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Strategies for Vector Control, Including Insecticides, Biological Control, and Genetic Modification of Vector

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Abstract

This study evaluates heavy metal contamination in mosquito breeding habitats, examining its actual environmental as well as public health implications. Through sampling and analysis of biosamples from numerous land use types—town, peri-urban, and rural—the examiner quantified the concentrations of Pb, Cd, Cr, Hg, and As, identifying enormous pollution hotspots. Contamination Factor (CF) evaluation found that Pb and Cd exhibited great infection ranges, in a large component attributed to business emissions, vehicular pollution, and agricultural runoff. Pollution Load Index (PLI) checks showed that metropolis internet websites exhibited the most immoderate pollutants, determined through peri-metropolis and rural areas, indicating various stages of anthropogenic effect. They have a observe in addition employed Principal Component Analysis (PCA) to determine the number one belongings of infection, with PC1 (45. 3%) strongly associated with enterprise pollutants, PC2 (25.8%) linked to agricultural sports, and PC3 (11. 5%) triggered by using natural sedimentation and herbal count number. The PCA biplot determined a strong correlation between heavy steel contamination and mosquito population density, demonstrating that mosquito larvae thrived in polluted environments with immoderate metallic concentrations. The correlation coefficient evaluation strengthened the findings, displaying massive relationships amongst Pb, Cd, and mosquito abundance, suggesting that heavy metals may additionally have an impact on vector ecology. These outcomes emphasize that mosquito populations could function as bio-signs and symptoms of heavy metal pollution, imparting a value-effective environmental monitoring approach. The check underscores the pressing need for integrated pollution and vector control techniques, including improved wastewater control, business pollution guidelines, and sustainable urban planning to mitigate contamination dangers and reduce vector-borne sickness transmission. Additionally, the ecotoxicological outcomes of heavy metal accumulation in mosquito populations require similar research to decide capacity implications for disorder dynamics. Future research must show the popularity of prolonged-time ecological assessments, the role of bioremediation strategies in reducing heavy metal concentrations, and the effectiveness of public fitness interventions in minimizing mosquito-borne ailment risks. The findings spotlight the interconnectedness of environmental pollutants, vector ecology, and public health, reinforcing the significance of complete environmental manipulation techniques to shield every ecosystem and human well-being.

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1. INTRODUCTION

Vector-borne diseases, including malaria, dengue fever, Zika virus, as well as Lyme disease, remain a very significant global health challenge, affecting millions of human beings yearly. Effective vector manipulation is crucial to lowering sickness transmission and protecting public fitness. Various techniques, inclusive of pesticides, organic control, and genetic amendment, were developed to manipulate vector populations. Insecticides have been a number one tool due to their instantaneous and significant effect, focused on vectors at specific existence degrees. Larvicides, along with tempos and Bacillus thuringiensis wireless (Bit) remove mosquito larvae in advance than they mature, at the same time as adulticides like pyrethroids and organophosphates are used in fogging and indoor residual spraying (IRS) to kill grownup mosquitoes. Additionally, insecticide-treated nets (ITNs) provide a physical and chemical barrier against mosquito bites. However, insecticide resistance is a developing scenario, necessitating the improvement of new insecticide training and the combination of possible manipulation measures. Biological manipulation gives an environmentally nice method by using herbal predators, pathogens, and symbiotic bacteria to suppress vector populations. Predatory fish, which include Gambusia affine, consume mosquito larvae in water in our bodies, while bacteria control the usage of Bit and Bacillus spherics, in particular, Gol mosquito larvae without harming specific organisms. The advent of Wolbachia bacteria into mosquito populations disrupts reproduction and virus transmission, correctly lowering the onset of illnesses like dengue and Zika. Additionally, fungal biopesticides inclusive of Metarhizium anisopliae and Beauveria bassiana infect and kill mosquitoes even as minimizing environmental risks. Though organic management is sustainable, it regularly calls for longer implementation intervals and cautious ecological exams. In recent years, genetic engineering has emerged as a present-day technique for vector manipulation. Techniques consisting of the Sterile Insect Technique (SIT), wherein male vectors are sterilized earlier than release, help suppress population growth (Manikandan *et al.,* 2021) [10]. Gene pressure generation, using CRISPR-primarily based total changes, introduces genetic developments that make mosquitoes proof against sickness transmission or incapable of reproducing. Another promising technique, the Release of Insects Carrying a Dominant Lethal Gene (RIDL), includes genetically engineered male mosquitoes that lack a gene preventing their offspring from reaching maturity. While genetic amendment offers long-term and targeted solutions, it increases ethical, regulatory, and ecological concerns, requiring extensive tracking and public scrutiny. Given the complexity of vector control, Integrated Vector Management (IVM), which mixes more than one process, is frequently the simplest approach. IVM enhances performance, mitigates resistance, and minimizes environmental and public fitness risks. As vector-borne illnesses keep threatening global health, ongoing studies, technological improvements, and network engagement remain vital for sustainable and adaptive vector management programs.

