while dominance was used to identify whether the community was dominated by one or a few taxa. These indices provided a broader ecological interpretation of community balance and pollinator distribution in each treatment zone.

Data analysis was conducted in several stages. First, descriptive statistics were calculated to summarize microclimatic variables, chili pepper yield, and pollinator community metrics in each treatment zone. The results were presented as mean, standard deviation, and relevant distribution values. Second, data normality was examined using the Shapiro–Wilk test, while homogeneity of variance was assessed using Levene's test. If the data met parametric assumptions, differences between the blessing and cursing zones were tested using an independent samples *t*-test. If the assumptions were not met, the Mann–Whitney U test was applied as a non-parametric alternative. This analytical procedure is consistent with statistical guidance emphasizing the importance of selecting tests based on data distribution and research design (Brezina, 2020; Salman & Aleem, 2024). Effect size was also calculated to determine the practical magnitude of differences between treatment zones, not merely statistical significance.

To strengthen interpretive validity, microclimatic variables were considered as potential covariates when necessary. This step was important to reduce the risk of attributing ecological or agronomic differences solely to verbal treatment without considering environmental variation. The interpretation of findings therefore focused on whether the blessing zone showed better agronomic performance and pollinator community indicators than the cursing zone under relatively comparable microclimatic conditions. Any observed difference was interpreted cautiously by considering possible mediating factors, including consistency of care, researcher attention, microhabitat condition, crop maintenance, and pollinator activity patterns. This methodological position was adopted to maintain scientific rigor while allowing ecotheology to be examined empirically as a value-based framework for sustainable agroecosystem management.

Result and Discussion

Result

This section presents the empirical patterns observed in the two ecotheological treatment zones: the blessing zone, which received prayer and positive verbal expressions, and the cursing zone, which received controlled negative verbal expressions. The results are organized into three analytical dimensions: microclimatic comparability, chili pepper growth and yield performance, and pollinator community structure. Microclimatic data are presented first to determine whether both zones were environmentally comparable during observation. Chili pepper yield variables are then examined to describe agronomic responses across zones. Finally, pollinator community indices are analyzed to assess whether the treatment zones differed in ecological quality and biodiversity patterns. The discussion interprets these findings cautiously by positioning the ecotheological treatment not as a direct metaphysical causal factor, but as a possible value-based praxis that may influence care, attention, and agroecosystem management behavior.

Microclimatic Conditions Across Treatment Zones

The microclimatic measurements indicate that both treatment zones had relatively comparable environmental conditions across the three observation intervals. As shown in Table 1, temperature, relative humidity, light intensity, wind speed, and altitude did not show extreme differences between Zone A and Zone B. In the morning interval, Zone A recorded a slightly higher temperature than Zone B, while Zone B showed a slightly lower wind speed. During midday, both zones experienced similar increases in temperature and light intensity, indicating that the observation areas were exposed to comparable daytime radiation. In the afternoon, temperature and light intensity declined in both zones, although wind speed was slightly higher in Zone B.

Table 1. Average microclimate by zone and observation interval

Zone	Interval	Temperature (°C)	RH (%)	Light (μmol m^{-2} s^{-1})	Wind (m/s)	Altitude (m)
Zone A	07.00–09.00	27.3	86	491	0.86	120
Zone A	11.00–13.00	31.0	69	960	1.24	120
Zone A	15.00–17.00	29.9	76	605	1.17	120
Zone B	07.00–09.00	26.6	84	460	0.58	120
Zone B	11.00–13.00	31.3	67	951	1.27	120
Zone B	15.00–17.00	30.0	73	595	1.50	120

Table 1 demonstrates that the two zones were not characterized by major microclimatic contrasts. This is important because temperature, humidity, light intensity, and wind speed can influence pollinator activity, flower visitation, and plant physiological processes. The relatively similar microclimatic profile suggests that differences in chili yield and pollinator community metrics should not be attributed solely to environmental variation. However, because wind speed and humidity showed minor fluctuations between zones, these variables should still be considered in interpreting pollinator activity, particularly because flying insects are sensitive to weather conditions during transect observations.

Chili Pepper Growth and Yield Performance

The chili pepper yield data show that Zone A, which received prayer and positive verbal expressions, produced higher values across all measured agronomic indicators than Zone B. As presented in Table

2, the average number of fruits per plant in Zone A was 59.56 ± 6.54, compared with 55.00 ± 3.64 in Zone B. The average fruit weight was also higher in Zone A, with 7.51 ± 0.51 g compared with 7.15 ± 0.56 g in Zone B. A similar pattern was observed for fruit length and total yield per plant. Zone A recorded an average fruit length of 11.28 ± 0.72 cm and total yield of 447.22 ± 49.60 g per plant, whereas Zone B recorded 10.79 ± 0.55 cm and 392.44 ± 50.32 g per plant.

Table 2. Chili pepper growth and yield by treatment zone (mean ± SD)

Zone	Number of fruits/plant	Average fruit weight (g)	Fruit length (cm)	Yield (g/plant)
Zone A	59.56 ± 6.54	7.51 ± 0.51	11.28 ± 0.72	447.22 ± 49.60
Zone B	55.00 ± 3.64	7.15 ± 0.56	10.79 ± 0.55	392.44 ± 50.32

The pattern in Table 2 suggests that the blessing zone showed better descriptive agronomic performance than the cursing zone. The most notable difference was observed in total yield per plant, where Zone A produced approximately 54.78 g more than Zone B. This result is visually reinforced in Figure 1, which displays the comparison of chili pepper yield between the two treatment zones. The figure should be used to help readers quickly identify the direction and magnitude of the yield difference, while the table provides more detailed information on the specific yield components.

