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Users opinion about synthetic, bio- and nano-biopesticides

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ABSTRACT

With a growing global population, the demand for food, clothing and shelter became crucial for sustaining life. Moreover, the COVID-19 pandemic/endemic, along with the threat of other endemics, posed significant challenges in ensuring the delivery of nutritionally rich food. To address this, the World Health Organization (WHO) recommended the ban of some highly toxic chemical pesticides. Excessive consumption and exposure to pesticides possibly contributed to a decline in the human immunity levels making our fight against the pandemics more difficult and challenging. During the lockdown COVID-19 crisis, we conducted a survey to gather insights from farm landers (FLs), garden lovers (GLs), domestic front users (DFUs) predominantly from India, but also from other regions worldwide. The survey aimed at better understanding the usage of pesticides, both chemicals (CPs), bio-pesticides (BPs) or both, and their global utilization. A statistical survey with seven rudimentary sections was designed to receive the inputs (elementary inputs, awareness and perception, pesticide utility, health, ecology, and alternatives for safer trials) with fairness and care. The data was statistically analyzed within each group of population, revealing significant variations within the groups. Our study indicated that FLs (44.7 %) predominantly used BPs, GLs (18.8 %) relied on CPs, while DFUs (100.0 %) used a combination of both without any specific intention. Correlation analysis, given by R (correlation coefficient) and p (probability of obtaining an equal or more extreme effect than the found considering the null hypothesis as true) values revealed the existence of a positive and significant relationship between the selected variables, such as level of education (LOE) and gender, with the adoption of new alternatives (2loglikelihood = 64.743, with $\chi^2 = 128.4$, degrees of freedom (df) = 24, p<*0.05, **0.01, and *** 0.001) through multinomial regression analysis, indicating the fitness of the model. Likewise, our study primarily focused on exploring the insights for the development of nano-biopesticides, as improved alternatives to the existing solutions.

1. Introduction

During the pandemic/endemic COVID-19 crisis, and frequent concerns for eruption of other endemics, providing food with the essential nutrients and minerals became a huge challenge for a rapidly increasing global population. The Food and Agriculture Organization (FAO) of the United Nations reported that only 50 % of the habitable land is currently used for agriculture, and it is expected that the cultivable land will decrease by 2050 (Benke and Tomkins, 2017; Viana, 2022). This poses further stress on supplying food for the growing demand, which is aggravated by the diminishing quality of water resources.

Agriculture is a vital sector for the economy, employing 60 % of India's rural population and approximately 2.5 billion people worldwide (Meena et al., 2022; Akecha et al., 2021; Carvalho, 2017). The United Nations (UN), a statutory body, in collaboration with the World Heath Organization (WHO) proposed specific criteria and objectives for pesticide usage, aiming to safeguard human health and protect the eco-systems by advocating the reduction of highly toxic pesticides (Carvalho, 2017; Lopez-Carmen et al., 2022; Chellappandian et al., 2018). The reason is that the persistent excessive use of pesticides and fertilizers raised concerns about health risks, resistance in pest populations, and ecological damage (Zhang et al., 2015).

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Unfortunately, pesticide usage has been increasing since the last century, with global utilization estimated to exceed 2,000,000,000 tons of synthetic pesticides (CPs). Argentina, China, and USA are among the major users. The worldwide utilization was predicted to scale up as 3,500,000,000 tons by the end of 2020 (Sharma et al., 2019). Food production (~45 %), which is often affected due to pest infestations, plays a crucial role in the world economy and crop yields contribute to the gross domestic product (GDP) in the global market.

The world economy is expanded by the food production and crop yields, that improve the gross domestic product (GDP, %) in the global market (Mellor, 2017). However, crop protection is challenged by pest attacks, during the entire process from production to storage and distribution, leading to the extensive usage of pesticides and fertilizers (Lopez-Galvez et al., 2019). Some banned pesticides and fertilizers caused health issues for both front applicators and end-consumers (Abhilash and Singh, 2019). To address these concerns, efforts are being made to reduce pesticide usage and explore safer alternatives (Sharma et al., 2019). Bio-pesticides and nano-biopesticides are gaining attention due to their eco-friendliness and effectiveness.

Pesticide users, whether due to ignorance or intentionally, often apply excessive amounts of chemical pesticides (CPs) to crops or areas infested with pests, in an attempt to achieve higher yields. However, this practice indirectly leads to increased toxicity, making the product unsuitable for consumption and living. The drift of CPs, through air and rain, causes mixing with soil, air, and water during spraying, compromising their purity. Indirect inhalation and exposure to CPs can have severe health consequences for both humans and the environment (Chellappandian et al., 2018). To address these dangers, new alternatives are emerging to enhance overall safety. Life threatening diseases like diabetes, cancer, birth defects, Alzheimer's or Parkinson's, thyroid problems and infertility are on the rise at an alarming rate (Kim et al., 2017).

Nevertheless, to overcome the negative impacts associated with CPs, targeted alternatives, such as bio-pesticides (BPs) and nano-biopesticides (NBPs), are attracting attention, due to their eco-friendliness. These alternatives, derived from natural sources, offer a safer and more sustainable approach to pest management. They provide suitability, stability, sustainability, and help to overcome resistance issues through low-dose modifications and cost reduction while ensuring the safety of both humans and the ecosystem. Plant-based options are considered the best and safest alternatives (Chellappandian et al., 2018). The use of small scale (micro and nano) materials for pest control is rising also in the Indian-subcontinent. A shift away from the use of CPs took place when their pesticidal activity was found to be significantly ineffective in controlling pests such as *Helicoverpa armigera*, *Spodoptera litura,* and cotton pests (Mishra et al., 2020). In India, biological control methods are attracting attention as cost-effective, eco-friendly and safer alternatives to CPs, with neem (*Azadirachta indica*) and its derivatives being the most commonly used bio-pesticides (Mishra et al., 2020).

Recent findings show the efficacy of wood-apple (*Limonia acidissima*), *Epaltes divaricate*, and *Avicennia marina* as BPs (Chellappandian et al., 2020; Amala et al., 2021; Yogarajalakshmi et al., 2020). These bio-pesticides can be derived from plant-based materials, microbials (fungi, bacteria, viruses), or pheromones. In spite of their many advantages, BPs still have a long way to go in terms of sustainability, as there are many gaps to be filled and obstacles to be addressed.

Nanotechnology is the best solution for overcoming the existing barriers of BPs, aligning with other environmental remediation methodologies (Yadav et al., 2021). The next best suitable alternatives are NBPs, that offer a relevant solution to the challenges at hand (Zhang et al., 2020). Researchers of several areas have been dedicating significant efforts to maintain the safety standards for food and water, preserving the sustainability mandated by the Environmental Protection Agency (EPA) and WHO.

As the world collectively strives to overcome the devastating COVID-19 pandemics through vaccinations and other preventive measures, it becomes crucial to investigate potential factors contributing to a decline in the necessary immunity levels to fight the disease. In the present study, we tried to gather and analyze the views of several people, including farm landers, garden lovers, medical and paramedical professionals, frontline workers engaged in the battle against COVID-19, and domestic users. Our objective was to gain a better understanding of pesticide utilization across the globe during the first and second historic waves of the pandemics. The work focused on specific segments shown in Fig. 1, with an emphasis on the fundamental factors of health, ecology, fairness, and care in pesticide applications. Ultimately, our research aimed to provide valuable insights into better alternatives to the existing trends, and identify obstacles and opportunities for the use of synthetic, bio-, and nano-biopesticides by the communities worldwide.

2. Materials and Methodology

A comprehensive multi-step segmented random sampling survey was conducted between May 2020 to July 2020 to unveil the primary factors disrupting the protection of the eco-system (including the well-being of humans, flora and fauna). To achieve this goal, it is imperative to embrace new logical approaches that combine conventional behavioral sciences with biological, physical and chemical factors. These new approaches should focus on thoroughly assessing the risk factors associated with human exposure to pesticides and the safety compliance of consumed food. In our survey work, we specifically concentrate on the behavioral aspects of pesticide users, (Liu et al., 2015) aiming to understand the unintended consequences inflicted on the eco-system and the pressing requirements for new cost-effective, resourceful, and non-toxic alternatives.

This survey analysis was conducted during the first wave of the devastating COVID-19 crisis, in various zones across India, with additional contributions from individuals worldwide. To ensure diverse and valuable inputs, a random selection was employed, gathering insights from different segments of the population, as presented in Table 1. The data were collected through scheduled direct and telephonic interviews, video calls, and virtual conferences conducted via platforms like Zoom and Google Meet. The accumulated data were subsequently validated by some inputs received through Google forms. The collected data were further analyzed using descriptive statistics, as described in Section 2.5.

2.1. Targeted zones

The survey targeted specific geographic regions, including the alpine areas of Eastern Ghats known for growing pepper, coffee, and ornamental flowers, in Tamil Nadu (TN), India. Additionally, it focused on the rice growing plains of TN and Chhattisgarh (CG), India, as well as the vegetable growing fields of TN, CG, Rajasthan and Andhra Pradesh (AP), India. Furthermore, a small but diverse sample of vegetable growing areas in USA, Malaysia, Canada, and Australia were included. This deliberate selection encompassed a wide range of geographical variations, allowing us to gain insights into the fundamental practices used for pest management in different locations.

2.2. Targeted population

The survey targeted individuals from various backgrounds and professions to obtain a diverse range of perspectives. Three major groups of people were specifically selected: those involved in pest control and pesticide usage, and individuals from the medical sector, who dealt with the consequences of pesticide exposure. Haris (Haris and Binti, 2019) indicated that "the smaller the size of sample, the larger is the in-depth understanding for a decision-making model". The total sample size consisted of 150 individuals (P).

The first segment of sampling process involved two subgroups: farm landers (FLs) (50 participants (N1)) who provided insights into the

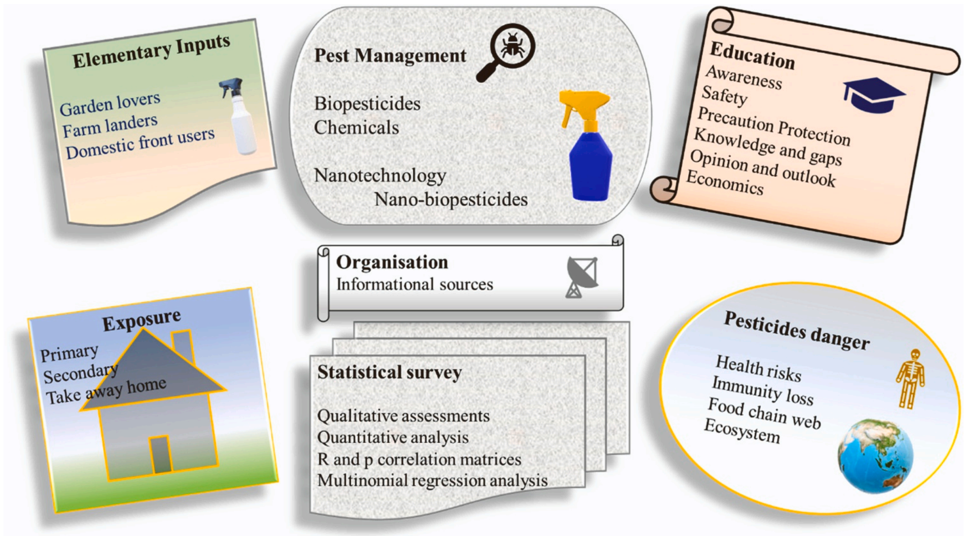

Fig. 1. Overview of the study plan and statistical survey segments.

Table 1
Sampling module used in the survey operation.

S. No.	Section A Population Targeted (P = 150)	Sample size targeted (N)	Sample size responded (n)	Age group	Section B Targeted zone
1.	Farm landers (Chemical / bio-pesticide utilisers /others)	50 (N1)	47 (n1)	27–82	Vegetable and rice growing fields of India (CG, TN, AP, Rajasthan) / USA
2.	Garden Lovers (Chemical / bio-pesticide utilisers / others)	50 (N2)	48 (n2)	25–75	Garden lovers across the globe (India / Malaysia / USA / Australia / Canada)[§]
3.	Domestic front users	50 (N3)	48 (n3)	20–80	TN, CG, AP, Telangana-India
	Total	**150 (N)**	**143 (n)**	**20–82**	
4.	Doctors and paramedical staff/ House Surgeons/ Organic activist/ Human resource advisor (volunteers)		Very few	20–82	Hilly areas of eastern ghats - TN, CG, India, House Surgeons (India).

practices adopted by CP and BP users. The second segment focused on garden lovers (GLs) (50 participants, (N2)), who directly and indirectly implemented control measures to eradicate pest populace (using CPs or BPs). The third segment targeted domestic front users (DFUs) (50 participants, (N3)) who intentionally or unintentionally used pesticides for pest management. Additionally, the survey involved the participation of a few volunteers (15 members from among the 150 P), namely organic activists (KL), human resource advisors (KL), dieticians (from USA), medical practitioners (India), paramedical staff (India), and house surgeons (India). These volunteers, who worked with rural and urban victims of pesticides, provided valuable insights through their involvement in clinical trials and practical experience. By including individuals from different strata and professional backgrounds, the survey aimed to capture a comprehensive view of pesticide usage and its consequences across various sectors.