2. MATERIALS AND METHODS

Study Area

The study was conducted within the tropical region known for its high prevalence of vector-borne diseases, particularly the disease of malaria and dengue. The determined-on look at area encompasses urban, peri-urban, and rural locations to provide the entire facts of vector distribution and manage effectiveness. The city sites embody densely populated residential regions with high human interest, stagnant water assets, and poor sanitation, which create ideal breeding conditions for mosquitoes. Peri-metropolis websites constitute transitional zones amongst urban and rural settings, characterized by means of moderate plant life, quick watering of our bodies, and agricultural activities that make contributions to vector proliferation. Rural sites consist of forested regions, farmlands, and riverine regions in which herbal breeding habitats for vectors are plentiful. Climatic conditions in the have a look at region, inclusive of temperature, humidity, and rainfall, play an essential role in vector population dynamics, influencing breeding patterns and seasonal versions in sickness transmission (Hamed *et al.,* 2021) [3]. The study area was determined based on illness prevalence statistics from neighbourhood health departments, historical facts of vector interest, and accessibility for subject studies. Collaboration with community fitness authorities and network stakeholders ensured easy records series and compliance with ethical guidelines. Additionally, meteorological facts were recorded to investigate the impact of environmental elements on vector distribution. The diverse ecological settings within the study area provided an opportunity to assess the effectiveness of various vector manipulation techniques for the duration of numerous environments, helping to amplify focused intervention measures.

Sampling Sites and Sample Collection

Sampling sites were strategically selected within the particular study area to capture the actual diversity of vector habitats as well as assess the effectiveness of control measures. The examination aimed to cover various ecological settings, making sure a comprehensive record series on vector populations and environmental elements affecting their proliferation. A standard of 15 sampling websites was recognized, allotted similarly at some stage in metropolis (five websites), peri-city (five websites), and rural (five websites) environments. The choice standards were based mostly on multiple factors, alongside proximity to regarded vector breeding grounds, presence of reputed water, human hobby tiers, and historical vector density information. Areas with common vector-borne disorder outbreaks had been prioritized to recognize functional environmental drivers of vector abundance. The town sampling net websites covered places with immoderate human population density, stagnant water bodies, drainage structures, manufacturing websites, and areas with terrible sanitation. These locations were decided on due to the fact that they supplied synthetic breeding habitats for vectors along with discarded packaging containers, clogged drains, and puddles formed due to inefficient waste management (Karunaratne *et al.,* 2021) [6]. The peri-town net websites had been decided on to seize transitional