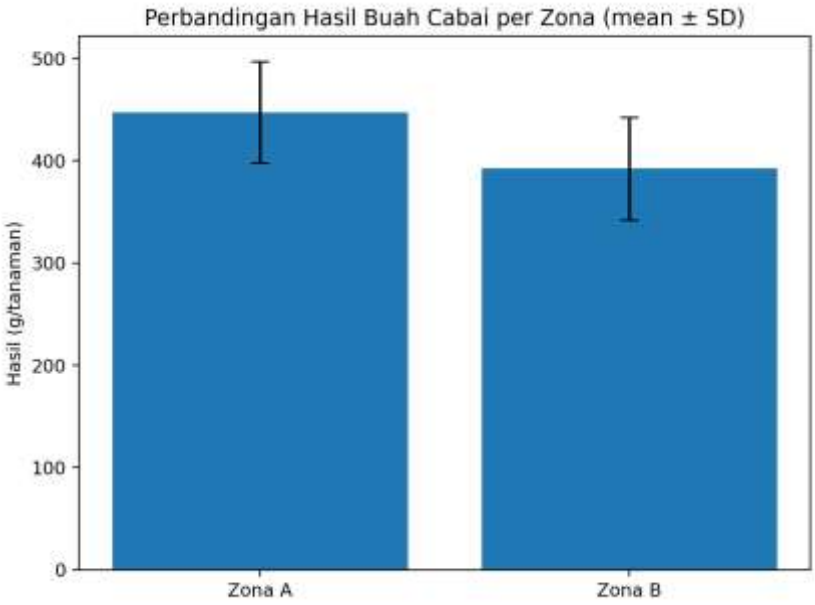


Figure 1. Comparison of chili pepper yield by treatment zone (mean ± SD)

Descriptively, the higher yield in Zone A may indicate that the blessing treatment was associated with more favorable crop performance. Nevertheless, this finding should be interpreted cautiously. Without inferential statistics, the difference should not yet be claimed as statistically significant. Instead, the result provides an empirical basis for further statistical testing using an independent samples *t*-test or a non-parametric alternative, depending on data normality and variance homogeneity. From an ecotheological perspective, this pattern may be interpreted as a possible outcome of more attentive and care-oriented interaction with the crop environment rather than as direct evidence that verbal expressions independently caused plant growth differences.

Pollinator Community Structure

The pollinator community indices also show a more favorable ecological pattern in Zone A than in Zone B. As shown in Table 3, the Shannon diversity index was higher in Zone A, with a value of 2.10 ± 0.13, compared with 1.91 ± 0.20 in Zone B. This indicates that the blessing zone had a more diverse pollinator community. The Margalef richness index was also higher in Zone A, suggesting greater taxonomic richness. Evenness values were relatively close between zones, but Zone A still showed a slightly higher value, indicating a more balanced distribution of pollinator individuals across taxa. Meanwhile, the dominance index was lower in Zone A than in Zone B, suggesting that the pollinator community in Zone A was less dominated by one or a few taxa.

Table 3. Pollinator community indices by treatment zone (mean ± SD)

Zone	Shannon (H′)	Margalef (R)	Evenness (E)	Dominance (D)	Richness (S)	Individuals (N)
Zone A	2.10 ± 0.13	2.22 ± 0.22	0.88 ± 0.03	0.15 ± 0.02	10.89 ± 0.93	88.00 ± 15.76
Zone B	1.91 ± 0.20	2.01 ± 0.28	0.86 ± 0.07	0.18 ± 0.05	9.33 ± 1.32	63.89 ± 10.03

Table 3 indicates that Zone A supported a more diverse, richer, and more abundant pollinator community. The total number of individuals observed in Zone A was 88.00 ± 15.76, while Zone B recorded 63.89 ± 10.03. This difference suggests that the blessing zone may have offered more favorable ecological conditions for pollinator activity. Figure 2 further illustrates the difference in Shannon diversity between the two zones, showing that Zone A had a higher pollinator diversity value.