2.3. Sampling protocols and data collection

The survey was conducted using a segmented approach, consisting of seven different sections, as shown in Fig. 2, to gather comprehensive data. Initially, informal conversational interviews were carried out with a few selected candidates to gain insights into the essence of our work (In, 2017). These interviews helped shaping a detailed questionnaire that aligned with the key objectives of work (Julious, 2005). A well-defined set of (standard) questions was utilized in the questionnaire to ensure consistent data collection practices (Sreejesh et al., 2014).

The questionnaire survey aimed at providing quantitative data about attitudes, opinions, and trends of the sample population, focusing on the perspectives of FLs, GLs and DFUs insights. It sought to gather information regarding pesticide utility (CPs/BPs), health issues (CPs/BPs), awareness, alternative options, environmental concerns, and other relevant variables (Wang et al., 2017). The questionnaire section was divided into three parts, namely, a cover letter, the main content, and a closing segment.

Data collection involved scheduled direct and telephonic interviews from the sample audience of 150 participants (P = 150), followed by video calls conducted through platforms like Zoom and Google Meet. The collected data were subsequently cross-verified with inputs received through Google forms, and further analyzed. Material documentation was maintained to ensure accurate and consistent information with necessary variations (Khan and Damalas, 2015). A set of 93 selected questionnaires was prepared to address specific situations and gather relevant insights (Quandt et al., 2013; DuPont et al., 2021). Interviews were carried out using the local dialects and direct interactions were used during interviews to accommodate participants with limited literacy, particularly among pesticide users facing the challenges of the COVID-19 pandemics.

In order to gather targeted insights from specific respondents, customized Google forms were used, using tailored sets of questions divided into 7 different sections. Oral telephonic interviews were conducted, according to the established protocols, to obtain additional supportive information. Among the total targeted sample size of 150 persons (P), which consisted of 50 participants from each segment of FLs/GLs/DFUs (N1 = 50, N2 = 50, and N3 = 50), a small percentage (4.7 %) did not respond. As a result, the analysis was conducted based on a majority of the participants (95.3 %), accounting for 143 active respondents (n). Among these, the final numbers were n1 = 47, n2 = 48,

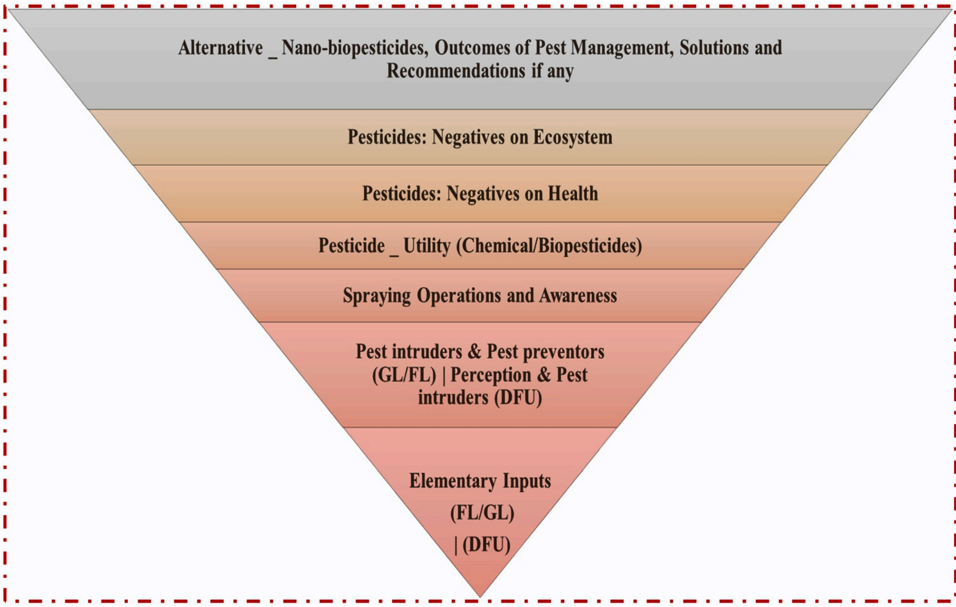

Fig. 2. Multi-step segmentation into 7 key zones for data analysis.

and n3 = 48, representing the completed responses from each group (FLs/GLs/DFUs, respectively).

2.4. Measurement of experimental variables

The objective of this study was to collect accurate and detailed information for agricultural and other extension applications of pesticides (CPs/BPs/others). The study used both primary (semi-structured interviews, observation, and questioning) and secondary (historical, documented, governmental) sources of information. Considering the objective of the study, primary data was chosen as the main source.

A mixed method was adopted, combining two types of approaches, namely qualitative (open-ended, unrestricted, allowing individuals to provide a wide range of answers based on their own perspectives and experiences) and quantitative (close-ended, providing respondents with a set of specific answer choices or options to choose from a predefined list of response categories or options), to ensure a comprehensive and unbiased response from the respondents. This approach, as described by Creswell (2014), allows for a better understanding and interpretation of the research questions, facilitating communication and capturing a wide range of diverse perspectives. Thus, considerable effort was made to interact with the respondents, allocating time and priority to their participation.

To assess the perception related to agricultural and other extended applications, 4-point and 5-point Likert scales were used (those are commonly used rating scales to measure attitudes, opinions, perceptions, and beliefs of individuals; as respondents indicate their level of agreement or disagreement with a statement or express their subjective evaluation of a particular item). The 4-point scale included categories such as “yes, always (A)”, “yes, sometimes (S)”, “rarely (R)”, and “not at all (N or No)”. The 5-point scale with options such as “yes, always (A)”, “yes, sometimes (S)”, “rarely (R)”, “not at all (No)”, and “unaware (Un)” or “strongly agree (SA)”, “agree (Agr)”, “neutral (Neu)”, “disagree (Dis)”, “strongly disagree (SD)” was used as per the situational needs. In some cases, 2 was also used (Al-Zahrani et al., 2019; Ntow et al., 2006). These scale measurements (4-point Likert and 5-point Likert scales) helped us to visualize the inferences drawn from the data (see Fig. 3). The raw-data collected through interviews and questionnaire were coded in a separate Microsoft Excel sheet to facilitate the review of information.

2.5. Statistical description

The descriptive statistical analyses in this study were conducted using MS-Excel and Statistical Package of Social Sciences (SPSS) software. These analyses allowed for a systematic evaluation and interpretation of the collected data. The following statistical techniques were employed:

1) Descriptive Statistics were used to summarize and describe the main features of the data. These included:
   Frequency Counts: Involving counting the number of occurrences of each value or category in the dataset;
   Percentages: Fractional representation of values expressed on a scale of 100 to provide a better understanding of the data distribution:
   Mean: Measure of central tendency used to determine the typical or average value of the dataset;

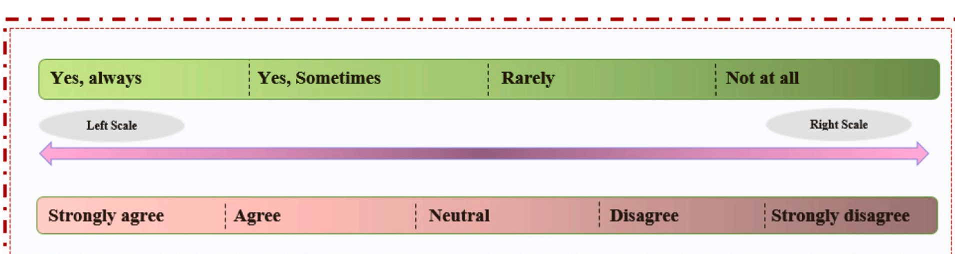

Fig. 3. Scale indicating the observation of the data collected.

Standard Deviation (S.D.): Measure of dispersion that quantifies the variability of data points from the mean.

2) Pearson's Chi-Square (χ^2) Test: Statistical test used to assess whether there is a significant association between categorical variables; it calculates the squared differences between the observed and expected frequencies divided by the expected frequencies (a larger χ^2 value indicates a stronger association between the variables).
3) Deviance: Measure of the discrepancy between the observed data and the fitted values from a statistical model.
4) p-value: Measure of the level of statistical significance; a small p-value (typically less than 0.05 or 0.01) supports the presence of a significant association between the variables. To indicate the level of significance achieved in the analysis, asterisks were commonly used (* for $p<0.05$, ** for $p<0.01$, and *** for $p<0.001$).
5) Non-parametric Tests (NPar tests), namely Kruskal-Wallis's H test (K-W H test) and Mann-Whitney U Test (M-W U test), were employed to test whether ranked groups (two or more) were statistically significantly different. These tests are useful when the assumptions of parametric tests are not met, and they determine if the ranked groups with the variables are independent (IV) or dependent (DV) in comparison to the ordinal variable under test. The significance level chosen was $p<*0.05$.
6) Pearson's correlation coefficient (R): Measure the strength and direction of a linear relationship between two continuous variables; it ranges from − 1 to + 1, with + 1 indicating a perfect positive correlation, − 1 indicating a perfect negative correlation, and 0 representing no correlation; the associated p-value indicates the statistical significance of the correlation.
7) Multinomial Logistic Regression Analysis (MLRA): Statistical technique used to model the relationship between a categorical dependent variable with three or more categories and one or more independent variables; allowing the handling of multiple outcome categories. In this analysis, the − 2LL value (2 log-likelihood) is used to assess the goodness of fit of the model, indicating how likely a particular population to produce the observed sample. The higher the − 2LL value, the better the model fits the data.

3. Results

A total of 150 individuals (P) from various sectors across the globe participated in this study. The respondents were mainly from India (specifically from rice and vegetable growing plains, and mountainous areas cultivating coffee and pepper in TN, CG, AP and Rajasthan). To improve the work, participants from other countries like USA, Canada, Australia and Malaysia enthusiastically volunteered to participate in this study. To enrich the study, professionals from different backgrounds, including medical doctors, paramedical staff and house surgeons actively contributed their perspectives, despite the ongoing pandemic situation. The demographic data collected from the participants, are presented in the Supporting information. Table S1a (FLs/GLs/DFUs), revealed that the age of the respondents ranged from 23 years old minimum to 82 years old maximum. Table S1b corresponds to the economic working levels of respondents in the FLs/GLs class. Further details can be found in Supporting information.

3.1. Elementary inputs

3.1.1. Elementary inputs (FLs/GLs/DFUs), $N = (N1 + N2 + N3) = 150$ | ($n1 = 47$/ $n2 = 48$ / $n3 = 48$)

The primary data collected and documented, as presented in Table S2a of Supporting information, provides valuable insights into the widespread utilization of pesticides among FLs/GLs/DFUs groups. The analysis reveals a significant prevalence of pesticide usage, with most respondents falling on the "yes, always" (A) to "yes, sometimes" (S) scale for both FLs (74.5 %), GLs (70.8 %) and DFUs (78.3 %).

3.1.2. Elementary inputs (FLs/GLs), $N = (N1 + N2) = 100$ | ($n1 = 47$/ $n2 = 48$)

Furthermore, when examining the check-ups conducted on soil/plants (general) for both groups (FLs: 74.5 %, GLs: 70.8 %), FLs predominantly rated them on the A to S on the 4-point Likert scale (70.2 %), indicating a proactive approach towards monitoring and assessing their agricultural practices. In contrast, GLs exhibited a different trend, with 56.3 % rating their check-ups on the opposite end of the scale, indicating a relatively lower emphasis on regular monitoring. Further details can be found in Table S2b of Supporting information.

3.1.3. Elementary inputs (DFUs, $N3 = 50$ / $n3 = 48$)

Similarly, parallel check-ups were performed to gather essential inputs from DFUs, and the collected data is documented in Table S2c of Supporting Information. The analysis revealed a noteworthy trend, with the majority of urban respondents falling on the left side scale of 4-point Likert scale (DFUs: 78.3 %), indicating a higher disposition towards pesticide usage among urban DFUs compared to their rural counterparts. Thus, showing that frequent application of pesticide is inevitable. Further details can be found in Supporting information.

3.2. Pests and knowledge

3.2.1. Pest intruders and pest preventors (FLs/GLs, $N = (N1 + N2) = 100$ | $n1 = 47/n2 = 48$)

The data collected and compiled in Table S3a of Supporting information, provides clear evidence that a significant portion of the respondents (68.0 % FLs, 66.7 % GLs) indicated that their sites were infested with pests either sometimes or always. The responses were analyzed using a scale ranging from A to R, with some respondents falling on the left end of the 4-point Likert scale and others on the right end of the same scale. Further details can be found in Supporting information.

3.2.2. Perception and pest intruders (DFUs, $N3 = 50$ / $n3 = 48$)

The data presented in Table S3b of Supporting information provides insights into the respondents' attitudes and practices related to water storage procedures for domestic purposes. The results indicated that 66.7 % of the respondents had positive responses, falling on the left scale, while 33.4 % had negative responses, falling on the right scale. This demonstrated a mixed perception among the respondents regarding water storage procedures. Further details can be found in Supporting information.

