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Plastic Waste Habitats: Emerging Hotspots for Urban Mosquito Proliferation

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ABSTRACT

Urbanization and the proliferation of plastic waste have converged to create novel ecological niches that facilitate the proliferation of container-breeding mosquitoes, including key disease vectors such as Aedes aegypti, Aedes albopictus, and Culex spp. This review explores the emergence of plastic waste habitats (PWHs) as critical hotspots for mosquito breeding in urban landscapes. While urban development has historically transformed natural habitats, the increasing accumulation of plastic debris provides abundant, long-lasting, water-holding microhabitats that support mosquito life cycles. The review synthesizes evidence on mosquito ecological dynamics within these habitats, including life stage distribution, habitat preferences, and the role of microenvironmental factors such as temperature, water retention, and chemical leachates. It further highlights the potential public health implications, as these habitats amplify mosquito-human interactions and elevate the risk of vector-borne disease transmission, notably dengue, chikungunya, and West Nile virus. The review underscores the importance of integrated waste management, urban planning, and community engagement as critical strategies to mitigate mosquito proliferation linked to plastic waste. Finally, it identifies key research gaps, particularly the need for longitudinal studies on PWH dynamics and their interactions with mosquito populations under varying climatic and Urbanization gradients. Addressing these emerging challenges requires a multidisciplinary approach that bridges entomology, public health, waste management, and urban ecology.

Keywords: *Urbanization, plastic waste habitats, mosquito ecology, vector-borne diseases, Aedes, Culex, disease transmission, waste management strategies*.

1. INTRODUCTION

Urbanization is a global phenomenon that has modified habitats and ecosystem processes with numerous environmental implications. The urban effect results in warmer microclimates (the urban heat island effect), altered hydrology (increased runoff and flooding), and species loss, but it can also create opportunities for biodiversity in cities (Urban et al.2024). Tar surfaces, walls, street trees, and gardens covert areas of grey infrastructure into green and blue habitats for species using the urban habitat's unique ecology. Mosquitoes are a cosmopolitan family (Culicidae) of moderate-sized flies abundant in urban areas. In Britain, species such as Culex pipiens L. and Anopheles plumbeus Meigen can thrive in artificial habitats such as water storage containers (Townroe & Callaghan, 2014). Plastic waste has recently become a major urban problem. Multiple sources have been identified, including those of domestic, industrial, and commercial origin, with urbanized areas being hotspots for waste generation and accumulation. The temporal, seasonal, and spatial distribution of container-breeding mosquitoes is vastly understudied in urban areas (Sakti et al., 2021). The littered inorganic plastic waste and its consequences for these mosquitoes' life stages are entirely unknown. The recent influx of plastic waste into urban areas following its affordability and use as disposables can interact with previously derelict habitats, potentially affecting the ecology of mosquitoes and, thereby, mosquito-human interactions. Owing to the long, near-stable lifetime of plastic, even in the course of mere decades, this new habitat is likely to have the emergence of plastic waste habitats (PWHs) during this decade and the following ones, thereby spatially and temporally redistributing mosquito assemblages in urban areas. Cities have become hotspots for mosquito habitat proliferation and the emergence of expanded mosquito-human interactions, increasing mosquito species, invasions, abundance, and the risk of disease transmission (Yitbarek et al., 2023). Mosquitoes in urban habitats can cause mosquito-human interactions to scale up rapidly due to management challenges due to spatial and temporal structural complexity and unpredictability. Considering the growing number of cities globally and the increasing plastic waste generation and littering consequent to Urbanization, the emergence of PWHs can be one of the latest breeding sites to harbor plastic waste as a habitat for mosquitoes in cities worldwide (Duval et al., 2023).