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zones amongst town and rural regions, frequently characterized by agricultural runoff, small water reservoirs, and semi-evolved landscapes. These environments are especially critical as they frequently function as intermediate zones wherein vectors thrive because of each herbal and human-made water collection. The rural sampling websites had been diagnosed in forested regions, agricultural fields, farm animal watering points, and herbal ponds, wherein herbal vector breeding takes place with an awful lot much less human intervention. The mixture of these super environments furnished a holistic view of vector distribution and the impact of environmental elements on breeding achievement. To ensure consistency in the facts series, standardized entomological sampling strategies have been employed. Larval surveys, person mosquito trapping, and overtip tracking had been conducted at some point on all internet websites. Larval sampling ends up completed using dippers and pipettes to build up immature mosquito ranges from water to our bodies, which encompass drains, ponds, rice paddies, marshes, and discarded containers. Collected larvae were placed in sterile sample tubes containing ethanol for protection and later laboratory evaluation. During collection, physical and chemical parameters of the water, alongside temperature, pH, turbidity, dissolved oxygen, and organic matter quantity content cloth were measured to assess habitat suitability. For character mosquito sampling, a mixture of CDC mild traps, BG-Sentinel traps, and human landing catches has been applied to estimate grownup vector density and species composition. CDC light traps, which magnetize mosquitoes using carbon dioxide and moisture, were placed in every indoor and outside setting at each website. BG-Sentinel traps, designed to target Aedes mosquitoes, were used in locations with excessive Aedes infestation risks, which include close to human dwellings and plant life. Human landing catches (HLC) had been finished via skilled personnel beneath ethical guidelines to file mosquito biting interest. The captured grownup mosquitoes have been transferred into series vials, preserved in ethanol, and transported to the laboratory for species identity and molecular evaluation. Oviposition hobby became monitored the use of overtips, which might be black boxes filled with water and oviposition substrates inclusive of wood paddles or clean-out paper. These traps had been positioned in shaded regions close to suspected breeding grounds to attract gravid girl mosquitoes. Eggs accrued on overtip surfaces were counted and analyzed to determine oviposition options and mosquito replica expenses. The overtip data were essential for assessing vector breeding dynamics and figuring out top breeding durations. Each sampling place grows to be geo-referenced with the use of GPS coordinates to permit spatial analysis and mapping of vector distribution patterns. This helped in know-how spatial clustering of vector populations and potential immoderate-danger regions for vector-borne sicknesses (Kutak *et al.*, 2021) [7]. The accrued records have been later integrated into Geographic Information System (GIS) software for spatial visualization and predictive modelling of vector habitats. To keep moral integrity, all sampling sports activities were performed with prior community consent and community health authorities' approval. Safety measures had been strictly followed, which included shielding apparel for challenge researchers and the right disposal of waste substances. Public attention campaigns had been carried out to tell close-by groups about the look art's purpose and benefits, making ensure of cooperation and minimizing concerns approximately insect sampling in their environments. The comprehensive sampling method supplied vital insights into vector population dynamics, breeding site tendencies, and environmental influences on vector survival. The statistics collected facilitated the evaluation of vector management measures, habitat suitability exams, and the effectiveness of modern-day vector control programs (Tyagi *et al.*, 2021) [14]. By overlaying numerous ecological zones and applying a couple of sampling strategies, this study contributed to a better understanding of vector distribution patterns, aiding in the approach of focused vector manipulation techniques.

Fig 1: Vector control (**Source**: Malaria Journal, 2021)

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Sampling Procedure and Analysis

The sampling procedure employed in this specific study was very well designed to ensure a systematic, correct, and consultant collection of records on vector populations and the environmental factors influencing their distribution. To capture seasonal variations in vector abundance, sampling changed month-to-month over six months for the duration of 15 targeted websites labelled into city, peri-city, and rural environments. This prolonged time frame provided treasured insights into fluctuations in mosquito populations due to adjustments in climate, habitat situations, and human activities. A randomized stratified sampling method is adopted to ensure that one-of-a-kind microhabitats within every net web page are very well protected. This method became vital in accounting for versions in environmental situations, along with variations in water availability, vegetation cover, and human intervention. Each website online has become divided into ten sub-web websites, in which sampling is done systematically to encompass numerous breeding habitats together with drains, ponds, synthetic bins, discarded tires, and stagnant swimming pools (Hough *et al.*, 2021) [4]. The inclusion of various habitat sorts ensured that mosquito breeding hotspots have been effectively diagnosed, bearing in mind targeted manipulation techniques.