3.3. Spraying operations and danger awareness (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150$ | $n1 = 47$/ $n2 = 48$/ $n3 = 48$)

The study examined the behavioral patterns related to precautionary measures and protection during the process of mixing/spraying pesticides, including the use of protective shields, washing hands and changing clothes. The results, as depicted in Fig. S1 of Supporting information, clearly demonstrate a strong inclination towards the right side of the 4-point Likert scale in Fig. 3, indicating a high level of accountability, knowledge, and awareness among the respondents, regarding pesticide toxicities. Further insights can be gained from the findings presented in Table S4 of Supporting information. The data reveals a prevalent positive trend towards the left side of the 4-point Likert scale in Fig. 3 in all the three evaluated groups. Further details can be found in Supporting information.

3.4. Pesticide utility (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150$ | $n1 = 47$/ $n2 = 48$/ $n3 = 48$)

The study analyzed the duration of pesticide usage, which generally ranged from approximately 2 to 40 years. The results of Fig. 4 clearly suggest that the frequency of pesticide application varied depending on

Fig. 4. Perception and awareness of pesticide toxicity among respondents.

the type of pests and crops. For CP (conventional pesticide) users, the values ranged from a minimum of 4.5 % to a maximum of 58.1 %, while for BP users, the values ranged from a minimum of 7.7 % to a maximum of 41.0 %.

Furthermore, the study assessed the effectiveness of a single dose of pesticide spray in eradicating all the pests. The results revealed that the percentage of users reporting a single dose as sufficient varied from a minimum of 7.7 % to a maximum of 38.5, 45.4, 37.5 % for CP users, and from 10.3 %, 39.5, 41.0, 35.4 % for BP users. It was observed that the concentration of pesticides applied generally varied between low, medium and high levels.

Participants expressed their opinions regarding the dosage of pesticides applied, with many considering that low dosages were insufficient. The views on this matter varied between a minimum of 3.9 % to a maximum of 50.0 % for CP users and from a minimum of 7.9 % to a maximum of 42.1 % for BP users. The data showed a right shifted distribution (R and No), suggesting the need for more frequent applications of pesticides.

A significant variation was observed in the collected ordinal values, as evidenced by the statistical analysis with a confidence interval of 95 %. See Table S5 of Supporting information for some insights of statistical parameters, namely χ^2 and K-W H tests.

3.5. Negative effects on health (FLs/GLs/DFUs, N = (N1 + N2 + N3) = 150 | n1 = 47/ n2 = 48/ n3 = 48)

Based on the data presented in Table 2, it can be inferred that a significant percentage of non-threatening illnesses were reported by all three groups: FLs (65.9 %), GLs (70.9 %), DFUs (66.7 %) for both categories of pesticide application (CPs/BPs). A significant analysis revealed an important variation among the ordinal values obtained, with a confidence interval of 95 %.

Furthermore, the analyses revealed that there was a substantial increase in life-threatening illnesses among the population, specifically among self-applicators and their family members: FLs (53.2 % / 87.2 %) / GLs (56.3 % / 89.6 %) / DFUs (54.2 % / 75.0 %) for both classes (CPs/BPs) of pesticides, respectively. Fig. 5 depicts the data collected.

The most common chronic life-threatening health issues reported by respondents and family members (Fig. 6) were hypertension, diabetics, heart failure, cholesterol, gastroenterological issues, liver malfunctioning, kidney failures, thyroid, cancer, Alzheimer's, Parkinson's, sickle cell anemia (more prevalent in CG), tuberculosis, arthritis, breathing disorders, pulmonary disorders, COVID-19, among others. See Table S6 of Supporting information for some insights about the statistical parameters, namely χ^2 and K-W H tests.

3.6. Negative effects on the eco-system (FLs/GLs/DFUs, N = (N1 + N2 + N3) = 150 | n1 = 47/ n2 = 48/ n3 = 48)

Important answers were obtained from all participants across the three groups regarding their perception of pest preventor threats to the environment and eco-system (Table 3). The responses on the left side of the 5-point Likert scale (from A to R) indicated that a considerable percentage of respondents [(70.2 %: house / 53.1 %: locality) for FLs, (66.7 %: house / 56.2 %: locality) for GLs and (58.4 %: house / 58.4 %: locality) for DFUs] reported being adversely affected by various incidents, both in small and large scale. Our reports also highlight the disturbance caused by noxious pest preventors to water bodies and atmospheric air. The left side of the 5-point Likert scale, with responses from A to R, indicated a significant level of disturbance to these essential elements of nature [(47.6 % water bodies, 53.2 % atmospheric air) for FLs, (47.9 % water bodies, 47.9 % atmospheric air) for GLs and (43.8 % water bodies, 54.1 % atmospheric air) for DFUs]. Furthermore, the reports indicate the unfortunate death of harmless organisms due to pest preventor usage. The responses from left side of the 5-point Likert scale show the percentage of respondents reporting such deaths (from A to R) (FLs 53.1 %, GLs 70.9 %, DFUs 75.0 %). This highlights the negative impact of pesticide application on non-target organisms and the overall biodiversity. Statistical analysis revealed a significant variation among the ordinal values collected, with a confidence interval of 95 %. The χ^2 value inferred that the variable 'liberal use of pesticide' is statistically dependent on variables like 'contamination of water bodies', 'air', and 'death of fishes, birds, frogs, etc.,' at $p<*0.05$ with (χ^2 *43.303, *63.944, and *47.928 / df 12) respectively. Likewise, K-W H test indicated that there is a statistical significance difference between the categories of 'negative effects on the ecosystem' as IV and 'liberal use of pesticides' as DV at $p<*0.05$.

3.7. Alternative nano-biopesticides, outcomes of pest management, solutions and recommendations (FLs/GLs/DFUs, N = (N1 + N2 + N3) = 150 | n1 = 47/ n2 = 48/n3 = 48)

Our analytical data presented in Table 4, is divided into three sections: opinions, views and outlook, and alternatives. The opinion section is further divided into 4 sub-categories. The results on the left of the 5-point Likert scale (from SA to Agr) indicate the following observations: (1) "Diseases are very serious/and timely action-prevents them": FLs 74.4 %, GLs 66.7 %, DFUs 73.0 %; (2) "Immunity gets retarded by chemical pesticides": FLs 70.2 %, GLs 64.6 %, DFUs 68.8 %); for (3) "Immediate action to control pests pesticides": FLs 70.2 %, GLs 64.6 %, DFUs: 70.1 %; (4) "Is it easy to control pests?": FLs 48.9 %, GLs 62.5 %, DFUs 52.1 %). Varied opinions were observed in all the four cases, with a narrow range from 14.6 % to 19.8 %. A significant variation was observed for the ordinal values collected with a confidence interval of 95 %. However, the χ^2 value found between the variables 'liberal use of pesticide' and the variables in the opinion section, such as 'deposits of pesticides in the food', 'immunity gets retarded by chemical pesticides' and 'immediate action should be taken', inferred that they are statistically dependent at $p<*0.05$, (χ^2 *23.860 / df 9, *30.677 / df 12 and *31.965 / df 12).

Similarly, the results for the viewpoint/outlook section were divided into 3 parts: (1) The results were unanimous towards the left side of the 5-point Likert scale (from SA to Agr) for "Food production with deposits of pesticides leads to chemical poisoning" with 100.0 % agreement from all 3 groups (FLs, GLs and DFUs). (2) "Chemical pest controllers cause unpleasant consequences", 100.0 % agreement from all three groups, agreement with the reports of Liu et al (Liu et al., 2015). (3) "Exterminating pests: Is it beneficial?" - predominantly left side of the 5-point Likert scale response from SA to Agr (FLs 87.2 %, GLs 77.1 %, DFUs 79.2 %). The overall results indicated that the entire population had a strong viewpoint (100.0 % left-handed shift over the scale 5-point Likert). A significant variation was observed for the ordinal values collected, with a confidence interval of 95 %. The χ^2 value between the selected variables inferred that 'deposits of pesticides in the food' are dependent on 'immediate action should be taken' at $p<*0.05$, (χ^2 *50.744 / df 12). Moreover, the K-W H test indicated a statistical significance difference between the categories of 'opinion and view point' as IV and 'liberal use of pesticides', 'education', and 'residential status' as DV at $p<*0.05$.

The comparative analysis of BPs/CPs in terms of time consumption, cost-effectiveness (commercial), labor-intensive work (self-prepared) and frequency of application (Fig. 7) showed high preference for BPs (> 91.5 %) in the first case, while CPs (> 89.6 %) were favored in the second case. The third case, labor-intensive work (self-prepared), was dominated by BPs (> 91.5 %), and the fourth case, frequency of applications, was governed by BPs (> 91.7 %). The K-W H test indicated a

Table 2
Respondents perception of negative effects of pesticides on human health. (FLs/GLs/DFUs, N = (N1 + N2 + N3) = 150 | n1 = 47/ n2 = 48/ n3 = 48).

	FLs: 47 (n1)				GLs: 48 (n2)				DFUs: 48 (n3)			
	A	S	R	No	A	S	R	No	A	S	R	No
Non-threatening illness												
Symptoms of illness while mixing/spraying	8 (17.0)	23 (48.9)	6 (12.8)	10 (21.3)	9 (18.8)	25 (52.1)	5 (10.4)	9 (18.8)	7 (14.6)	25 (52.1)	6 (12.5)	10 (20.8)
Non-threatening illness-later	19 (40.4)	16 (34.0)	8 (17.0)	4 (8.5)	18 (37.5)	16 (33.3)	10 (20.8)	4 (8.3)	17 (35.4)	20 (41.7)	8 (16.7)	3 (6.3)

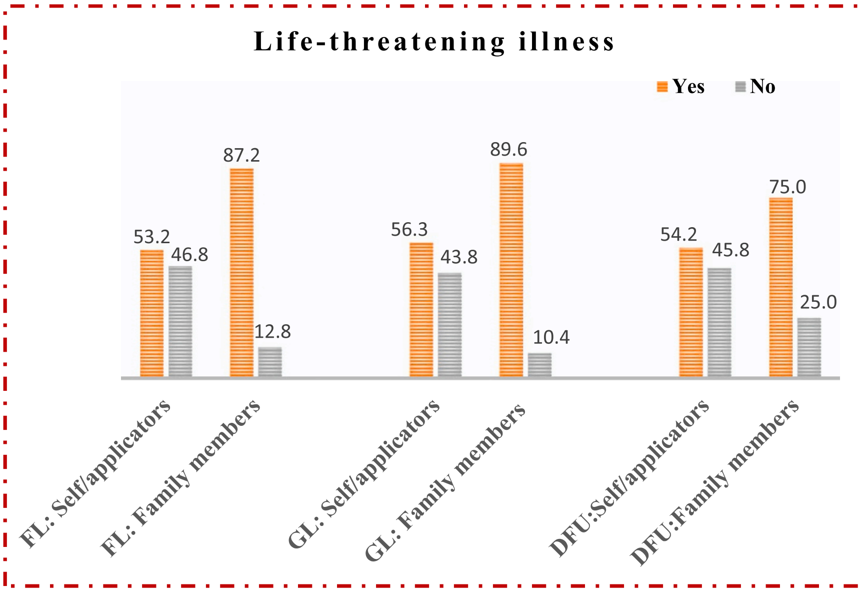

Fig. 5. Negative effects on health. Life-threatening illness: self-applicators or family members (%) (df = 1).

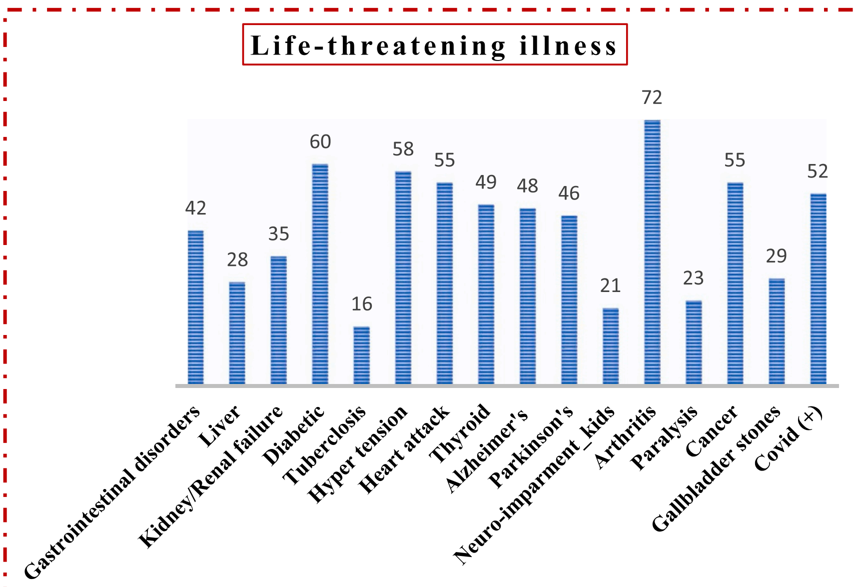

Fig. 6. Negative effects on health. Life-threatening illness suffered by all groups.

statistical significance difference between the categories of ‘comparative analysis of CP and BP’ as IV and ‘nature of pesticides’ as DV at p<*0.05.