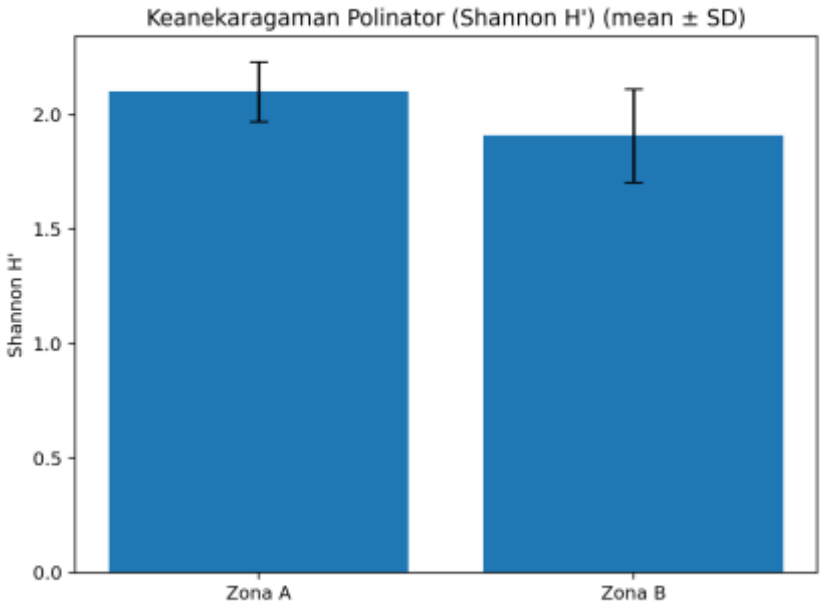


Figure 2. Pollinator diversity based on Shannon index (H′) by treatment zone (mean ± SD)

The higher Shannon index in Zone A indicates that the pollinator community in this zone was not only more abundant but also more diverse. This is ecologically meaningful because higher pollinator diversity may contribute to more stable pollination services, particularly in crop systems that benefit from insect visitation. Figure 3 strengthens this interpretation by showing the difference in species richness between the two zones. Zone A recorded higher richness than Zone B, suggesting that the blessing zone may have provided a more supportive microhabitat for different pollinator taxa.

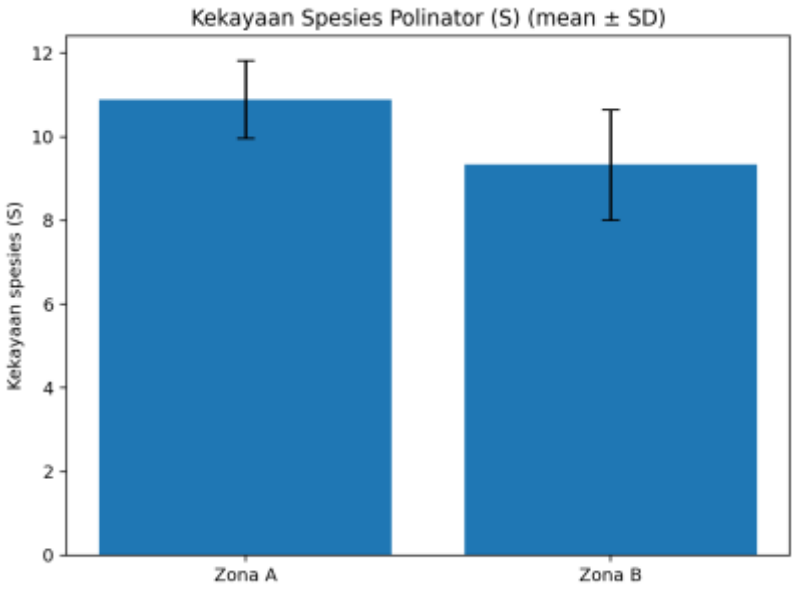


Figure 3. Pollinator species richness (S) by treatment zone (mean ± SD)

Taken together, the pollinator data suggest that Zone A had better ecological community indicators than Zone B. The combination of higher Shannon diversity, higher Margalef richness, higher species richness, greater abundance, and lower dominance indicates a more balanced pollinator assemblage. However, as with the chili yield data, these findings should be interpreted descriptively unless supported by inferential testing. Statistical comparison is needed to determine whether the observed differences are significant and not merely due to sampling variation.

Discussion

The present study shows that the blessing zone produced higher chili pepper yield and supported a more diverse pollinator community than the cursing zone, while microclimatic conditions remained relatively comparable between the two zones. This finding is consistent with the broader pollination literature, which emphasizes that insect pollinators contribute to crop productivity through pollen transfer, flower visitation, and improved reproductive success. Blili et al. (2025) reported that many global food crops depend at least partly on animal-mediated pollination, while Regmi et al. (2025) emphasized that wild and managed pollinators contribute not only to food security but also to biodiversity stability and farmer livelihoods. In this context, the higher yield and pollinator diversity observed in the blessing zone may indicate that a more supportive ecological condition can enhance crop performance, although the present study should not yet be interpreted as proving direct causality between verbal treatment and plant productivity.

The result is also aligned with the findings of Pinheiro-Costa & Mesquita-Neto (2026), who showed that insect pollination significantly improved several chili production indicators, including fruit number, fruit length, fruit diameter, fruit weight, seed number, seed weight, and yield. The present study similarly found higher fruit number, average fruit weight, fruit length, and yield per plant in the zone where pollinator abundance and diversity were also higher. This comparison strengthens the interpretation that pollinator community quality may be a functional ecological pathway connecting agroecosystem condition with chili productivity. However, unlike Nasrin et al., the present study does not isolate pollination treatment through exclusion or controlled pollinator

access; therefore, the relationship between pollinator metrics and yield should be interpreted as associative rather than experimentally causal.

The higher pollinator diversity in the blessing zone is further supported by Cooley & Vallejo-Marín (2021), who reported that the presence of animal pollinators increased chili fruit set under field-realistic conditions in southern India. This is important because earlier greenhouse-based studies sometimes underestimated the role of animal pollination in chili crops. The present study contributes to this debate by showing that, under open-field agroecosystem conditions, chili yield differences may correspond with differences in pollinator richness, abundance, and diversity. Thus, the findings support the argument that chili pepper should not be treated merely as a self-pollinated crop, but as a crop whose productivity may be strengthened by pollinator activity, particularly in ecologically diverse field conditions.