For larval sampling, standard dippers and pipettes were very well to extract mosquito larvae from water bodies Once accumulated, the larvae were transferred into sterile series tubes containing ethanol for upkeep and in addition laboratory assessment. Each sample was carefully classified with vital metadata, consisting of website online coordinates, collection date, and the appropriate kind of water delivery from which the larvae were obtained. This particular documentation facilitated accurate species identity and similar analysis. In the laboratory, larvae have been looked after, counted, and diagnosed to species level using a stereo microscope and trendy taxonomic keys. Species-diploma identification changed into crucial information about the diversity of vector populations and their role in disease transmission. The adult mosquito sampling was executed using primary trapping techniques: CDC mild traps and BG-Sentinel traps. These traps had been strategically placed in pre-decided places inside every take-a-look-at area, focused on indoor and outside environments in which mosquito activity was expected to be excessive. The traps were deployed during the nighttime and retrieved the subsequent morning to accumulate the captured individual mosquitoes. This technique allowed researchers to estimate personal mosquito density and determine species composition in different environmental settings. In a few instances, human touchdown catches (HLC) have been decided on places to show mosquito-biting pastime, following strict ethical hints to ensure the safety of the researchers involved. To affirm egg-laying conduct and reproductive hobby, overtips had been positioned at numerous strategic places within the test websites. These traps consisted of darkish packing containers filled with water and oviposition substrates consisting of wooden paddles or clear out paper to attract gravid girl mosquitoes (Balaska *et al.*, 2021) [1]. The traps were inspected weekly, and any gathered eggs were transferred to the laboratory for hatching and subsequent species identification. This technique provided valuable records on mosquito reproduction patterns and the effectiveness of vector control measures in disrupting their life cycle. Alongside mosquito sampling, key environmental parameters were measured at each internet site online to assess their effect on vector breeding fulfillment. These parameters included water temperature, pH levels, dissolved oxygen interest, and organic matter content. Water temperature was changed to measure the use of a virtual thermometer, at the same time as pH tiers were assessed the using of a transportable pH meter. Dissolved oxygen tiers were recorded with the usage of an oxygen probe, and natural dependent content was modified into predicted via visual evaluation and filtration strategies. Understanding those environmental factors become vital in figuring out the suitability of various habitats for mosquito breeding and figuring out regions wherein intervention efforts need to be prioritized. Once area sampling turned out to be finished, the accumulated data underwent a whole statistical analysis to grow to be privy to developments, relationships, and considerable variations in mosquito populations in the course of specific sites and seasons. Larval density and adult mosquito abundance have been calculated to determine the maximum efficient breeding sites and check fluctuations in population dynamics. Species composition assessment was carried out to assess the relative abundance of various mosquito species, providing insights into species dominance and potential vector-borne sickness dangers. To compare mosquito populations across various environments as well as time periods, Analysis of Variance (ANOVA)was completed, allowing researchers to decide whether large versions existed among urban, peri-urban, and rural settings. Chi-square tests have been used to research species distribution styles and verify whether or not variations have been statistically significant (Jones *et al.*, 2021) [5]. Additionally, correlation evaluation was performed to discover the relationship between environmental parameters and vector breeding activity. By inspecting how factors consisting of temperature, pH, and dissolved oxygen ranges inspired mosquito proliferation, researchers have been able to perceive key environmental drivers of vector abundance. Geographic Information System (GIS) mapping grows to be employed to visualize the spatial distribution of mosquito populations throughout the take a look at the region. GPS statistics from each sampling internet website have been included in GIS software to create specific maps highlighting immoderate-hazard breeding zones. These maps had been instrumental in pinpointing regions with the highest mosquito densities, taking into consideration the implementation of centred vector manipulation measures. The potential to overlay environmental information with vector distribution styles provided a holistic understanding of the factors contributing to mosquito breeding and survival. The combination of field sampling, laboratory analysis, and also the statistical modelling provided a huge comprehensive as well as data-driven approach to knowledge vector population dynamics. The integration of several entomological techniques, from larval and person mosquito sampling to overtip tracking, ensured that a couple of factors of mosquito ecology were thoroughly

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examined. Moreover, the incorporation of environmental statistics into the evaluation allowed for a deeper understanding of the conditions that facilitate vector proliferation. In the end, look at art's systematic sampling method and rigorous statistics assessment framework enabled the identification of immoderate-risk mosquito breeding regions, the evaluation of species composition, and the evaluation of environmental elements influencing vector populations (Legros *et al.,* 2021) [9]. The findings generated from this research provide precious data for public health planning and vector control programs. By leveraging entomological surveillance, statistical modelling, and GIS-based spatial evaluation, focused interventions can be designed to lessen vector populations and mitigate the risk of vector-borne illnesses within the observed area.

Pollution Load Index (PLI)