The third and final section focused on “alternatives” and was divided into 5 sub-sections to understand the perception of respondents of CPs, BPs, or both. The responses varied:

(1) “Pest prevention measures adopted were successful” - predominantly on the right scale of 5-point Likert scale (Fig. 3) from Dis to SD in all 3 groups (FLs 57.4 %, GLs 58.3 %, DFUs 60.4 %).
(2) “Conventional methods - sufficient in controlling pests” similar right scale of 5-point Likert scale (Fig. 3) views from Dis to SD (FLs 59.5 %, GLs 58.3 %, DFUs 60.9 %).
(3) “Nanotechnology-better solution” - had dominating left-scale responses from SA to Agr in the 5-point Likert scale (Fig. 3) (FLs 63.9 %, GLs 64.6 %, DFUs 64.6 %).
(4) “Nanoproducts - better sustainability” - similar left-scale responses from SA to Agr in the 5-point Likert scale (Fig. 3) (FLs 66.0 %, GLs 66.7 %, DFUs 60.4 %).
(5) “Nano-biopesticides resolve the problem of chemical/bio-pesticides” - warm left scale responses from SA to Agr in the 5-point Likert scale (Fig. 3) (FLs 66.0 %, GLs 66.7 %, DFUs 64.6 %).

The majority of participants, whether literate or “poor-literate” enthusiastically agreed with the new concept of “nano-biopesticides” and expressed curiosity about their toxicity (FLs 80.9 %, GLs 83.4 %, DFUs 83.4 %) (SA - Neu). The above responses were left-shifted on the scale. A significant variation was observed for the ordinal values collected, with a confidence interval of 95%. The χ^2 value between the variables ‘Were the measures adopted by you successful’ and ‘are conventional methods sufficient’, ‘nanotechnology could offer a better solution in controlling pest populace’, and ‘nano-biopesticides as alternatives’ suggested that the variables are statistically dependent at

Table 3
Respondents perception of negative effects of pesticides on the eco-system. (FLs/GLs/DFUs, N = (N1 + N2 + N3) = 150 | n1 = 47/ n2 = 48/ n3 = 48).

	FLs: 47 (n1)					GLs: 48 (n2)					DFUs: 48 (n3)				
Negatives:	A	S	R	No	Un	A	S	R	No	Un	A	S	R	No	Un
Domestic animals (locality): Affected	7 (14.9)	14 (29.8)	10 (21.3)	12 (25.5)	4 (8.5)	5 (10.4)	12 (25.0)	11 (22.9)	15 (31.3)	5 (10.4)	12 (25.0)	15 (31.3)	6 (12.5)	11 (22.9)	4 (8.3)
Accident: House	5 (10.6)	13 (27.7)	15 (31.9)	14 (29.8)	0 (0.0)	7 (14.6)	14 (29.2)	11 (22.9)	16 (33.3)	0 (0.0)	6 (12.5)	14 (29.2)	8 (16.7)	20 (41.7)	0 (0.0)
Accident: Locality	5 (10.6)	11 (23.4)	9 (19.1)	15 (31.9)	7 (14.9)	7 (14.6)	10 (20.8)	10 (20.8)	13 (27.1)	8 (16.7)	7 (14.6)	14 (29.2)	7 (14.6)	12 (25.0)	8 (16.7)
Water bodies: Contaminated	1 (2.1)	13 (27.7)	8 (17.0)	12 (25.5)	13 (27.7)	4 (8.3)	9 (18.8)	10 (20.8)	16 (33.3)	9 (18.8)	2 (4.2)	11 (22.9)	8 (16.7)	16 (33.3)	11 (22.9)
Atmospheric air: Contaminated	3 (6.4)	15 (31.9)	7 (14.9)	11 (23.4)	11 (23.4)	5 (10.4)	10 (20.8)	8 (16.7)	15 (31.3)	10 (20.8)	5 (10.4)	16 (33.3)	5 (10.4)	14 (29.2)	8 (16.7)
Deaths: Fish, birds, frogs, etc.	8 (17.0)	12 (25.5)	5 (10.6)	14 (29.8)	8 (17.0)	13 (27.1)	15 (31.3)	6 (12.5)	13 (27.1)	1 (2.1)	11 (22.9)	19 (39.6)	6 (12.5)	9 (18.8)	3 (6.3)

N = total number persons who were targeted in each segment, n = total number of persons who responded from FLs/GLs/DFUs. Number of respondents (n (%)).

Table 4
Nano-biopesticides: outcomes of pest management, solutions and recommendations. (FLs / GLs / DFUs, N = (N1 + N2 + N3) = 150 | n1 = 47/ n2 = 48/ n3 = 48).

	FLs: 47					GLs: 48					DFUs: 48				
Opinion:	SA	Agr	Neu	Dis	SD	SA	Agr	Neu	Dis	SD	SA	Agr	Neu	Dis	SD
Diseases- very serious/ timely action-prevents it	19 (40.4)	16 (34.0)	8 (17.0)	3 (6.4)	1 (2.1)	18 (37.5)	14 (29.2)	8 (16.7)	4 (8.3)	4 (8.3)	20 (41.7)	15 (31.3)	7 (14.6)	4 (8.3)	2 (4.2)
Immunity gets retarded- chemical pesticides	17 (36.2)	16 (34.0)	7 (14.9)	5 (10.6)	2 (4.3)	19 (39.6)	12 (25.0)	9 (18.8)	4 (8.3)	4 (8.3)	18 (37.5)	15 (31.3)	9 (19.8)	5 (10.4)	1 (2.1)
Immediate action- to control pests	18 (38.3)	15 (31.9)	8 (17.0)	4 (8.5)	2 (4.3)	18 (37.5)	13 (27.1)	8 (16.7)	6 (12.5)	3 (6.3)	18 (37.5)	16 (33.3)	7 (14.6)	4 (8.3)	3 (6.3)
Easy to control pests	8 (17.0)	7 (14.9)	9 (19.1)	11 (23.4)	12 (25.5)	6 (12.5)	5 (10.4)	7 (14.6)	14 (29.2)	16 (33.3)	7 (14.6)	8 (16.7)	8 (16.7)	12 (25.0)	13 (27.1)
Viewpoint/Outlook	**SA**	**Agr**	**Neu**	**Dis**	**SD**	**SA**	**Agr**	**Neu**	**Dis**	**SD**	**SA**	**Agr**	**Neu**	**Dis**	**SD**
Food produce with deposits of pesticides-chemical poisoning	39 (83.0)	8 (17.0)	0 (0.0)	0 (0.0)	0 (0.0)	28 (58.3)	20 (41.7)	0 (0.0)	0 (0.0)	0 (0.0)	32 (66.7)	16 (33.3)	0 (0.0)	0 (0.0)	0 (0.0)
Chemical pest controllers- unpleasant consequence	26 (55.3)	21 (44.7)	0 (0.0)	0 (0.0)	0 (0.0)	26 (54.2)	22 (45.8)	0 (0.0)	0 (0.0)	0 (0.0)	28 (58.3)	20 (41.7)	0 (0.0)	0 (0.0)	0 (0.0)
Exterminating pests: Is it beneficial	5 (10.4)	5 (10.4)	9 (19.1)	12 (25.5)	16 (33.3)	5 (10.4)	7 (14.6)	8 (17.0)	12 (25.5)	16 (33.3)	5 (10.4)	5 (10.4)	9 (19.1)	12 (25.5)	16 (33.3)
Alternatives	**SA**	**Agr**	**Neu**	**Dis**	**SD**	**SA**	**Agr**	**Neu**	**Dis**	**SD**	**SA**	**Agr**	**Neu**	**Dis**	**SD**
Pest prevention measures adopted were successful	4 (8.5)	6 (12.8)	10 (21.3)	12 (25.5)	15 (31.9)	5 (10.4)	7 (14.6)	8 (16.7)	12 (25.0)	16 (33.3)	5 (10.4)	6 (12.5)	8 (16.7)	13 (27.1)	16 (33.3)
Conventional methods- sufficient in controlling pests	5 (10.6)	5 (10.6)	9 (19.1)	12 (25.5)	16 (34.0)	5 (10.4)	7 (14.6)	8 (16.7)	12 (25.0)	16 (33.3)	5 (10.4)	5 (10.4)	9 (18.8)	12 (25.0)	17 (35.4)
Nanotechnology- better solution	17 (36.2)	13 (27.7)	8 (17.0)	5 (10.6)	4 (8.5)	17 (35.4)	14 (29.2)	8 (16.7)	5 (10.40	4 (8.3)	17 (35.4)	14 (29.2)	7 (14.6)	6 (12.5)	4 (8.3)
Nanoproducts- better sustainability	17 (36.2)	14 (29.8)	9 (19.1)	5 (10.6)	2 (4.3)	17 (35.4)	15 (31.3)	8 (16.7)	4 (8.3)	4 (8.3)	15 (31.3)	14 (29.2)	9 (18.8)	6 (12.5)	4 (8.3)
Nano-biopesticides- resolves the problem of chemical/bio-pesticides.	17 (36.2)	14 (29.8)	7 (14.9)	5 (10.6)	4 (8.5)	18 (37.5)	14 (29.2)	8 (16.7)	4 (8.3)	4 (8.3)	16 (33.3)	15 (31.3)	9 (18.8)	4 (8.3)	4 (8.3)

N = total number persons who were targeted, n = total number of persons who responded from FLs/GLs/DFUs. Number responded (n (%)).

p<*0.05, with df 16 and χ^2 (*527.840, *300.456 and *264.646, respectively) from alternatives sub-section.

Likewise, the χ^2 value between selected variables indicated that 'class of pesticide users' is statistically independent on 'nano-biopesticides' as alternatives (χ^2 *0.555 / df 8) and 'educational qualification of the respondent' is statistically dependent on 'nano-biopesticides' as alternatives (χ^2 *66.003 / df 16) at p<*0.05. The K-W H test indicated a statistical significance difference between the categories of 'alternatives' as IV and 'education', 'residential status', and 'liberal use of pesticides' as DV at p<*0.05, while there is no statistical significance difference between the categories of 'alternatives' as IV and 'gender' as DV at p<*0.05.

An inter-dependent correlation was observed with R and P correlation matrices. Specific variables such as awareness, perception, precautions, prescription adherence, practices adopted, health issues (family and ecosystem), extermination of pests and new alternative approaches were considered in relation to age, gender, LOE, status and health. The results from Table 5 indicated positive correlations for some

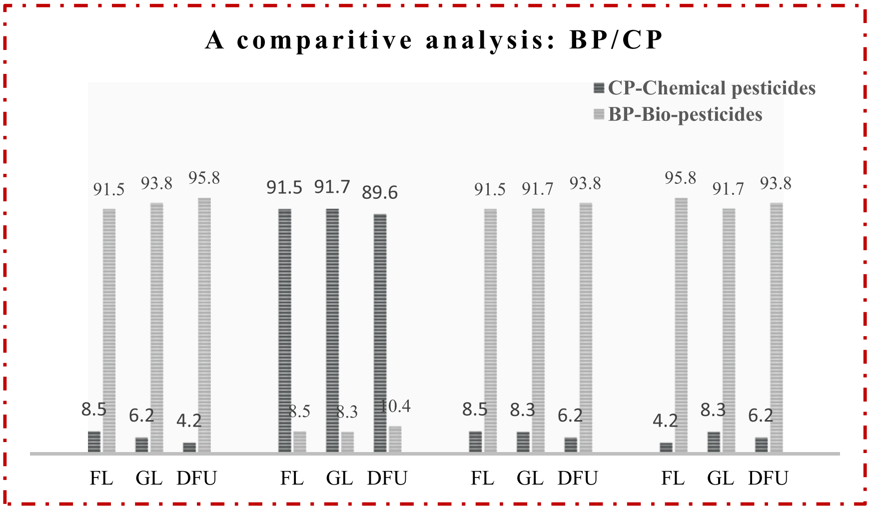

Fig. 7. A comparative analysis between BPs and CPs. *Note: The quantifiable values mentioned in the figures indicate the percentage of the responses received. The abbreviations used in the figures represent the following: Yes. always, A/ Yes, sometimes, S/ Rarely, R/ Not at all, N or No/ Unaware, Un, SA: Strongly agree / Agr: Agree / Neu: Neutral / Dis: Disagree / SD: Strongly disagree and † FLs: Farm Landers/ GLs: Garden Lovers/ DFUs: Domestic Front Users.

Table 5
Correlation matrix indices between the selected variables.

Variable	Positive correlation	Negative correlation
Age (D1)	Q4 * (L), Q8 ** (L),	LOE**(L), Status**(L)
Gender (D2)	Q4 * (L), Q7 * (L), Q8 ** (L),	Q1 **(L), Q2 **(L), Q3 * (L)
LOE (level of education) (D3)	Q4 **(M), Q7 **(M), Q8 **(H)	Q1 **(H), Q2 **(H), Q3 **(H), Q5 **(M), Q6 **(M)
Status (D4)	Health* (L), Q1 **(H), Q2 **(M), Q3 **(M), Q5 **(L)	Age**(L), LOE**(M), Q4 **(M), Q8 **(M)
Health (D5)	Q1 **(L), Q2 **(L), Q3 **(M)	LOE**(L), Status* (L), Q4 **(L), Q8 **(M)
New alternative (D6)	Gender**(L), LOE**(L), Q4 **(H), Q7 * (L), Q8 **(H)	Status* (L), Health**(L), Q1 **(H), Q2 **(H), Q3 **(M), Q5 **(L), Q6 **(M)

**. Correlation is significant at the 0.01 level (2-tailed), * . Correlation is significant at the 0.05 level (2-tailed). L-Low, M-Medium, H-High level of significance. Age (D1), gender (D2), LOE (D3), status (D4), existing health issues (D5), New alternatives (D6), applicational practices (Q1), awareness in general (Q2), perception towards toxicities (Q3), precautions observed (Q4), prescription followed (Q5), improper attitudes (Q6), preservation of eco-system (Q7), and extermination of pests (Q8).

variables and negative correlations for others.