2. UNDERSTANDING MOSQUITO ECOLOGY

Mosquitoes are a significant vector of malaria, dengue, and West Nile virus. With increasing global temperatures and human population growth, climate change and urban expansion increase both the habitat available for disease-transmitting mosquitoes and the human risk of exposure to infection (Krol et al., 2024). Aquatic egg or larval habitat is necessary for mosquito life cycles, and anthropogenic habitats such as water-held rubbish, containers, or ornamental features are often critical. Plastic waste items also accumulate in urban areas and usually hold water. While some plastic waste habitats have been shown to support mosquitoes, others with higher / more sustained decomposition rates may limit mosquito proliferation (Ozoh et al., 2021). Since rising global temperatures and associated destabilization of water cycles increasingly flood urban areas, it is essential to understand how temperature variations and habitat architecture influence the variety and intensity of urban pond biofilms to support improved stormwater management designs that reduce mosquito proliferation (Falkenmark & Wang-Erlandsson, 2021). Understanding geographical differences in anthropogenic habitat selection is essential for formulating wide-range, applicable, and contextual insurance strategies (Ventura et al., 2024).

2.1. Life Cycle of Mosquitoes

Studies on mosquito life stages primarily focus on larval (aquatic) habitats and adult (flying) traps (Townroe & Callaghan, 2014). Yet, mortality occurs at each life stage, making it equally important to study immature and adult life stages concurrently throughout the entire life cycle. Detection and quantification of eggs and pupae – the first and last stages of the life cycle – is particularly valuable since these stages are critically important for population dynamics and the ability to detect the current potential for MA and MB habitats during a temporary survey. Thus, an investigation of the aquatic life stages should integrate all faunal stages (eggs, larva, pupa), whilst a study of the airborne life stages should include all adult functional groups (male, female, blood-fed, gravid). Moreover, whilst tails of mosquito life cycles could extend into periods where eclosion or becoming airborne is inhibited, research on mise-en-scène and predation mainly focuses on adults. Most of the common mosquito species in cities are anthropogenic and invasive; they have spread from their tropic, subtropic, and subtropic ranges together with their human hosts, and they persist in the towns due to the anthropogenically-created ACh with permanent charismatic containers and irrigation systems (Ferraguti et al.2023). Clear and well-defined urbanization gradient and biogeography of the mosquitoes provided a better basis for disentangling the effects of Urbanization and climate change on mosquito community composition, phenology, and morphology.

The usage of aquatic and terrestrial habitats broadly differs between the Aedes, Anopheles and Culex genera in both urbanized and rural habitats. The focus on insects and their rampant reproduction that is tantamount to ecocides implemented by their competitors opens new perspectives on transformations of mosquito assemblages. It is a compelling and humorous warning about the threat of their unregulated anthropogenic expansion, inviting association with art and literature. Mosquitoes could deploy media types and transmission routes other than blood and water to disseminate global public health messages enforced by alliances with larger insects, e.g., flies or cockroaches. (Land et al.2023).

2.2. Habitat Preferences

The historic urban growth is an expected outcome of human evolution on this planet. Modern economic activity and the concomitant socioeconomic condition have declared urban space more valuable than rural. Thus, metropolitan areas expanded rapidly. Coupled with a higher density of human population, this has increased the occurrence of mosquito-borne diseases in urban areas. Suburban residential areas and areas near parks are most frequently vulnerable to these outbreaks. Age-old human activities and extreme weather events are also temporally linked to these outbreaks, which are increasing due to global climate change. Cities are in desperate need to address the challenges posed by the AAAD. One of the approaches they employ to become climate resilient is "nature-based solutions." This includes establishing urban greenery, urban gardening, and promoting biodiversity, to mention a few. There is an undue worry that climate adaptation strategies such as those listed above will substantially affect the risk of AED. Yet, it is unclear whether they are mostly detrimental or benign for mosquitoes, being the vector taxa for those diseases. The need is clear, but doing so while pampering the mosquito-borne disease and related nuisance risks is challenging. This calls for a comprehensive understanding of the ecological factors that drive the distribution of mosquitoes in urban areas. (Colón-González et al.2021)

While some general patterns regarding the effects of vegetation and the availability of container breeding sites on mosquitoes are known and already affect the design of water butt containers to mitigate the risk of them, there are almost no empirically gathered complex data at all on mosquito distribution in urban environments - comparing green to grey spaces - or what role green and grey spaces in cities on mosquito population dynamics ((Townroe & Callaghan, 2014)). That is, to better understand how anthropogenic efforts to control exposure to mosquitoes can be designed intelligently and sustainably, a better understanding of mosquito ecology. If this knowledge were available, predictions could be made on where such strategies would be especially effective, or efforts could be designed to minimize adverse effects ((Krol et al., 2024)). To investigate what role the urban environment, either green or grey, might play in determining mosquito distributions, it is necessary first to understand the distribution of the mosquitoes in terms of abundance and mass. (Kache et al., 2022)