The findings also correspond with Indonesian research by Aminatun et al. (2023), which found that flowering trap crops influenced pollinator insect visitation on chili plants and that marigold-based trap cropping could support chili production without inhibiting pollinator visits. This comparison is relevant because both studies highlight the importance of field-level ecological management in chili cultivation. However, the present study differs from Aminatun et al. by not focusing on floral trap crops as a habitat-management intervention, but on ecotheological verbal treatment as a symbolic and behavioral ecological praxis. This distinction strengthens the novelty of the present research because it expands chili pollinator studies beyond habitat manipulation and introduces religious-ethical practice as a possible dimension of agroecosystem care.

The result is also comparable with Tri Atmowidi et al. (2022), who reported that stingless bees, particularly *Trigona* species, can function as effective pollinators for chili pepper and increase chili production. Although Putra et al. focused more specifically on managed stingless bee pollination, the present study focuses on naturally observed pollinator communities across treatment zones. The similarity lies in the shared conclusion that pollinator presence is agronomically meaningful for chili production. The difference lies in the present study's attempt to connect pollinator diversity with a broader ecotheological framework, suggesting that sustainable crop production may be influenced not only by biological agents but also by the ethical orientation of human management practices.

Tri Atmowidi et al. (2022) also demonstrated that stingless bee pollination can increase fruit formation and reduce abnormal fruit formation in several horticultural crops. Although their study examined strawberry and melon rather than chili, it strengthens the broader argument that tropical stingless bees are important pollination agents for horticultural productivity. The present study extends this perspective by showing that higher pollinator abundance and diversity may also be associated with better chili yield indicators. Nevertheless, because the present study did not measure pollinator efficiency at the species level, future research should identify which pollinator taxa contributed most strongly to chili flower visitation and fruit formation.

From the perspective of pollinator conservation, the present findings are consistent with global evidence that pollinator decline is driven by land-use change, management intensity, pesticide exposure, climate change, pathogens, and habitat degradation. Dicks et al. (2021) identified multiple global drivers and risks associated with pollinator decline, while the IPBES assessment emphasized that pollinators are essential for food production and that high pollinator diversity supports ecosystem stability. In this study, the blessing zone's higher Shannon diversity, richness, and abundance may indicate a more favorable microhabitat condition for pollinator activity. However,

because the study did not directly measure pesticide exposure, surrounding vegetation composition, nesting resources, or floral resource availability, these ecological mechanisms remain plausible explanations rather than confirmed causal pathways.

The ecotheological interpretation of the findings is supported by Conradie (2020), who argues that ecotheology involves both critique of ecological destruction and constructive contribution to public ecological discourse. Messias (2024) similarly emphasizes that ecotheology can develop into ecospirituality when ecological concern becomes embodied in daily practice. In relation to the present findings, the blessing treatment can be interpreted as a form of ecological spirituality that may encourage attentiveness, patience, and responsibility toward plants, insects, and land. This does not mean that prayer or positive words directly caused higher yield, but that such practices may function as ethical reminders that shape more careful agroecosystem interaction.

The behavioral pathway is further supported by studies on religiosity and pro-environmental behavior. Karimi et al. (2022) found that religiosity can influence pro-environmental behavior directly and indirectly through perceived behavioral control, subjective norms, and environmental attitudes. In Indonesia, Sa'id et al. (2024) also found that religiosity significantly predicts pro-environmental behavior among university students. These studies support the interpretation that religious or spiritual orientation may shape ecological behavior through values, norms, and perceived responsibility. Therefore, the present study's blessing treatment is best understood as a care-mediated practice rather than a supernatural intervention; its possible effect lies in how it may encourage more mindful observation, more consistent crop care, and more respectful interaction with the agroecosystem.

The present study also resonates with national studies on Islamic ecotheology and environmental care. Rohman et al. (2024) showed that Islamic eco-theology can be integrated into Islamic Religious and Character Education as an ethical-spiritual basis for environmental education. Sabtina & Mahariah (2025) similarly found that Islamic ecotheological values internalized through school culture can foster students' environmental care character. Compared with these studies, the present research moves beyond educational and character-formation settings by testing ecotheological praxis in an agricultural field context. This is a significant extension because it translates ecotheological discourse from curriculum, school culture, and moral education into measurable agroecosystem indicators, including crop yield and pollinator community metrics.

The acoustic-stimulus dimension of the study must be interpreted with caution. Demey et al. (2023) reviewed evidence that plants may perceive sound and respond to certain acoustic stimuli, while Khait et al. (2023) demonstrated that stressed plants can emit airborne ultrasonic sounds that carry information about plant condition. Chowdhury et al. (2014) also reported that sound vibration may influence plant growth and signal responses under controlled conditions. These studies suggest that plant–sound interaction is a legitimate scientific topic, but they do not justify a direct claim that ordinary human speech, prayer, or negative words automatically produce measurable yield differences. Therefore, the present study should frame acoustic influence only as an exploratory hypothesis requiring strict control of frequency, intensity, distance, duration, and environmental interference.