MLRA was conducted to identify the influential factors that affected the respondents' attitude. A set of 11 independent variables (IVs) representing demographics and other inputs were randomly selected to understand their impact on the outcome variable. The results from the MLRA model, presented in Table 6, showed that 4 IVs were statistically significant out of the 11 IVs chosen, with − 2LL values of the model as 64.743, with χ^2 (128.4), df (24), at p<*0.05, **0.01, and ***0.001 levels. The pseudo R^2 values are an indicative measure of accuracy for the model, where the values ranging from 0 to 1 (or 0 % and 100 %) are categorized as McFadden, Nagelkerke and Cox and Snell (Mubushar et al., 2019). Those values (80.0 %, 66.5 %, 59.2 %, respectively) indicate the model accuracy in explaining the influence on the respondents' attitudes. Other goodness-of-fit measures, such as χ^2 and Deviance were within acceptable ranges, with Deviance at p>*0.05, (χ^2 (64.743), (df 116), (Sig. 1.000), indicating a good model fit. χ^2 was not significant at p<*0.05 (χ^2 91.124), (df 116), (Sig.∼ 1.000) (where Sig. is Significance).

The majority of the respondents in the study covered a wide range of age groups with the majority falling between the ages of 28 and 82 (≤ 30: 12 (8.4 %), 31–45: 50 (35.0 %), 46–60: 58 (40.6 %), and ≥ 61^+: 23 (16.1 %)). These age groups were represented in all the three wings considered (FLs, GLs and DFUs). The parametric estimations conducted on the data revealed a correlation between the age and urban dwelling. The average age of the respondents was calculated to be 49.22, and this factor showed mutual significance with living in urban areas, with a statistical significance level of p<*0.05. Furthermore, the LOE was found to have a considerable impact on decision making, which was further influenced by urban dwelling. This influence was statistically significant, with a p<**0.01 and p<*0.05 for the UG and PG groups, respectively. The study also found that urban dwelling had a statistically significant influence on access to informational services, with a p<*0.05. Additionally, the data indicated that governmental authorities had a strong influence over decision making, with a statistical significance at p<*0.05 level.

Table 6
MLRA model based on choice of living (dwelling) as a dependent variable.

	Explanatory independent variables	β	Std. Error	Wald	df	Significance
Social Status	Age	0.129	0.056	5.360	1	*0.021 (p<*0.05)
	Level of education (LOE) (UG/PG)	- 4.091 / − 3.135	1.520 / 1.322	7.246 / 5.621	1	**0.007 / *0.018 (p<**0.01, *0.05)
	Gender	1.496	0.919	2.651	1	0.103^{is}
	Residency	17.479	Very high	0.000	1	0.999^{is}
Utility	Pest controllers used	0.927	0.882	1.103	1	0.294^{is}
	Number of years used	2.932	2.307	2.071	1	0.150^{is}
	Frequency of usage (less)	-3.027	0.979	9.566	1	**0.002 (p<**0.01, *0.05)
	Informational services (Govt)	-6.610	2.655	6.198	1	*0.013 (p<*0.05)
View	Eco-system	1.730	1.632	1.124	1	0.289^{is}
	New alternative	2.200	1.586	1.923	1	0.165^{is}

-2 log likelihood (−2LL): 64.743, Significance: (p<*0.05, **0.01), is: insignificant, df: degrees of freedom.

4. Discussion

The on-going work presently focusses on assessing the need for new technological advancements, like nano-biopesticides, in the field of pesticide application, both in agricultural and domestic settings. The scope of demography expanded beyond medical and geographical sciences to include the social sciences on a larger scale. To conduct preliminary evaluations, collected responses from a diverse range of participants were obtained, resulting in an overall response of 96.7 %. This value clearly indicates a strong positive reaction and receptiveness to our approach.

Various demographic factors such as age, gender, educational status, area of residence, type of residency, area of farmland (FL), economic working levels (FLs/GLs), site: farmland/garden status, human power/manpower were found to influence the respondents' perceptions, approaches, and the need for knowledge about pesticide utilization and its advantages and disadvantages. Literacy plays a crucial role in establishing positive correlations, encouraging intellectual development, poverty eradication, economic growth, and the formation of a mature and advanced society (Shammi et al., 2020).

The demographic data reveals that 143 respondents (n), categorized as farmers, gardeners, or domestic users (FLs ($n1 = 47$) /GLs ($n2 = 48$) /DFUs ($n3 = 48$)) spanned a wide range of age groups from over 20 to over 80. As expected, knowledge, maturity, dedication, and pragmatism strengthen with age. Gender, the second most important observation criteria, revealed that literate females were more pro-active in embracing new approaches compared to semi-literates. We noticed that females, in spite of their busy schedules, showed a positive attitude towards our work, as evident from Table S1a, where 80.0 % of female respondents provided a favorable response. Females, predominantly responsible for pesticide handling in domestic settings, showed an overall positive outlook, compared to males, which contradicts the findings of Rohlman et al (Rohlman et al., 2007). In large agricultural areas, pesticide handling was predominantly carried out by men. The quantity and frequency of pesticide application were also associated with age and gender, indicating their significant influence on application choices and usage.

Educational status was the next influential factor. As shown in Table S1b, a larger segment of the respondents from FLs/GLs/DFUs belonged to literate groups, while a few were from the rural sectors in CG/TN, categorized as "poor-literacy", with limited cognitive skills. Furthermore, some participants held higher qualifications such as Masters/Doctorate/Post-doctorate degrees. This data clearly reveals a comparatively better literacy rate compared to the previous report of Shammi et al (Shammi et al., 2020). Most literate respondents (aged between 25 and 82) had a positive attitude towards new technologies and innovative approaches. However, they also expressed concerns about the potential long-term harmful effects of the new innovative products. While some educated people preferred traditional chemical pesticide application methods, others adhered to the perceived safety of BPs. Respondents categorized as "poor-literacy" showed little or inadequate knowledge about new technologies, with some having sufficient knowledge but being reluctant to adopt new methods.

Socioeconomic status is a complex aspect of social strata influenced by geographical, cultural, societal, educational, occupational, and financial factors. The data from Tables S1a and S1b highlight the significant impact of socioeconomic status on decision making. Regarding (1) "area of living", responses predominantly came from people living in urbans areas, indicating a dominance of urban dwellers over rural respondents.

In terms of (2) "residency", for DFUs/FLs/GLs, the order of dominance was observed as follows: ownership: apartment > ownership: villas > rental > accommodation shared. This data clearly revealed that the majority of respondents had individual accommodations, indicating a comparatively better and stable economic status.

When considering (3) "Area of farmland (FL)", the following order of dominance was observed: < 5 acres, > 5–20 acres, > 20–50 acres, > 50 acres and none. This information suggests that many respondents cultivated their crops on small plots of land, while some had significant areas of cultivation.

For (4) "Site status": FLs/GLs, ownership status dominated FLs, while rental occupancy predominated GLs.

In terms of (5) "Economic working levels" (FLs/GLs) site status (farmland/garden status), and employed manpower, it was evident from the data that socio-economic status was comparatively better among respondents, as hired laborers outweighed the volunteers. Volunteer participation was minimal in many regions in India compared to economically prosperous countries. In the case of GLs, we observed that the respondents themselves or their spouses were the primary individuals responsible and actively involved. DFUs appreciated the use of novel product as they were frequently using only CPs. A significant portion of FLs/GLs welcomed new technologies, while a few remained non-responsive, probably due to the unawareness of the latest developments. Overall, economically higher strata showed greater appreciation for new innovations, while lower strata were reluctant towards adopting new approaches. Statistical significance from χ^2 test with dependency indicated the association was good enough for consideration.

4.1. Elementary inputs

4.1.1. Elementary inputs (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150$ | ($n1 = 47$/ $n2 = 48$ / $n3 = 48$)

The elementary inputs were analyzed based on the primary data results presented in Table S2a for FLs/GLs/DFUs. The analysis clearly indicates that pesticides are widely used by all groups of population, whether educated or not, to control pests, including vermin or microbial infestations (Iqbal et al., 2016). However, there are some variations and perspectives among the respondents regarding pesticide usage.

(1) Use of pesticides: The respondents, regardless of their education level, generally employ CPs/BPs for controlling pests. However, some individuals are hesitant to use pesticides, due to concerns about the potential impact of CPs on soil quality.

(2) Use of natural repellents/anti-feedants: Many people still adhere to the traditional practice of using natural elements, along with CPs, for fumigation or spraying. Natural elements like *Vitex negundo*, *Azadirachta indica* (oil/dried leaves), *Allium sativum* (dried part of plant), BT (Bacteria), etc., are used during field preparation, sapling transplantation, and field maintenance, especially for short term or cash crops. The use of botanical pesticides (BP) or natural repellents/anti-feedants offers a safer alternative to CPs, with lower or no risks to ecosystems and human well-being (Senthil-Nathan, 2020). This inclination towards environmentally safe agricultural practices reflects the intensification of organic food production and the increased global demand for safer organic products (Chandukishore et al., 2023).

(3) Impact on pollinators: The liberal use of pesticides and fertilizers (CPs/BPs/others) led to a reduction in the attraction of pollinators and birds. The decline in eco-friendly creatures is an alarming signal and a serious concern, indicating that the situation was not effectively controlled. Therefore, a viable alternative is immediately required. This observation aligns with findings from Traba et al (Traba and Morales, 2019). Hence, the observed data clearly indicates that pesticide use, depending on the location of application, has adverse effects (Poirier et al., 2021). In terms of productivity, the obtained results suggest that the annual productivity for farm-landers decreased, when changing to BPs, but remained satisfactory for garden holders. This trend was evident from the data received. New users showed a growing inclination towards organic farming practices, while older farmers tended to stick with organic or to the older versions of pesticides. Some

FLs/GLs believed that the use of alternatives to chemical pesticides could be either labor-intensive or not cost effective, and they felt that the required potentials were not quickly met. Statistical significance from χ^2 with dependency indicates a strong association that warrants consideration. On the other hand, the independence between liberal use of pesticides and annual output suggests that 'liberal use of pesticide' alone does not influence 'the annual production of the harvest'.

4.1.2. Elementary inputs (FLs/GLs, $N = (N1 = N2) = 100$ | $n1 = 47/n2 = 48$)

The elementary inputs related to the analytical practices were examined based on the primary data results presented in Table S2b for FLs/GLs.

Check-ups: Parameters related to soil/plants health and general/pesticide residues such as acidity, alkalinity, minerals, pesticide residues levels, etc., receive relatively less attention from FLs/GLs. However, interviews with the population revealed that pesticide residues were present at different concentrations, as reported by some respondents. The work of Aktar et al. reported high toxicities of pesticide residues in soil (Aktar et al., 2009). Statistical significance from χ^2 test with dependency indicates a strong correlation for the collected ordinal data.

4.1.3. Elementary inputs (DFUs, $N3 = 50$ / $n3 = 48$)

Equivalent tests were carried out to obtain primary outputs from DFUs. The results presented in Table S2c confirmed that urban areas had more pest population than the rural environments, as expected (Meftaul et al., 2019). The urban population liberally used pesticides to eliminate pests, as reported elsewhere, (Carvalho, 2017) possibly due to the limited space and the increasing population density in urban areas. Negligence regarding pest control was rare among urbans, as they were aware of the pest-related risks to their pets. Hence, the frequency of pesticide application was higher in urban locations compared to rural regions. Statistical significance from χ^2 test with dependency indicated a strong association worthy of consideration.

All three groups of the population, including urban and rural respondents, relied on natural repellents and antifeedants, which are secondary metabolites produced by plants, to control pests in a traditional manner. Various natural components, such as lemon, neem and its by-products, *Eucalyptus* oil, lavender, citronella, *Vitex negundo*, and others were commonly used (Lopez-Carmen et al., 2022). While the audience mainly focused on CPs/BPs to control common pests (vermin/microbial), a significant portion of the population switched mainly to BPs, (Haris and Binti, 2019; Sivapragasam, 2009) while a few individuals continued to rely on chemical alternatives. A small percentage of participants emphasized the use of Integrated Pest Management (IPM) approaches and other pest control strategies (Pretty and Bharucha, 2015; Rajapandian and Kadarkarai, 2023). Interestingly, some participants, who were pet owners, reported that their animals were always adversely affected by pests and the pesticides applied. In fact, the potential adverse effects of CP exposure (CPE) were particularly challenging and hard to interpret. Studies related to pet and farm animals revealed that environmental toxins can be harmful, hindering and damaging the development of neurological organ systems (Burns et al., 2013). However, the statistical significance from the χ^2 test with independence between 'liberal use of pesticides' and 'natural repellants' suggests an indirect signal that calls for suitable alternatives.