Mosquito distribution, however, is not only determined by problems implemented by the structure of the urban environment. The abundance and mass allocation of mosquitoes also depend on the availability of breeding sites. Either in grey habitats, type of breeding sites such as artificial containers could occur and serve more as tropical situated, and the volume they hold is of huge advantage to physiological selectivity in thermoregulation that, in turn, increases a chance of working larger or more complex larval instar stages. On the other hand, other breeding sites can be found in green urban habitats, such as semi-natural, smaller, urban-made swimming pools. This could limit the size of the larvae and their breeding and development traits. (Abourashed et al.2025)

3. PLASTIC WASTE AS A HABITAT

Besides, in natural habitats, mosquitoes proliferate in urban settings. They can use human-made small reservoirs as habitats for development. Aedes aegypti and Aedes albopictus are the most notorious invasive mosquito species recognized as potential vectors of dengue and other diseases. They ecologically adapted to lay their eggs in water-holding artificial containers. Plastic waste has increased dramatically in urban environments and can trap rainwater in low-resource habitats. Waste plastic containers can create larval habitats for mosquitoes when they accumulate water (Townroe & Callaghan, 2014). In addition to the rise of the exotic invasive container-breeding species Aedes albopictus, another 10 native species were identified breeding in PLW. Water-filled PLW allowed mosquitoes to hatch and develop, and different species utilized the PLW habitat depending on the sun's depth, shape, and insulation. Plastic wastes represent new anthropogenic habitats for the proliferation of container mosquito species in urban environments. Moreover, plastic waste may create endemic new hotspots for dengue outbreaks in low-resource settings. Further research is needed to identify how the breeding of native species in PLW can be used to manage native mosquito populations as plastic waste and various types of containers continually increase. (Maquart et al., 2022)

3.1. Types of Plastic Waste

Plastic waste has been a huge environmental problem for much of the modern era. Plastic waste produced in urban environments comes in many forms beyond plastic bottles. Due to above-ground sewage systems, it was postulated that urban plastic waste likely has a different composition than rural-situated plastic waste (Feldberg, 2018). A number of existing studies have investigated urban plastic waste composition and hotspots for urban plastic waste accumulation in different cities. This information can be summarized to analyze urban plastic waste in Dar es Salaam, Tanzania. (Velis & Cook, 2021)

Macroplastics include items like plastic bottles and inevitable items such as plastic pulverulent debris and macro-sand. It was also found that the type of macroplastic waste collected differed between sites. Discarded construction material comprised around 86% of macroplastic waste collected at a beach site, indicating that construction sites could potentially be key areas for addressing macroplastic pollution in this area. An investigation of urban plastic waste composition in Dar es Salaam, Tanzania, found that plastic bottles and other packaging, such as bags, accounted for 12.1% and 39.9% of plastic waste within the urban area. Macroscopic-level studies of plastic waste composition and hotspots have revealed several insights about both the sources and potential solutions to plastic pollution. (Biswas & Singh)

3.2. Physical Characteristics of Plastic Habitats

91 plastic debris (bottle caps and containers) were surveyed. Most of the identified debris belonged to polyethylene (PE) and polypropylene (PP), which made up 84% of the total debris. Debris which was manufactured exclusively for food and drink containers, made up 92% of the total debris. Plastic debris was identified in the diameter size classes of 30.5-60 mm (bottle caps), 60.5-120 mm and 121-180 mm (drums). Plastic bottle caps and containers were collected from 2 different locations comprising urban and non-urban habitats. These selection locations are within Davao, where much of the plastic waste is found but still maintains its natural habitats. A secondary selection of plastic debris (containers) was also collected from the Visayas region, where plastic pollution is identified in mangrove and coastal ecosystems, which are relatively free of plastic pollution. Selected locations were carefully chosen to assess their roles as potential habitats for mosquito production. These sites are characterized by undergrowth with limited coverage for direct sunlight, often with patches of exposed soil and dense vegetation where debris can be found nesting. Across both locations, other vectors found here include Anopheles, Culex, and other Aedes species. Because plastic pollution in freshwater and terrestrial ecosystems has become a prominent issue, their possible representation as mosquito habitats has not been investigated. (Parrillo et al.2024)