The novelty of this study lies in its interdisciplinary integration of ecotheology, agroecology, crop productivity, and pollinator community analysis. Previous studies have discussed ecotheology primarily as a theological, educational, or ethical framework, while pollinator studies have generally

focused on biological, ecological, or agronomic mechanisms. This study bridges these domains by examining whether ecotheological verbal praxis is associated with measurable field indicators, including chili yield, microclimatic comparability, and pollinator diversity. In this sense, the contribution of the study is not the claim that verbal blessing directly increases plant growth, but the development of an empirical framework for examining how spiritual-ethical practices may mediate care-oriented agricultural behavior and biodiversity-sensitive farming.

This study implies that sustainable agriculture can be strengthened by integrating ecological science with local religious and ethical values. Practically, ecotheological praxis may serve as a culturally meaningful approach for farmers, religious communities, and agricultural educators to promote care for soil, plants, pollinators, and biodiversity through concrete practices such as reducing land disturbance, maintaining flowering vegetation, limiting excessive pesticide use, monitoring pollinator activity, and improving crop care consistency. Theoretically, this study shows that ecotheology can be empirically operationalized without abandoning scientific caution by linking spiritual practice with measurable agroecosystem indicators, including biodiversity, crop performance, and ecological behavior. It also suggests that agroecosystem quality is shaped not only by physical habitat conditions, but also by human ethical orientation and daily management behavior, particularly in agricultural societies where religious values influence environmental decision-making.

Several limitations should be acknowledged. First, the current findings are primarily descriptive; therefore, the study cannot yet establish strong causal relationships between verbal treatment, pollinator metrics, and chili yield. Second, although microclimatic variables were relatively comparable, other ecological factors such as soil fertility, pest pressure, pesticide exposure, flowering density, surrounding vegetation, irrigation consistency, and crop health were not fully controlled. Third, the study did not measure the actual behavioral differences of caretakers or farmers, making the care-mediated pathway theoretically plausible but not yet empirically verified. Fourth, the acoustic component of the verbal treatment was not standardized in terms of frequency, decibel level, duration, and distance, which limits the possibility of testing plant response to sound scientifically. Fifth, pollinator identification was limited to observed field taxa and did not measure pollination efficiency per species. Future research should use larger samples, repeated seasonal observations, controlled treatment protocols, behavioral observation of crop care, species-level pollinator identification, and statistical models that can test direct and indirect pathways between ecotheological praxis, care behavior, pollinator diversity, and crop productivity.

Conclusion

This study demonstrates that the blessing zone, characterized by prayer and positive verbal expressions, showed higher chili pepper yield and more favorable pollinator community metrics than the cursing zone, while microclimatic conditions remained relatively comparable across both treatment areas. The higher number of fruits, average fruit weight, fruit length, and total yield per plant in the blessing zone were accompanied by greater pollinator diversity, richness, abundance, and lower dominance, suggesting a possible association between care-oriented ecological praxis and improved agroecosystem performance. From an ecotheological perspective, these findings indicate that blessing creation may function as an ethical-spiritual practice that strengthens attentiveness, responsibility, and relational care toward plants, pollinators, and the surrounding environment. However, the results should not be interpreted as evidence that verbal expressions directly cause

plant growth; rather, the most scientifically cautious interpretation is that ecotheological practice may operate indirectly through more consistent care, observation, and microhabitat management. The novelty of this study lies in its integration of ecotheology with measurable agroecological indicators, particularly crop yield and pollinator community structure. These findings imply that sustainable agricultural practices may be strengthened by combining ecological science with culturally and spiritually meaningful values, especially in farming communities where religious ethics influence environmental behavior. Future studies should employ larger samples, controlled acoustic protocols, direct measurement of crop-care behavior, species-level pollinator identification, and inferential statistical analysis to clarify the causal pathways between ecotheological praxis, pollinator diversity, and crop productivity.

References

Al-Attas Bradford, A. (2022). Religion, animals, and the theological anthropology of microbes in the Pandemicene. *Religions, 13*(12), Article 1146. https://doi.org/10.3390/rel13121146

Aminatun, T., Budiwati, B., Rahmawati, Y. F., Widiyanti, D. N. A., & Fahdah, L. A. (2023). The effects of flowering trap crops on diversity and longevity of pollinator insect visitation on chili plants. *Biodiversitas Journal of Biological Diversity, 24*(2), 887–893. https://doi.org/10.13057/biodiv/d240226

Barkmann, F., Huemer, P., Tappeiner, U., Tasser, E., & Rüdisser, J. (2023). Standardized butterfly surveys: Comparing transect counts and area-time counts in insect monitoring. *Biodiversity and Conservation, 32*(3), 987–1004. https://doi.org/10.1007/s10531-022-02534-2

Beling, A. (2023). The Catholic Church in times of ecological crisis: An "unusual suspect" in advancing the transition to sustainability? *Religion and Development, 2*(1), 103–125. https://doi.org/10.30965/27507955-20230018

Bicksler, A. J., Mottet, A., Lucantoni, D., Sy, M. R., & Barrios, E. (2023). The 10 elements of agroecology interconnected: Making them operational in FAO's work on agroecology. *Elementa: Science of the Anthropocene, 11*(1), Article 00041. https://doi.org/10.1525/elementa.2022.00041