4.2. Pests and knowledge

4.2.1. Pest intruders and pest preventors (FLs/GLs, $N = (N1 + N2) = 100$ | $n1 = 47/n2 = 48$)

The presence of plant pathogen pests in nature has the potential to disrupt plant growth through the introduction of diseases. The consequences of this infestation include significant losses in the yield of harvested materials. Nevertheless, specific vermin pests and certain microbials play crucial roles in the overall ecosystem. Some of them, although detrimental to plant health, are significant for bio-stimulation (Sreevidya et al., 2021a). It is essential to control the population of these pest intruders when their numbers increase excessively. The approach to pest control varies depending on the specific nature and type of pest intruders encountered (Batista et al., 2023; Manochaya et al., 2022). The results obtained from the open-ended questionnaire not only revealed different types of plant pest pathogens causing various diseases and damages but also generated interest among the participants, who shared their experiences with pests that commonly attack their plants. These results align with the reviews of Khan et al. (2019a). The attacks of plant pathogen pests often result in substantial losses, which are largely dependent on weather changes (Nwofor et al., 2022; Pautasso et al., 2012).

The data presented in Table S3a shows that many respondents (FLs and GLs) occasionally or permanently, face severe pest infestations in their respective areas. Pesticides play an important role in the eradication of plant pathogens/vermin. In order to overcome the massive damages caused by plant pest pathogens, FLs and GLs used different methods to monitor and manage these intruders. Respondents were forced to use pesticides to control this problem. The interviewees believed that weather changes contributed to increased pest populations. Some participants (FLs and GLs) reported that new pest infestations generally occurred during the summer season. Participants from the hot plains of CG/AP/TN (India) reported that pests were airborne, possibly indicating viral attacks on the vegetable crops. Weather was reported to have a significant influence on the pest appearance and invasion, especially in the post-monsoon season (India) and after rainfall (in other parts of the world) due to increased tropical humidity (Nwofor et al., 2022). The climatic swings generally disturbed the existing synchronization between the cambium activity of the woody host and colonizing levels of the plant-pathogen. These observations align with the reports of Pautasso et al. (2012). Statistical significance from χ^2 test with dependency indicated the association between 'climate' and 'new pests' seen was notably good.

Insights obtained from the demo interviews, conducted with a segment of the population, helped us to refine the questions according to the situational needs. The analysis of FLs and GLs preferences for pest preventors depended on factors such as the type of pest, nature crops or plants, season of application and exposure to atmospheric conditions. The data collected showed that most participants believed that the choice of pesticides depended on the type of pest. They were compelled to extensively use pesticides to combat unavoidable pest infestations. However, the analysis of dietary exposure and pesticide residues in food, as reported by Ling et al. (2020), highlighted potential health threats to pre-school children of Taiwan. Similarly, a study from Li et al., indicated that the liberal usage of CPs could cause serious impairment of the ovarian function (Li et al., 2018). Thus, CPE might result in neurological disturbances in children, including those in the womb of pregnant women (Berman et al., 2011). Hence, it is crucial to prioritize the eradication of deep-rooted pathogens.

Furthermore, atmospheric conditions and weather changes influence the usage of CPs and BPs. The data values on the left scale indicate that the choice of pest preventors or controllers is significantly governed by the two major factors, i.e., the nature of crops and plants and the season of application, as seen in Table S3a. Direct interactions with people revealed that during rainy weather, there were more instances of pesticide drift, and sometimes, a higher frequency of application was needed. Our findings align with the reports of Delcour et al. (2015). Frequent application of CPs not only decreases soil fertility, resulting in low-nutrient productivity, but also increases the dispersion of pesticides in the air and water, negatively impacting the eco-system. To reduce the frequency of application and minimize toxicity, it is crucial to explore viable alternative measures. The reports agree with Khan et al. (2019a) who concluded that, despite different approaches to assess and control pest pathogens, no definitive solution dealing with limited pesticide use was found. Therefore, innovative measures should be incorporated into conventional systems to enhance plant-disease management and increase productivity. Additionally, the introduction of nanoparticles (NP) or nano-composites (NC), as NBPs, could serve as micro/macro nutrient enhancers for the soil and plants. Both literate and semi-literate respondents agreed that exposure of pesticides to heat and moisture is not advisable as it reduces the efficacy of the applied substance.

4.2.2. *Perception and pest intruders (DFUs, N3 = 50 / n3 = 48)*

Ensuring safety and hygiene is crucial for maintaining a healthy living environment. Unfortunately, many people worldwide are unable to adhere to the desired rules and measures due to various reasons, such as lack of awareness, challenging conditions, poverty, and more. Analyzing the views and perceptions of DFUs regarding the current conditions, we found that most of the population was aware of the importance of safety and hygiene. However, these measures varied depending on whether they lived in urban or rural areas (Meftaul et al., 2019).

To evaluate the results, we analyzed the current status and insights obtained. The data inputs for the status were further divided into simpler segments for better understanding. The data output from Table S3b, revealed the following findings:

(1) Water storage procedures (for domestic purposes) were well taken care of, with a predominance of positive responses on the left scale. This included internal cleaning of tanks and sterilization of portable water, indicating a proactive approach to ensure clean water.
(2) Stagnation of waste water or rain water was identified as a major cause for mosquito breeding, leading to massive application of pesticides to control them. Approximately 50.0 % of the respondents took measures to prevent the stagnation of unwanted water, while the other half seemed unconcerned. This clearly indicated the need for frequent pesticide application to avoid vulnerable diseases like dengue, malaria, etc.
(3) Water quality and microbial evaluation were not frequently conducted, given the reports received. Regular monitoring and routine check-ups for water quality would help preventing the spread of diseases like cholera, dysentery, and other chronic ailments, like gastrointestinal disorders. The data indicated that the respondents did not prioritize checking the quality of stored water.
(4) Participants reported heavy losses of food products due to storage pests, especially during the post-monsoon. They expressed the need for an immediate and simple solution, as also stated by other authors (Khan et al., 2019a; Mesterhazy et al., 2020). The data revealed that neglecting household cleanliness, improper handling of food wastes and weather conditions were major contributors to an increase in pest populations. It is known that the presence of pests and mold formation in houses and food can lead to several heath issues (Xiao et al., 2021). Indoor dampness and high moisture levels also increase the risk for developing bronchial disorders like asthma in children (Baxi et al., 2016). This is a global issue that requires safe and immediate action for an effective protection.

4.3. *Spraying operations and danger awareness (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150 \mid n1 = 47/\ n2 = 48/\ n3 = 48$)*

Each individual has unique behavioral patterns, which form a complex matrix that is not fully understood. Behavioral attitudes are inconsistent and vary depending on situational needs, partially influenced by environmental proximity, and acquired knowledge (Burns et al., 2013). In the study on "Perception/Awareness towards pesticidal utility", the judgmental attitude of the population towards pesticide application in the three major groups (FLs, GLs, DFUs) was analyzed. From the bar graph of Fig. S1, it is clear that all three groups took great care to ensure that pesticides were not accessible to children, unlike the findings of Mlayeh et al. (2020). The reports on the right scale demonstrate a responsible approach driven by knowledge and awareness of pesticide toxicities. Taking precautions and prioritizing protection are effective ways to mitigate the hazards faced by pest control applicators (Fan et al., 2015). The data shows an improvement in knowledge and personal protection practices among the population. Statistical significance from χ^2 test with dependency indicated that the association between 'toxicity awareness of pesticides' and 'not accessible to children' was comparatively good.

To effectively mitigate the perils and threats faced by pest control applicators, safety precautions and protection should be followed at the primary level (Fan et al., 2015). The reports of the Table S4 confirm an advancement in the knowledge and personal protection among the population. There is a high level of positivity towards the left scale in all three measured groups, which differs from the awareness reported by Mubushar et al (Ntow et al., 2006). However, among the three groups, GLs showed the highest positivity of 100.0 % all the three sub groups, whereas DFUs only had a maximum positivity of 87.5 %, and FLs had a maximum positivity of 90.8 % towards the left scale. This clearly indicates that DFUs require more safety precautions, compared to the other two groups. 'Awareness of pesticide toxicities' was significantly dependent on 'precautions and protection taken'. χ^2 indicated a suitable association with the variables considered.

The next section in the cognitive domain focused on utilities. The earlier reports of Khan et al (Khan and Damalas, 2015) indicated that FLs were less concerned about proper handling procedures, and responsiveness needed improvement. From the data collected in our work, we noted that awareness regarding mixing combinations was relatively better for all three groups (FLs, GLs, DFUs). However, reutilizing pesticide application tools for other purposes was less common, although not negligible. The data indicated the need for increased knowledge and awareness among users, as they seemed too careless, in spite of being aware of pesticide toxicity. Storing the unused mixtures is another matter of concern, with FLs falling towards the middle, indicating the dominance in S and R on the 4-point Likert scale. On the other hand, GLs and DFUs, although aware of pesticide toxicity, store the unused mixtures for later use, prioritizing cost-reduction and minimizing waste. Approximately 15.0 % of the population from all three groups were found to be using expired pesticides for pest control. Our analysis further indicated that only around ≤ 23.0 % did not follow the label recommendations, possibly due to avoidance or failure to read the label instructions. Not following the recommendations on the label and using expired doses disrupts correct routines, increases pesticide exposure, intensifies risks to human and animal health and hampers environmental detoxification (Waichman et al., 2007). 'Awareness of pesticide toxicities' was significantly dependent on 'utilities'. χ^2 indicated a suitable association with the variables considered.

Further information revealed that the majority of FLs, GLs and DFUs agreed that potency and stability of pesticides were affected by climatic variations, while a small minority held a different opinion. However, a significant portion of FLs, GLs and DFUs strongly believed that climatic conditions alter the nature and efficacy of the applied pest control agents. Drifts caused by rain after application can compromise efficacy, as reported elsewhere (Carvalho, 2017). Similarly, extremely hot and sunny climates can also change the effectiveness of the applied pesticides, (Meftaul et al., 2019) destabilizing the environment.

4.4. *Pesticide utility (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150 \mid n1 = 47/n2 = 48/n3 = 48$)*

Pests are a threat, not only in agriculture but also in domestic settings, causing widespread devastation. Pesticide application is an attempt to solve the problem. However, the positive and negative aspects of pesticide usage give rise to uncertainties. Changes in lifestyle and dietary habits, along with increasing global demand for nutritious food, (Frona et al., 2019) necessitate sustainable growth and development in the food and agriculture sectors to meet annual harvest production requirements (Pontes et al., 2020). However, an equal increase in pest populations undermines the availability of nutritious food. The use of CPs is convenient but can cause troubles in various areas (Holme et al., 2016). BPs are considered safer alternatives for sustainability, but have their own pros and cons. Additionally, weather changes can also affect pesticide handling. As more people are switching to safer substitutes, the selection of pest control methods involves new approaches (Carvalho, 2017; Mnif and Ghribi, 2015).

Our study on pesticide utility among the three major groups also revealed an increasing number of people switching to safer modes. Fig. S2 indicates a clear trend: half of the populace (FLs and GLs) completely opted for bio-pesticides as safer alternatives, (Goswami et al., 2022; Yadav et al., 2023) while one-third of the populace (FLs and GLs) chose to use both CPs and BPs. The remaining one-fifth (FLs and GLs) continued to use CPs. The application of BPs and the use of comprehensive organic farming practices ensures long-term sustainability, based on geographical factors and social practices. It is worth noting that commercial CPs recklessly and liberally used by FLs and GLs, such as malathion, carbofuran, phorate, sulfur, endosulfan, monocrotopos, and other common chemicals, might pose major risks and lead to symptoms like skin/eye irritation, headache/fever, fatigue/weaknesses, and even life threatening effects, often experienced by pesticide applicators (Lu et al., 2010). CPs applied during spraying operations can mix with soil, air, and water due to drift caused by air and rain, degrading the purity of nature. Inhalation and exposure to CPs indirectly result in severe health issues for humans and the environment. To address these dangers, new safe ventures are being explored to promote overall safety (Thorat et al., 2023). On the other hand, the choice of bio-pesticides ranges from commercial products to self-prepared ones using botanicals (Moshi and Matoju, 2017). FLs, GLs, and DFUs utilize alternatives such as garlic, neem by-products, chili flakes, bacteria, ash, castor oil, *Bacillus thuringiensis* derivatives, chrysanthemum, tobacco leaf, Monterey LG6155, AgroThrive, spinosad, soap nut solution, cow's urine, fish waste, and baking soda as BPs to control pests. Studies also showed the effectiveness of marine algae with non-toxic secondary metabolites in controlling pests like mosquitoes and microbials (Karthi et al., 2020). The fermentation process involved in the preparation of self-prepared products using biological specimens like mustard oil cake, garlic, fish waste, etc., can produce an unpleasant smell probably due to the formation of amino-acids and alkaloids, leading to common symptoms like nausea and severe headache. FLs, GLs, and DFUs extensively used BPs to control pests. Pests can develop resistance to CPs after-long term application, which explains the shift towards traditional BPs by FLs, GLs and DFUs to protect their crops and gardens (Rana et al., 2020). The duration of pesticide application ranges from approximately 2 to 40 years. CP users often make their choice based on cost, efficacy, or both, while BP users rely on the advice from governmental or non-governmental organizations (NGOs), and prioritize potency, quality and safety when selecting commercial products. FLs and GLs used organophosphates and carbamates, either deliberately or unknowingly, for getting a good yield of crops in India, (Kumar et al., 2016). FLs and GLs in extreme western (Rajasthan) or eastern states of India chose safer alternatives (BPs), while many users from within or outside India opted for NBPs to combat aphids and mealybugs; also nano-silica and nano-silver were used to fight other pests (Yadav et al., 2021; Barik et al., 2008; Tarighi and Nejad, 2023). The frequency of application of CPs and BPs varied from weekly to half yearly, depending on the situation, being applied either single or in combination, according to the needs of GLs and FLs.