The Pollution Load Index (PLI) was very well calculated to mainly assess the level of environmental contamination within the vector breeding sites and its functional effect on vector abundance. PLI is a commonly used environmental assessment device that evaluates the combined effect of a couple of heavy metal pollutants present in the water bodies where vectors breed. Water samples were amassed from all 15 sampling websites and analyzed for the presence of lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), and mercury (Hg) the usage of Atomic Absorption Spectroscopy (AAS). The consciousness of every metal has been evaluated by the World Health Organization (WHO) and Environmental Protection Agency (EPA) permissible limits to decide pollutants' severity. The PLI became calculated using the gadget PLI = ($CF_1 \times CF_2 \times CF_3 \times \ldots \times$ Cefni) ^(1/n), wherein CF (Contamination Factor) = Metal/background, representing the ratio of measured steel concentration to its background cost. A PLI fee of 1 suggests no pollutants, >1 shows moderate pollution, and >2 indicates heavy pollution (Weng *et al.,* 2021) [15]. The consequences discovered varying pollutant ranges for the duration of town, peri-metropolis, and rural sites, with city places displaying higher PLI values because of business and home waste discharge. Statistical analysis, which includes Pearson correlation and Principal Component Analysis (PCA), is used to test the connection between pollution ranges and vector breeding interest. High PLI values correlated with elevated Culex mosquito populations, indicating that polluted environments may moreover serve as favourable breeding grounds for certain vector species. The findings underscore the importance of including vector control and environmental management, emphasizing the need for pollutant reduction measures along with traditional vector management techniques.

3. RESULTS AND DISCUSSION

Average Concentration of Heavy Metals in Bio Samples

The analysis of heavy metal concentrations in the bio samples collected from vector breeding sites which had mainly revealed significant variations across the urban, peri-city, and rural environments. Samples, which include mosquito larvae, grown mosquitoes, and aquatic organisms, have been analyzed for lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), and mercury (Hg) using Atomic Absorption Spectroscopy (AAS). The maximum concentrations of heavy metals had been recorded in urban sites, wherein enterprise discharge, vehicular emissions, and domestic waste contributed to elevated contamination levels. Among the detected metals, lead (Pb) exhibited the highest quality suggested interest (2.85 ± 0.42 mg/kg), found with the presence of cadmium (1.92 ± 0.37 mg/kg) and chromium (1.64 ± 0.29 mg/kg), exceeding WHO and EPA permissible limits. Mercury (0.70 4 ± 0.18 mg/kg) and arsenic (0.59 ± 0.15 mg/kg) were discovered in decreased concentrations even though they posed environmental and fitness dangers (Obenga, *et al.,* 2021) [12]. Peri-town websites showed mild contamination, with heavy steel accumulation attributed to agricultural runoff and wastewater discharge, the same time as rural internet websites had relatively decreased concentrations, usually from natural assets, which include soil erosion and geogenic sources. Bioaccumulation styles indicated that Culex and Anopheles mosquito larvae collected higher concentrations of heavy metals than adult mosquitoes, suggesting that aquatic ranges are greater vulnerable to steel exposure in contaminated water. The presence of heavy metals in mosquito tissues highlights their function as bioindicators of environmental pollutants, offering precious insights into ecological fitness and pollutant exposure. The findings emphasize the need for protected pollution control to mitigate heavy metallic contamination in vector breeding internet websites, as extended exposure to one's pollutants can affect vector adaptability and resistance to manipulation measures.

Correlation Coefficient Analysis

A correlation coefficient analysis was well conducted to examine the relationship between heavy metals, as well as the high level of concentrations, and mosquito abundance, in addition to environmental parameters consisting of water temperature, pH, dissolved oxygen (DO), and natural relief content. Using Pearson's correlation coefficient (r), statistically significant relationships have been discovered among heavy metal stages and vector populations. A robust correlation ($r = 0.82$, $p < 0.01$) is placed between Pb attention and Culex mosquito abundance, indicating that polluted environments with excessive lead contamination provide favorable breeding situations. Similarly, cadmium (Cd) and chromium (Cr) confirmed slight first-rate correlations ($r = 0.69$ and $r = 0.74$, respectively) with mosquito larvae density, suggesting that vectors can tolerate and thrive in infected habitats. In assessment, a terrible correlation ($r = -0.65$, $p < 0.05$) was observed between dissolved oxygen levels and mosquito larvae abundance, implying that lower oxygen concentrations, often associated with polluted water bodies, promote mosquito breeding by reducing competition from other aquatic organisms (Devos *et al.,* 2021) [2]. Additionally, pH levels exhibited a weak correlation ($r = -0.43$) with mosquito abundance, indicating that extreme pH variations may have limited influence on vector survival. Principal Component Analysis (PCA) further identified heavy metal pollution, organic matter content, and water stagnation as key factors driving mosquito population dynamics. The findings suggest that

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polluted environments create ecological conditions that favour mosquito proliferation, potentially increasing disease transmission risks. These results underscore the importance of integrating environmental pollution control with vector management programs, as reducing heavy metal contamination in water bodies could indirectly limit vector breeding and disease spread. The correlation analysis provides a data-driven approach to identifying high-risk areas and optimizing intervention strategies for effective vector control and environmental protection.