Blili, Y., Abou Nader, E., Pavez, I., Prosperi, P., Harbouze, R., Kyrgiakos, L. S., Kleisiari, C., Vasileiou, M., Angelopoulos, V., Vlontzos, G., & Kleftodimos, G. (2025). Assessing the economic impact of insect pollination on the agricultural sector: A department-level case study in France. *Environmental and Sustainability Indicators, 28*, Article 100944. https://doi.org/10.1016/j.indic.2025.100944

Bock, C. (2024). Ecospiritual praxis: Cultivating connection to address the climate crisis. *Religions, 15*(11), Article 1405. https://doi.org/10.3390/rel15111405

Bratton, S. P. (2002). J. Baird Callicott's critique of Christian stewardship and the validity of religious environmental ethics. In W. Ouderkirk & J. Hill (Eds.), *Land, value, community: Callicott and environmental philosophy* (pp. 237–251). State University of New York Press. https://doi.org/10.1515/9780791489345

Bratton, S. P. (2018). Eco-dimensionality as a religious foundation for sustainability. *Sustainability, 10*(4), Article 1021. https://doi.org/10.3390/su10041021

Brezina, V. (2020). Classical monofactorial (parametric and non-parametric) tests. In M. Paquot & S. T. Gries (Eds.), *A practical handbook of corpus linguistics* (pp. 473–503). Springer International Publishing. https://doi.org/10.1007/978-3-030-46216-1_20

Bruschini, C., Penco, M., Barghigiani, O., Bordoni, A., Pasquali, L., Salvati, V., Dapporto, L., & Cini, A. (2026). Estimating wild bee population size with validated distance sampling. *Insect Conservation and Diversity, 19*(3), 469–483. https://doi.org/10.1111/icad.70053

Bugannim, Y., Roziner, I., & Kishon-Rabin, L. (2025). Speech recognition in noise across the life span with cognition and hearing sensitivity as mediators of age effects. *Scientific Reports, 15*, Article 20575. https://doi.org/10.1038/s41598-025-05882-5

Chowdhury, M. E. K., Lim, H.-S., & Bae, H. (2014). Update on the effects of sound wave on plants. *Research in Plant Disease, 20*(1), 1–7. https://doi.org/10.5423/RPD.2014.20.1.001

Cooley, H., & Vallejo-Marín, M. (2021). Buzz-pollinated crops: A global review and meta-analysis of the effects of supplemental bee pollination in tomato. *Journal of Economic Entomology, 114*(2), 505–519. https://doi.org/10.1093/jee/toab009

Dada, A. D., Olusola, A. J., Awotoye, O. O., & Odiwe, A. I. (2025). A comparative assessment of species diversity and structural characteristics in undisturbed forest reserve and protected forest in the humid tropical rainforests of Southwestern Nigeria. *Discover Forests, 1*, Article 41. https://doi.org/10.1007/s44415-025-00035-y

de Diego-Cordero, R., Martínez-Herrera, A., Coheña-Jiménez, M., Lucchetti, G., & Pérez-Jiménez, J. M. (2024). Ecospirituality and health: A systematic review. *Journal of Religion and Health, 63*(2), 1285–1306. https://doi.org/10.1007/s10943-023-01994-2

Demey, M. L., Mishra, R. C., & Van Der Straeten, D. (2023). Sound perception in plants: From ecological significance to molecular understanding. *Trends in Plant Science, 28*(7), 825–840. https://doi.org/10.1016/j.tplants.2023.03.003

Dicks, L. V., Breeze, T. D., Ngo, H. T., Senapathi, D., An, J., Aizen, M. A., Basu, P., Buchori, D., Galetto, L., Garibaldi, L. A., Gemmill-Herren, B., Howlett, B. G., Imperatriz-Fonseca, V. L., Johnson, S. D., Kovács-Hostyánszki, A., Kwon, Y. J., Lattorff, H. M. G., Lungharwo, T., Seymour, C. L., et al. (2021). A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nature Ecology & Evolution, 5*(10), 1453–1461. https://doi.org/10.1038/s41559-021-01534-9

Dietrich, A. S., Carini, V., Vico, G., Bommarco, R., & Hansson, H. (2025). Changing the understanding of crop production: Integrating ecosystem services into the production function. *Ecological Economics, 230*, Article 108526. https://doi.org/10.1016/j.ecolecon.2025.108526

Doesborgh, S. J. C., van de Sandt-Koenderman, M. W. E., Dippel, D. W. J., van Harskamp, F., Koudstaal, P. J., & Visch-Brink, E. G. (2004). Effects of semantic treatment on verbal communication and linguistic processing in aphasia after stroke. *Stroke, 35*(1), 141–146. https://doi.org/10.1161/01.STR.0000105460.52928.A6

Ghersa, C. M. (2013). Agroecological basis for managing biotic constraints. In *Sustainable food production* (pp. 18–30). Springer New York. https://doi.org/10.1007/978-1-4614-5797-8_196

Giovanetti, M., Albertazzi, S., Flaminio, S., Ranalli, R., Bortolotti, L., & Quaranta, M. (2021). Pollination in agroecosystems: A review of the conceptual framework with a view to sound monitoring. *Land, 10*(5), Article 540. https://doi.org/10.3390/land10050540