Fig. 4 clearly indicates that:

(1) The frequency of pesticide application varies with the nature of pests and type of crop. The bar graph shows that the frequency of application of BPs is higher, compared to CP users, and might probably be due to a reduced amount of stability that leads to fast degradation of the pesticide, thus needing renewed applications (Chellappandian et al., 2018).
(2) BP users believe that a single dose of spray is insufficient to eliminate all pests, unlike CP users.
(3) The majority of FLs that use BPs share this opinion, while GLs have the opposite view, which may be attributed to the difference in the areas they need to cover (GLs need to spray less space with BPs, while FLs have more extensive areas). However, CP and BP users in the DFU group share similar views concerning the efficacy of a single spray, possibly due to the higher prevalence of pests in crowded urban areas (Aktar et al., 2009). The overall conclusion from the observed data is that FLs, GLs and DFUs have different opinions concerning CPs and BPs.
(4) The concentration of pesticides applied generally varies from low to medium to high, with people believing that low dosages are insufficient to control pests, either plant-pathogens or vermin, thereby needing more frequent applications (Zubrod et al., 2019). It is evident that at the grassroot-level, the effective use of BPs still faces important challenges, while CPs, although apparently more efficient, have long-term negative consequences, making them a challenge for the research community (Mishra et al., 2020).

Statistical significance from χ^2 test with dependency indicate a good association for consideration.

4.5. Negative consequences on health (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150 \mid n1 = 47/\ n2 = 48/\ n3 = 48$)

The expected increase in population by 2050, estimated to be around 9.8 billion by WHO (Chellappandian et al., 2018), indicates a significant shortfall in food-grain production considering consumption and losses, particularly considering the frequent occurrence of new pandemics. The growing population demands an increase in food consumption, which is related to food supplies and losses. According to Johnson et al. (2019) the supply rate of fruits and vegetables exceeds the consumption rate. However, substantial losses occur at different stages, including pre-harvest (approximately 1/3 of production: 1.110 metric ton (mt)/year), storage (approximately 420 mt: grains), and mycotoxin infection (approximately 210 million (M) tons). As a result, only 1/3 of the produced food is effectively used, leading to significant annual global losses caused by pest intruders (Mesterhazy et al., 2020). During the lockdown crisis in India in 2020–21, farmers incurred approximately 40 % yield losses, with 30 % attributed to unharvested products and 22 % due to storage losses (Tiwari et al., 2021). The global use of CPs is around 3.5 M tons, (Sharma et al., 2019; Thorat et al., 2023) with India ranking 12th in CP usage but having one of the lowest CP application rates (0.29 kg/ha) (Abhilash and Singh, 2019; Sharma et al., 2020). However, India is among the countries that started transitioning to BP application. In the studied areas of India, most farmers, gardeners, and DFUs, use CPs, BPs, or both to control pests affecting their crops and vegetables. While the recent shift to BPs, reduced the negative impacts of hazardous CPs, there are constraints associated with self-preparation, generally in the form of slurry, liquid or solid formulations.

Despite the ban on certain compounds, like organophosphate pesticides (OP), carbamates, organo-chlorine, etc., their usage continues (Lopez-Galvez et al., 2019). CP residues have been reported in human serum (Tunisia), (Araoud et al., 2010) children's urine (USA), (Meftaul et al., 2019) with urinary-metabolic problems found in many children (Washington), (Holme et al., 2016) breast-milk, (Kumar et al., 2016) and have been associated with various health complications. Neurodevelopment disorders have been more pronounced in areas with intensive pesticide application (Friedman et al., 2020).

Based on the data collected in Table 2, it can be inferred that a significant percentage (~71.0 %) of *non-threatening illnesses* were reported in all three groups (FLs, GLs, DFUs) for both categories (CPs and BPs) of pesticides. These high values raise concerns and call for immediate action. Medical professionals who volunteered to participate in our study expressed their opinion that mild toxic cases are generally not reported to them in a timely manner, unless some complications arise (Ssemugabo et al., 2020). This may be due to fear of losing job opportunities, lack of financial support, or ignorance and carelessness with health. However, many respondents (employers) mentioned that they take immediate actions to take care of their employees when faced with such situations, and strictly follow medical advice. This indicates a positive approach and reflects their educational level. Nevertheless, biased information is often received for various reasons (Chellappandian et al., 2018).

Similarly, the results of our study revealed a significant percentage (~90.0 %) of *life-threatening illnesses* among the population, including self-applicators and family members in all the three groups (FLs, GLs and DFUs) for both CPs and BPs. This high percentage is a serious concern that requires immediate action. Some reports suggest that both high and low levels of CPE are associated with poor mental-health. Some pilot studies performed in U.S, Europe, India, and other countries proved that agricultural workers, including farmers, exhibited extremely high levels of mental depression, compared to individuals with different occupations. The agricultural sector, unfortunately, seems to be strongly associated with poor mental-health status, mental-health disorders and depression, with an increased risk of suicide, even at lower levels of chronic exposures to CPs (Khan et al., 2019b).

The bar charts in Figs. 5 and 6 illustrate the implications of the collected data. Chronic distress and life-threatening illnesses, resulting from CPE, occur among farmers and their family members. The results clearly indicate a growing trend of conditions such as hypertension, diabetes, heart failure, Alzheimer's and Parkinson's diseases, cancer, thyroid disorders and even the ongoing COVID-19. These health issues may be attributed to the over consumption of CP-contaminated food products, direct exposure to CPs and other adverse impacts of pesticides (Dhananjayan and Ravichandran, 2018). The χ^2 test reveals statistical significance, indicating an indirect association between the variables 'liberal use of pesticides' and 'frequent use of pesticides', suggesting the presence of other adverse factors contributing to health deterioration.

4.6. Negatives on the eco-system (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150 \mid n1 = 47/\ n2 = 48/\ n3 = 48$)

A significant response was received from all the respondents (FLs, GLs, DFUs) regarding their perception of the threats posed by pest preventors to nature and the eco-system (Table 3). The participants of our study indicated that they heavily relied on pest control measures to combat the various unfavorable factors due to vermin, microbes, unwanted plants, and weeds. However, the use of CPs led to a significant decline in soil fertility (Mishra et al., 2020). Water, a critical resource, is globally depleted due to human overuse or unintentional/intentional negligence, and it is highly contaminated with chemical pesticides, which is a major concern (Yang et al., 2014). Similarly, pesticides not only had a drastic impact on air quality in urban areas but also in rural regions (Chellappandian et al., 2018; Thorat et al., 2023). Deposits of pest preventors on agricultural yields, water and soil are the main causes of ecological threats. To safeguard all living species, it is essential to avoid or control the excessive use of hazardous pesticides (Tudi et al., 2021).

Based on the inputs received, we observed (Table 3) a substantial increase in the number of domestic animals (in the vicinity) affected by pest preventors in FLs, GLs and DFUs, as indicated by the left shifted on the 4-point Likert scale. Additionally, accidents, either minor or major, occurring in households or localities, showed a balanced distribution among the three groups. We inferred that intentional accidents were prevalent in many cases. The received open-ended responses provided clear information. Medical professionals, including doctors, house surgeons, and para-medicals (who were volunteers in our study) concluded that a significant number of individuals in the age group of 12–30 years (~70 %) and women/men from higher age groups (~30 %) orally consumed these pest preventors for many reasons. Frontline workers reported that the affected victims or their associates do not reveal the exact required information (such as the nature of the pesticide, material consumed, time of consumption, weather conditions, etc.) required for a timely first aid. The left side of the 4-point Likert scale (from A to R) indicates that the majority of the population, either in society, locality or within households (FLs, GLs, DFUs) is adversely affected by incidents, highlighting the need for immediate attention.

Water and clean air are the major concerns. Our results clearly indicate that water bodies and atmospheric air are equally being polluted by the drift of harmful pest preventors, both in rural and urban areas. The left side of the 4-point Likert scale (from A to R) suggests that a significant portion of these essential elements of nature is being disturbed in various ways. This data emphasizes the urgent need for action to protect the eco-systems (Rajmohan et al., 2020). The primary producer-consumer-decomposer relationships in the food chain cycle (whether in soil, forests, grasslands or aquatic and terrestrial environments) are being damaged (Aktar et al., 2009; Hassaan and Nemr, 2020). Similarly, the death of harmless reptiles, amphibians, birds, and other organisms (in all three groups: FLs, GLs, DFUs) on the left-side of the 4-point Likert scale (from A to R) indicates a disruption and breakdown of the food chain cycle caused by the excessive use of pest preventors (Carvalho, 2017). The predators, who play a significant role in maintaining the eco-system balance, are also being affected. Thus, the food chain, which is crucial for the stability of ecosystems, is being compromised. The χ^2 test demonstrated statistical significance, highlighting a good association between the variables due to their evident dependency.

4.7. Alternative nano-biopesticides, outcomes of pest management, solutions and recommendations (FLs/GLs/DFUs, $N = (N1 + N2 + N3) = 150 \mid n1 = 47/\ n2 = 48/\ n3 = 48$)

The awareness of the potential negative effects of pest preventors on humans and eco-systems is leading to a growing interest in a green and sustainable revolution. The research community is actively exploring alternatives to chemical pesticides (CPs), due to the resilience of pests to these substances (Nuruzzaman et al., 2019). The presence of mutations in pests and microorganisms can confer resistance to CPs, and it is possible that the same may occur with alternative solutions targeting the same pests. However, new technological approaches and innovative practices are being developed to mitigate the harmful effects of pesticides used in agriculture and domestic settings. The adoption of suitable BPs and NBPs is becoming a trend towards sustainability, despite the frequent obstacles encountered (Kumar et al., 2021).

Analytical data depicted in Table 4 shows that most of the respondents strongly believe that immediate pest control measures should be taken, due to the difficulty of escaping pest intruders. The respondents recognize the seriousness of diseases caused by pests and understand that timely pest control can help preventing the spread of such illnesses. The data shows a right scale input for the 4th opinion, i.e., "Is it easy to control pests?", while the rest of the three questions were on the left scale (SA-Agr). The right scale shift inferred that it is not easy to control pests, and the frequency and quantity of pesticide applications are important factors to achieve effective control. This indirectly increases the exposure to pesticides, either directly or by ingestion through food produced and consumed, and raises concerns about the potential negative impact on human health. The respondents also thought that immunity gets retarded by the consumption and exposure of the pesticides through food and others (Meftaul et al., 2019). The respondents also expressed concerns about the presence of pesticides in fruits and vegetables generally available in the markets in India

(Fig. S3), such as the wax coating visibly seen on fruits to maintain their lustrous look. Statistical significance from χ^2 test with dependency for the variables 'liberal use of pesticides' and 'opinion' indicated a good association.

In the second section, the respondents expressed a strong opinion (100.0 % left-handed shift over the scale) that food produced with pesticide residues can lead to chemical poisoning in humans, animals, and eco-systems. They perceived chemical pest control measures as having detrimental consequences (100.0 % left-handed shift on the scale), (Hongsibsong et al., 2020) causing imbalances in the food chain cycle and damaging the relationship between primary producers, consumers and decomposers. Despite this awareness, there is a predominant leftward shift in responses, indicating a lack of action to address the broken food chain, leading to disturbances in the eco-system. A comparative analysis of BPs and CPs reveals both advantages and disadvantages for each category (Fig. 7), emphasizing the need for new technological approaches to achieve a better sustainability (Kumar et al., 2021). The χ^2 test revealed statistical significance and dependency between the variables 'deposits of pesticides' and 'immediate action', indicating a strong association.

The third section focuses on alternatives to conventional pest control methods. The majority of the population, including the less-educated individuals, showed a positive response to the introduction of new concepts. Conventional methods were perceived as insufficient to control all infestations, as pests developed tolerance with repeated applications. The right shift in responses in the scale (Dis to SD) indicated that alternatives might be helpful in resolving the existing problems. Nanotechnology-based alternatives, (Sreevidya et al., 2021b) referred to as "nano-biopesticides", could offer a better solution for pest eradication (Manchikanti, 2019). These nano-biopesticides offer advantages such as small size, enhanced surface-to-volume ratio, good stability, cost-effectiveness, and good degradation potential with green synthesis approaches (Lade et al., 2019). Dominant traits in controlling insects, microbials, bacterial, fungi, weeds, and other pests were inferred by research segments to give better results, while using alternatives to CPs/BPs in a very effective way (Chellappandian et al., 2018). The data analysis revealed that respondents from all three segments (FLs, GLs, and DFUs) had similar opinions and appreciated the new pragmatic approach of nanotechnology. The responses followed the order: FLs < GLs < DFUs, with one exception in the 4th segment, which may be attributed to a miscommunication or error. Notably, the DFUs dominated this sub-section, indicating that the majority of the respondents had a positive and optimist attitude, along with an appropriate knowledge. However, only a few had either used or were aware of the new trends available. The χ^2 test demonstrated statistical significance and dependency, highlighting a meaningful association among the variables within the 'alternatives' category. Furthermore, a notable correlation between 'education' and 'nano-biopesticides' underscores the influential role of the former in decision-making.