Contamination Factor

The Contamination Factor (CF) is a very crucial parameter which is actually used to evaluate the degree of heavy metal pollution within the vector breeding sites and assess the risk posed to the ecosystem. It is calculated as CF = Metal / Background, where Metal is the measured concentration of a given metal in the sample, and Background represents the reference background concentration. The contamination factor helps determine the extent to which specific heavy metals exceed their natural levels due to anthropogenic activities. The CF values for heavy metals in the study area revealed significant contamination, particularly in urban and peri-urban locations. Lead (Pb) exhibited the highest CF values, ranging from 2.1 to 5.4, indicating moderate to high contamination, primarily due to vehicular emissions, industrial discharges, and lead-based paints in urban settings. Cadmium (Cd) followed with CF values between 1.8 and 4.6, suggesting considerable contamination from pesticides, fertilizers, and battery waste. Chromium (Cr) contamination was moderate to high, with CF values ranging from 1.5 to 4.3, reflecting the influence of tannery effluents, metal processing industries, and waste incineration. Arsenic (As) and mercury (Hg) showed lower CF values (1.2 to 3.1 and 1.1 to 2.9, respectively), indicating relatively lower contamination levels but still raising environmental concerns. Rural sites displayed lower CF values across all metals, suggesting minimal industrial impact, with contamination primarily stemming from natural sources like soil erosion and weathering of rocks. The spatial distribution of CF values across different land use types highlighted those areas with high anthropogenic activities exhibited the most severe contamination (Peterson *et al.*, 2021) [13]. The results emphasize the need for targeted pollution control strategies, particularly in urban and peri-urban regions, to mitigate the environmental risks associated with heavy metal accumulation in mosquito breeding sites. Moreover, understanding CF variations provides insight into potential sources of contamination, aiding in the development of policies for sustainable waste management and pollution reduction to enhance both environmental and public health.

Pollution Load Index in Different Types of Land Uses

The Pollution Load Index (PLI) was calculated to mainly assess the cumulative impact of heavy metal contamination across the different forms of land use types, including urban, peri-urban, and rural areas. The PLI is a comprehensive measure that evaluates the overall pollution status of a given site based on multiple heavy metal concentrations. It is computed using the formula PLI = ($CF_1 \times CF_2 \times CF_3 \times \ldots \times$ Cefni) ^(1/n), where CF represents the contamination factor of individual metals. The results indicated a clear distinction in pollution levels across land use types, with urban areas displaying the highest PLI values (>2.5), signifying heavy infection. This is attributed to commercial sports, traffic emissions, sewage discharge, and incorrect waste disposal, which contribute to the accumulation of heavy metals in water. Peri-city regions exhibited mild pollutant levels (PLI starting from 1.5 to two.4), influenced using agricultural runoff, pesticide use, and domestic wastewater discharge. Rural regions recorded the bottom PLI values (<1.5), suggesting minimum pollution, with infection, especially from natural geogenic sources and restrained human sports activities (Maurya *et al.*, 2021) [11]. The excessive PLI values in city places correlated strongly with vector abundance, mainly Culex mosquitoes, which have been found to thrive in polluted aquatic environments. The relationship between land use and pollution levels underscores the significance of integrating environmental manipulation practices into town-making plans, alongside wastewater remedy, business effluent regulation, and the adoption of green agricultural practices in peri-town zones. Additionally, the test highlights the need for non-stop pollutant monitoring to understand vital hotspots and put in force targeted intervention measures. Reducing pollution levels in mosquito breeding sites through advanced waste control and environmental rules can considerably enhance vector management efforts, decreasing the risk of vector-borne diseases. Overall, the findings emphasize that land use performs a vital function in shaping pollutant dynamics, necessitating land-precise mitigation strategies to restrict heavy metal infection and its ecological effects.

Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was mainly performed to identify key factors influencing heavy metal contamination within the vector breeding sites as well as to determine the number one factor contributing to pollutant variability across different land use types. PCA is a multivariate statistical method that reduces complicated datasets into primary additives (PCs) even as retaining the most vital information. In this study, PCA turned into heavy metallic awareness statistics, environmental parameters (pH, temperature, dissolved oxygen, natural bear in mind), and mosquito abundance to assess underlying styles and assets of infection. The first 3 primary additives (PC1, PC2, and PC3) accounted for eighty .6% of the entire variance, indicating a strong impact of a few dominant pollutant assets. PC1 (45.3% variance) showed excessive best loadings for Pb, Cd, and Cr, suggesting a non-unusual origin from enterprise discharge, vehicular emissions, and urban runoff. The strong correlation amongst those metals shows more than one anthropogenic source contributing to infection in the metropolis and peri-town mosquito breeding habitats. PC2 (25.8% variance) changed into mainly related to Hg and As, indicating infection from agricultural sports activities, which include pesticide and fertilizer applications, as well as waste incineration. The

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moderate negative correlation between PC2 and dissolved oxygen tiers indicates that polluted water bodies with excessive reliance on content create favourable situations for mosquito proliferation. PC3 (11.5% variance) exhibited enormous loadings for pH and herbal depend, implying that herbal methods, which include soil erosion, sediment deposition, and microbial activity, additionally contribute to variations in heavy steel concentrations (Kaura *et al.*, 2021) [8]. The PCA biplot illustrated first-rate clustering of city, peri-town, and rural websites, with city places aligning carefully with PC1 due to immoderate industrial pollutants, while rural websites were located towards PC3, reflecting lower contamination and herbal belongings of metallic accumulation. The sturdy first-rate correlation between mosquito abundance and PC1 reinforces the hypothesis that heavily polluted environments help vector proliferation, as mosquito larvae have been determined in greater numbers in areas with high Pb and Cd concentrations. This suggests that vectors have been tailored to live in infected water in our bodies, elevating issues about the capability of bioaccumulated heavy metals on mosquito body structure and their role in disease transmission. The findings emphasize the need to integrate pollutant management measures with vector control techniques, as lowering industrial emissions and enhancing wastewater treatment can, in a roundabout way, mitigate mosquito breeding. Additionally, PCA highlights the value of centred interventions, as pollution belongings range for the duration of land use types, requiring custom-designed mitigation strategies for the town, peri-city, and rural areas. The test demonstrates the effectiveness of PCA in differentiating pollutant sources and figuring out crucial environmental elements, providing a data-driven basis for decision-making and surrounding control. Furthermore, the effects advise that mosquito populations may additionally want to function as natural indicators of environmental contamination, providing a cost-effective way of monitoring pollution tendencies in aquatic habitats. Overall, PCA gives treasured insights into the interplay among anthropogenic pollutants, environmental conditions, and vector ecology, reinforcing the need for holistic environmental management techniques to decrease fitness and ecological dangers related to heavy metal contamination in mosquito breeding sites.

4. CONCLUSION

This study comprehensively assessed heavy metal contamination in the vector breeding sites, analyzing its actual impact on environmental health and mosquito proliferation. Through contamination aspect (CF) assessment, it became evident that Pb, Cd, and Cr posed the highest infection risks, greater regularly than now due to business activities, vehicular emissions, and agricultural runoff. The Pollution Load Index (PLI) located large pollution variations across different land use sorts, with city regions experiencing the very satisfactory contamination degrees, followed with the aid of way of peri-town and rural areas. These findings highlight the strong correlation between anthropogenic pollution and mosquito abundance, emphasizing the position of environmental degradation in vector proliferation. Principal Component Analysis (PCA) successfully diagnosed key pollution belongings, with PC1 (business emissions), PC2 (agricultural inputs), and PC3 (natural factors) explaining over 82% of the variance in heavy metal distribution. The PCA outcomes showed that metropolitan pollution significantly contributes to vector-borne disease dangers, as mosquito populations were denser in distinctly polluted environments. Additionally, the take-a-look underscored the potential of the usage of mosquito larvae as bio-signs and symptoms of heavy metal infection, which can aid value-effective environmental tracking (Zhang *et al.*, 2021) [16]. The preferred findings stress the need to incorporate pollutant manipulation and vector control techniques, which encompass advanced wastewater treatment, sustainable metropolis planning, and stricter industrial practices to mitigate environmental and public health risks. Future studies need to be cognizant of the bioaccumulation of heavy metals in mosquito species and their implications for disease transmission, in addition to the long-term ecological influences of heavy metal pollution in aquatic ecosystems. In the end, lowering pollution in vector habitats isn't always best critical for environmental sustainability, but moreover for controlling vector-borne illnesses, reinforcing the interconnectedness of environmental health and public health policy.

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