Isaac, N. J. B., Cruickshanks, K. L., Weddle, A. M., Rowcliffe, J. M., Brereton, T. M., Dennis, R. L. H., Shuker, D. M., & Thomas, C. D. (2011). Distance sampling and the challenge of monitoring butterfly populations. *Methods in Ecology and Evolution, 2*(6), 585–594. https://doi.org/10.1111/j.2041-210X.2011.00109.x

Jones, R. W., Ornelas-García, C. P., Pineda-López, R., & Álvarez, F. (Eds.). (2023). *Mexican fauna in the Anthropocene*. Springer International Publishing. https://doi.org/10.1007/978-3-031-17277-9

Karimi, S., Liobikienė, G., & Alitavakoli, F. (2022). The effect of religiosity on pro-environmental behavior based on the theory of planned behavior: A cross-sectional study among Iranian rural female facilitators. *Frontiers in Psychology, 13*, Article 745019. https://doi.org/10.3389/fpsyg.2022.745019

Katumo, D. M., Liang, H., Ochola, A. C., Lv, M., Wang, Q.-F., & Yang, C.-F. (2022). Pollinator diversity benefits natural and agricultural ecosystems, environmental health, and human welfare. *Plant Diversity, 44*(5), 429–435. https://doi.org/10.1016/j.pld.2022.01.005

Khait, I., Lewin-Epstein, O., Sharon, R., Saban, K., Goldstein, R., Anikster, Y., Zeron, Y., Agassy, C., Nizan, S., Sharabi, G., Perelman, R., Boonman, A., Sade, N., Yovel, Y., & Hadany, L. (2023). Sounds emitted by plants under stress are airborne and informative. *Cell, 186*(7), 1328–1336.e10. https://doi.org/10.1016/j.cell.2023.03.009

Kitikidou, K., Milios, E., Stampoulidis, A., Pipinis, E., & Radoglou, K. (2024). Using biodiversity indices effectively: Considerations for forest management. *Ecologies, 5*(1), 42–51. https://doi.org/10.3390/ecologies5010003

Kozłowski, E., & Młyński, R. (2014). Effects of acoustic treatment on music teachers' exposure to sound. *Archives of Acoustics, 39*(2), 159–163. https://doi.org/10.2478/aoa-2014-0019

Leach, J. (2013). Mathematics, ancient and medieval. In *Encyclopedia of sciences and religions* (pp. 1229–1231). Springer Netherlands. https://doi.org/10.1007/978-1-4020-8265-8_1273

LeVasseur, T. J. (Ed.). (2025). *Religion and planetary climate crisis*. MDPI. https://doi.org/10.3390/books978-3-7258-5318-2

Liang, X., Yu, S., Ju, Y., Wang, Y., & Yin, D. (2025). Integrated management practices foster soil health, productivity, and agroecosystem resilience. *Agronomy, 15*(8), Article 1816. https://doi.org/10.3390/agronomy15081816

Liu, Y., Zhang, M., Peng, W., Qu, X., Zhang, Y., Du, L., & Wu, N. (2021). Phylogenetic and functional diversity could be better indicators of macroinvertebrate community stability. *Ecological Indicators, 129*, Article 107892. https://doi.org/10.1016/j.ecolind.2021.107892

Magni, P., Vesal, S. E., Giampaoletti, J., Como, S., & Gravina, M. F. (2023). Joint use of biological traits, diversity and biotic indices to assess the ecological quality status of a Mediterranean transitional system. *Ecological Indicators, 147*, Article 109939. https://doi.org/10.1016/j.ecolind.2023.109939

Messias, T. (2024). From ecotheology to ecospirituality in *Laudato sí*: Ecological spirituality beyond Christian religion. *Religions, 15*(1), Article 68. https://doi.org/10.3390/rel15010068

Morales-Luque, C., Carrillo-Franco, L., López-González, M. V., González-García, M., & Dawid-Milner, M. S. (2025). Mapping the neurophysiological link between voice and autonomic function: A scoping review. *Biology, 14*(10), Article 1382. https://doi.org/10.3390/biology14101382

Mweta, N., Juma, P., & Phiri, S. B. (2022). Conservation of natural forests through indigenous religious beliefs and practices: A case study of M'bona Cult, Nsanje District, Malawi. In *Socio-ecological systems and decoloniality* (pp. 157–177). Springer International Publishing. https://doi.org/10.1007/978-3-031-15097-5_8

Pereira, A. L. C., Taques, T. C., Valim, J. O. S., Madureira, A. P., & Campos, W. G. (2015). The management of bee communities by intercropping with flowering basil (*Ocimum basilicum*) enhances pollination and yield of bell pepper (*Capsicum annuum*). *Journal of Insect Conservation, 19*(3), 479–486. https://doi.org/10.1007/s10841-015-9768-3

Pinheiro-Costa, B. K., & Mesquita-Neto, J. N. (2026). First report of the comparative effectiveness of insect visitors for cranberry pollination and yield in Chile. *BMC Plant Biology, 26*, Article 375. https://doi.org/10.1186/s12870-026-08402-3

Prado, S. G., Collazo, J. A., Marand, M. H., & Irwin, R. E. (2021). The influence of floral resources and microclimate on pollinator visitation in an agro-ecosystem. *Agriculture, Ecosystems & Environment, 307*, Article 107196. https://doi.org/10.1016/j.agee.2020.107196