Interestingly, most of the respondents were unaware of nano-products being available; however, they believed that these new formulations had the potential to offer better stability and sustainability. This lack of awareness might be attributed to insufficient advertisement, limited marketing efforts, misinterpretation of new technological advancements, or a lack of non-promotion by NGOs, governmental organizations, or entrepreneurs (Singh and Burman, 2019).

Clarity of information is essential in presenting any new concepts (Sreejesh et al., 2014). Hence, the concept of "Nano-biopesticides" was clearly explained to all the respondents (Lade et al., 2019). *"Nano-biopesticides are tiny particles in the nano-range (very small-size), with a large surface area, prepared by using components derived from nature (biological/mineral) together with essential supplements of micro-nutrient salts* (Mnif and Ghribi, 2015)*. The product effectively inhibits the action of the attacking pests (vermin/microbials), even at a very low concentration or small quantity, when applied"*. For example, silver-nano-biopesticides were found to offer a viable solution for certain plant diseases, such as *Alternaria* leaf blight and leaf spot diseases observed in tomato, pepper, and potato (Kumar et al., 2021).

The respondents expressed curiosity regarding the toxicity of the nano-products. It was explained that due to their high effectiveness at low concentrations, less frequent applications proved to be sufficient (Nuruzzaman et al., 2019). Both literate and "poor-literate" respondents enthusiastically agreed with the introduction of this new concept of "nano-biopesticides", as it provided a potential solution to the problems associated with the usage of CPs and BPs.

Table 5 shows correlations denoted by * at $p<0.05$ and ** at $p<0.01$ among the selected variables, including Age (D1), Gender (D2), Level of Education (D3), Status (D4), Existing Health Issues (D5), New Alternatives (D6), Applicational Practices (Q1), General Awareness (Q2), Perception of Toxicities (Q3), Observed Precautions (Q4), Followed Prescription (Q5), Attitudes (Q6), Eco-system Preservation (Q7), and Pest Extermination (Q8) (Sarma, 2022). The correlational matrix analysis (R and P indices) clearly reveals several significant correlations. Age (D1) shows a positive correlation with LOE (D3) and status (D4), indicating that matured thoughts are associated with responsible pesticide use. Gender (D2) exhibited positive correlations with "new alternatives" (D6), Q4 (precautions observed), and Q8 (extermination of pests), suggesting that acceptance of new alternatives is beneficial to mankind and aligns with gender-based decision making. LOE (D3) displayed negative correlations with D1, Q5 (prescription followed), and Q6 (improper attitudes and human impairment), indicating the importance of following label recommendations and avoiding improper pesticide use, which can lead to human impairment. LOE showed positive correlations with Q4 (high), Q7 (preservation of the ecosystem), and Q8, highlighting the influence of literacy in adopting proper precautions while handling pesticides and protecting the ecosystem. Economic status (D4) exhibited an inverse relationship with D1 and D3, although with low significance. It also displayed inverse correlations with Q4 and Q8, suggesting that individuals from lower socioeconomic status may be less likely to practice proper precautions and may tend to exterminate beneficial pests. Health of family members (D5) showed a direct correlation with D4 (low) and an inverse correlation with D3 (low), indicating that decreased literacy levels contribute to increased health issues due to improper care and handling of pesticides. Q1 (applicational practices) displayed direct correlations with D4 and D5, indicating that economic status and family health influence the adoption of proper applicational practices. However, inverse correlations were found with D2 and D3, possibly due to an increase in poor literacy and gender bias in decision making. General awareness (Q2) exhibited a high direct correlation with Q1 but inverse correlations with D3 (high) and D2 (low). This suggests that increased poor literacy decreased awareness of the toxicities associated with pesticides. Perception about toxicities and pests (Q3) showed an inverse correlation with LOE (high), indicating that poor literacy is associated with a decreased perception of pesticide toxicities.

The correlation study emphasizes the need for new alternative approaches to address setbacks and negligence. New alternatives (D6) showed positive correlations with gender (D2), LOE (D3), Q7, and Q4 (high), while displaying inverse correlations with Q1, Q2, perception about toxicities (Q3), and Q6, as well as a low correlation with socioeconomic status (D4). This suggests that new approaches are necessary to address these issues. Socioeconomic status and family health exhibited negative correlations with new alternatives, indicating that decision making is influenced by pragmatism and financial resources. However, LOE and gender have a direct influence on the adoption of new approaches due to their awareness and perception of the toxicities associated with synthetic pesticides. Overall, these positive and inverse correlations highlight the potential of new alternatives in overcoming setbacks and negligence in pesticide use.

The data from MLRA, found in Table 6, was used to identify influential aspects like view, utility, social status that contribute to the outcomes among the respondents. The results indicate a positive outcome for the chosen concept. MLRA, as a flexible method, allows researchers to predict the significances of discrete dependent variables (DVs) based on one or more IVs (Mubushar et al., 2019). A lower value of maximum likelihood (LL) indicates a better fit (Al-Zahrani et al., 2019). The analysis focused on examining the influence of the choice of living (dwelling) on the adoption of new strategies for safe pest controller usage, which served as DV. The MLRA model, based on a set of 11 IVs, as depicted in Table 6, shows positive outcomes with four IV at $p<*0.05$ (age, LOE, informational resources and frequency of usage) and indicates the accuracy of the MLRA model.

Similarly, the observed pseudo R^2 is an indication of the accuracy of the model. The data reported, ranging from 0 to 1, fell within the McFadden, Nagelkerke and Cox and Snell categories, (Ntow et al., 2006) provides further indication of the model's accuracy. The model fitting criteria in this context demonstrated a 'Sig' value of 0.000, signifying a high level of significance at $p<***$ 0.001. This outcome indicates that the full model effectively and statistically predicted the dependent variable, thus confirming its goodness of fit. The inclusion of the pseudo R^2 model and other fitting criteria, which also exhibited strong significance, enriches the precision of the work. Additionally, measures such as χ^2 and Deviance were employed to assess the quality of fit. Notably, the Deviance value, with a significance level above *0.05, underscores a lack of statistical significance, thereby further affirming the model's overall suitability.

Among the chosen explanatory IVs, age plays a very important role in decision making. The parametric estimations demonstrated a significant mutual influence between age and urban living. Similarly, LOE had a strong influence in decision making and was further influenced by urban residence for the UG and PG groups. The individual attitude was strongly influenced by peer associations, media, like TV, radio, news-magazines, available literatures, neighbourhood, governmental and non-governmental organizations, and of course, internet news. Informational services had a significant impact, particularly in urban areas. We found that governmental authorities strongly influence decision making, likely due to subsidies provided to the population.

The perception of respondents about pesticide application is essential for pest management. However, safe measures need to be adopted for the welfare of the living species and for the protection of eco-systems (Abhilash and Singh, 2019). Nevertheless, the choice of pest preventors varies, depending on the knowledge perceived by the audience. The frequency of application of pest controllers depends on factors such as the nature of pests, season of application, type of crops and plants, etc. The frequency of application of pest controllers, in relation to dwelling as DV, shows statistical significance at $p<*0.05$ (Sig. 0.002). The remaining IVs, including social status (residency and gender), utility (pest controllers used and number of years used), and attitude (eco-system and new choice for pest preventors), were found to be insignificant in relation to the IV being examined, within this model, as indicated by likelihood ratio test values being $>*0.05$. MLRA maximizes the likelihood of the event's occurrence and helps to identify key factors influencing the adoption of nano-biopesticide usage among urban dwellers. The conclusive result of an impressive 90.2 % accuracy demonstrates the good performance of this model.

A few recommendations from the study participants and experts.

We were fortunate to receive valuable insights from several participants who kindly shared their view points on the subject. Their comments provided valuable additional perspectives. A selection is presented below.

- "Safeguarding the eco-system is my slogan. During this pandemic, we, the people, were forced to stay at home – this persuaded many to go into gardening and grow their own food as much as possible. An alternative safer approach is indispensable to lessen the loss and protect the life of oblivious consumers". - Dr. Tiripurasundari R. (Dietician).
- "Nature takes care of us; we should equally contribute for the betterment and take care of it in a safer mode with biopesticides". - Mr. Balaganesh (Financial advisor).
- "Nanotechnology and nano products offer a better sustainability to protect the future generations". - Dr. A.K. Singh (Professor, co-author of the study).
- "Prevention is better than cure, but when not able to practice it fully it is always better to go for safer alternatives. Learn lessons from this pandemic and not interfere too much with Nature". - Ms. Brinda Mishra (Teacher).
- "To protect our environment should be our motto. An unconventional new approach is essential to reduce the loss of life of ignorant end users". - Ms. Soudamini Ramakrishnan (Agro-Entrepreneur).
- "Nanotechnology extends a healthier swing with nano-bio products to submit its versatilities for future endeavors". - Dr. Y.R. Katre (Professor).
- "Exterminating the pests may hamper the food web, safer sections of practices curbs and controls their notorious bustles." - Dr. Mathangi Charan (Asst. Prof.).
- "Organic farming is the seed of life. Perhaps it is the nature's call for every one of us to reflect and sincerely think about the way of our living and not to take Nature's providence for granted. Covid-19 has taught sufficient lessons". - Ms. S.L. Tan (Organic Activist).
- "Inspired by the book 'Rising population of the world and increasing need to provide food' – I felt motivated to dedicate myself to this noble cause by choosing up agriculture and farming. Farming with a lot of hard work, not apprehensive about it – I willingly put in all the stannous effort, with new approaches being handy on my way." - Ms. N.V. Ratna (Agriculturalist).
- "Both quality and quantity of the food produce is a global concern. Insights to new switches ensures right quality of food, and this is imperative and vital". - Mr. Edison (Agriculturalist).
- "Let us protect the gift of nature, by adopting safer and cleaner ventures". - Ms. Lakshmi Raju (Homemaker).
- "It's time to wake up as we are left with no choice, and completely devastated by this pandemic wave. Build up immunity and strength (physically and morally). Ignorance is to be uprooted. Government and NGOs should provide good knowledge about practices to be adopted". - Ms. Jayasree S. (Homemaker).
- "Ensure safe mode of practices to avoid mental and physical trauma. Intentional/unintentional supplies of pesticides causes neurotoxicity. It should be controlled to ensure innocuous deliveries". - Dr. Ponrathi (Medical practitioner).
- "Don't play with nature, else nature would retaliate on you. Pesticide poisoning is in our hands, we can keep a full stop to it completely with endeavors and protect the eco-system for future". - Ms. Manjubashini (Frontline worker).
- "Love the nature as you love thyself. Let's together work for the betterment of the new cause". - Ms. Krithika Lakshmi (Human Resources Advisor).

5. Conclusion and outlook

Ensuring access to safe and clean food, water and shelter is essential for the well-being of all living species, regardless of whether they reside in urban or rural areas. The demand for increased food production, to sustain a growing need of population, led to the excessive use of fertilizers and pesticides. Unfortunately, the indiscriminate use of chemical pesticides resulted in environmental disruptions, health deterioration, activity impairment across various species, and the emergence of pesticide-resistant pests through genetic mutations. This study uncovered the fact that, despite the awareness of the detrimental effects of CPs on the environment, people continue to use them or rely on outdated prescriptions of safer but less effective BPs (Chellappandian et al., 2018). The continued use of pesticides can lead to compromised immunity and increased susceptibility to life threatening illnesses, especially

Alzheimer's, Parkinson's, and the recent COVID-19 pandemics, which exhibits high mutation rates. The loss of predators and extermination of pests disrupts the food chain, resulting in significant damage to the entire eco-system.

Correlation matrix studies showed that levels of education and gender directly influence the adoption of new approaches due to awareness and perceptions regarding the toxicities associated with synthetic pesticides. The logit model highlighted the influence of urban dwelling on the adoption of nano-biopesticides among the respondents.

The findings of this study reveal the advantages of nanotechnology, including sustainability, bio-compatibility, cost efficiency, man-power reduction, and minimal or no toxic effects. The novel value-based alternatives, namely biological pesticides and nano-biopesticides play a significant role in enhancing the quality of food production by effectively controlling pests that cause endemic outbreaks in various domestic settings. Governmental organizations, NGOs, adverting agents, and other communication platforms should emphasize the importance of these easily accessible alternatives, (Carvalho, 2017) to promote their growth also in economic sectors.

Overall, there is an urgent need to shift towards safer and more sustainable pest control strategies, such as NBPs, to mitigate the negative impacts of CPs on the environment, human health, and the overall ecosystem.

CRediT authorship contribution statement

Conceptualization: **AKS**; methodology: **SS, KS;** software: **SY**; validation: **AKS; AA; SACC**; formal analysis: **SY**; investigation: **SS**; resources: **FA**; visualization: **SS, SACC**; data curation: **YK**; writing—original draft preparation: **SS**; writing—review and editing: **AKS, SACC**. All authors read and agreed to the published version of the manuscript.

Declaration of Competing Interest

The authors of this paper declare they have no conflict of interest.

Data availability

Data will be made available on request.

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Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of Govt. V. Y. T. PG Autonomous College, Durg (protocol code IEC/GVYTPGACI 19 /DURG. Date- 30/10/2021) for studies involving humans.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.napere.2023.100058.

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