Reddy, P. V. R., Rajan, V. V., Mani, M., Kavitha, S. J., & Sreedevi, K. (2022). Insect pollination in horticultural crops. In M. Mani (Ed.), *Trends in horticultural entomology* (pp. 491–516). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-0343-4_15

Regmi, B., Dahal, S., Poudel, S. R., & Timberlake, T. P. (2025). Native pollinators in Nepal: Their importance, threats, and conservation needs. *Global Ecology and Conservation, 64*, Article e03934. https://doi.org/10.1016/j.gecco.2025.e03934

Rohman, A., Kurniawan, E., Syifauddin, M., Muhtamiroh, S., & Muthohar, A. (2024). Religious education for the environment: Integrating eco-theology in the curriculum of Islamic religious and character education to enhance environmental education in Indonesia. *Nadwa: Jurnal Pendidikan Islam, 18*(2), 201–226. https://doi.org/10.21580/nw.2024.18.2.21094

Sa'id, M., Wahyu, A. M., Muarifah, R., Qoyyimah, N. R. H., & Noorrizki, R. D. (2024). Religion and environment: The role of religiosity on pro-environmental behavior among university students in Indonesia. *KnE Social Sciences, 2024*(ICoPsy), 110–121. https://doi.org/10.18502/kss.v9i30.17510

Sabtina, D., & Mahariah, M. (2025). Internalizing Islamic ecotheology through school culture to foster eco-character. *Halaqa: Islamic Education Journal, 9*(2), 21–41. https://doi.org/10.21070/halaqa.v9i2.1754

Salman, H. M., & Aleem, D. N. (2024). An easy way to understand the research tools, scales and parametric & non-parametric tests. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4986837

Seddik, M. A., & Ali, M. A. (2025). Pollination by honeybee increases yield and quality of faba bean (*Vicia faba* L.) in semi-arid regions of Egypt. *Scientific Reports, 15*, Article 34113. https://doi.org/10.1038/s41598-025-20265-6

Sikorska, A., Gugała, M., Zarzecka, K., Domański, Ł., & Mystkowska, I. (2022). Morphological features of winter rape cultivars depending on the applied growth stimulators. *Agriculture, 12*(10), Article 1747. https://doi.org/10.3390/agriculture12101747

Stamin, F. D., & Cosmulescu, S. (2025). Assessing the vegetation diversity of different forest ecosystems in Southern Romania using biodiversity indices and similarity coefficients. *Biology, 14*(7), Article 869. https://doi.org/10.3390/biology14070869

Stokes, R. C., Venezia, J. H., & Hickok, G. (2019). The motor system's [modest] contribution to speech perception. *Psychonomic Bulletin & Review, 26*(4), 1354–1366. https://doi.org/10.3758/s13423-019-01580-2

Tai, S., Tang, Z., Li, B., Wang, S., & Guo, X. (2025). Intelligent recognition and automated production of chili peppers: A review addressing varietal diversity and technological requirements. *Agriculture, 15*(11), Article 1200. https://doi.org/10.3390/agriculture15111200

Atmowidi, T., Prawasti, T. S., Rianti, P., Prasojo, F. A., & Pradipta, N. B. (2022). Stingless bees pollination increases fruit formation of strawberry (*Fragaria × ananassa* Duch) and melon (*Cucumis melo* L.). *Tropical Life Sciences Research, 33*(1), 43–54. https://doi.org/10.21315/tlsr2022.33.1.3

Vikas, & Ranjan, R. (2024). Agroecological approaches to sustainable development. *Frontiers in Sustainable Food Systems, 8*, Article 1405409. https://doi.org/10.3389/fsufs.2024.1405409

Viliani, L., Bonelli, S., Vercelli, M., Roy, D. B., & Riva, F. (2022). Does a short Pollard walk transect capture butterfly and bee diversity? A test to inform pollinator monitoring and community science initiatives. *Insect Conservation and Diversity, 15*(6), 645–654. https://doi.org/10.1111/icad.12593

Walpole, M. J., & Sheldon, I. R. (1999). Sampling butterflies in tropical rainforest: An evaluation of a transect walk method. *Biological Conservation, 87*(1), 85–91. https://doi.org/10.1016/S0006-3207(98)00037-8

Yulisinta, F., Murniati, J., & Eigenstetter, M. (2024). Spiritual ecology and indigenous wisdom: Cultural foundations for sustainable environmental practices in Indonesia. *Religious: Jurnal Studi Agama-Agama dan Lintas Budaya, 8*(3), 185–202. https://doi.org/10.15575/rjsalb.v8i3.20237

Zhang, J., Liao, Z., Shen, X., Zhu, M., Chen, X., Feng, Z., & Zhang, Y. (2026). Urban expansion and butterfly diversity: The synergistic effects of impervious surface and vegetation cover. *Insects, 17*(5), Article 482. https://doi.org/10.3390/insects17050482

Zhou, W., Arcot, Y., Medina, R. F., Bernal, J., Cisneros-Zevallos, L., & Akbulut, M. E. S. (2024). Integrated pest management: An update on the sustainability approach to crop protection. *ACS Omega, 9*(40), 41130–41147. https://doi.org/10.1021/acsomega.4c06628