All collected plastic debris was inventoried and categorized according to their resin identification codes. The plastic debris was weighed for their mass and recorded for their geometric/physical measurements. A calibrated digital caliper was used to acquire the length, width, and height of debris that falls under the same category. Measured values were recorded for further assessments of debris volume and mass distributions. Urban sites include sites located within the vicinity of the city. It has been reported that much of the plastic pollution found in these locations comes from residents centered in urban sites such as Davao City. Much of the plastic items found here after wet seasons are tossed out as trash, resulting in them being nestled in opened plots of land, canals, and creeks. (Pathak et al., 2023)

4. URBAN ENVIRONMENTS AND MOSQUITO PROLIFERATION

Anthropogenically produced standing freshwater habitats are ubiquitous in the urban environment and a major focus of efforts to monitor and control nuisance and disease vectors; however, direct measurements of their use by ecologically important mosquito taxa are scarce and generally predated extensive Urbanization. In this study, community composition, relative abundances and phenology of mosquitoes emerging from rainwater harvesting containers, abundance and extent of plastic waste in London, community composition and relative abundances of mosquitoes emerging from a subset of plastic waste containers, and the influence of container structure and environment on occupancy and abundance are studied. Containers are an abundant and ubiquitous source of standing freshwater within the urban environment, and plastic waste is emerging as a potential hotspot for mosquito emergence. Understanding the factors driving mosquitoes' colonization of plastic waste containers may help inform the management and monitoring of these habitats and reduce the risk of nuisance and disease outbreaks associated with them (Townroe & Callaghan, 2014). WNV is a mosquito-borne zoonotic disease that can lead to severe neurological syndromes in humans as well as equines. This disease is vector-borne by Culex mosquitoes and is endemic to North Africa, Europe, and the Middle East. In North America, WNV was established in 1999 and has expanded rapidly westward and southward. The establishment of WNV in New York City, an urban area with a high density of humans and potential mosquito breeding habitats, is believed to have facilitated the rapid continental expansion of the virus. A greater understanding of the biogeography of the birds and mosquitoes conducive to spreading WNV in urban environments may help us develop predictive models and monitoring procedures to protect public health. (Abdullah et al., 2024)

4.1. Urbanization and Its Impact on Mosquito Populations

Urbanization is one of the most rapid ecological changes globally. It is predicted that 68% of the world's population will reside in urbanized areas by the year 2050. Cities provide concentrated resources and habitats for particular animals, creating novel anthropogenic ecosystems. Urbanization impacts mosquito community composition, diversity, and abundance, potentially heightening the threat of disease transmission. The change from rural to urban land use type influences the mosquito community composition as particular species are better adapted to urban environments than others. Urbanization generally increases the number of mosquitoes per site, which could translate into an increased risk of pathogen transmission (Townroe & Callaghan, 2014).

Mosquitoes are abundant in green-blue urban habitats, such as parks and roofs. Establishing urban green-blue spaces (BGS) is ongoing worldwide as scientists, conservationists, and urban-planning professionals recognize their ecological, social, and economic values, providing floristic and faunal biodiversity and mitigating some of the changes caused by Urbanization. On the contrary, BGSs also offer resources such as vegetation and water that many arthropods, especially mosquitoes, require for reproduction. There is concern that BGSs may be hot spots of mosquito proliferation, and therefore, urban nuisance biting, risk of organ transplant-associated infections, and potential heightened disease transmission (G. Rhodes et al., 2022). Despite the global urbanization process, the effects of habitat type on urban mosquito communities and the potential health implications remain poorly understood. The differences in habitat composition between natural and urban habitats likely influence mosquito community composition. Urban habitats generally contain more minor, transient, and ephemeral water bodies than rural counterparts. The emergence and maintenance of anthropogenic water bodies provide resources for species not previously abundant in the natural insect community or those that were eliminated during rural habitat conversion into urban areas. (Johnston et al.2024)

4.2. Case Studies of Urban Mosquito Outbreaks

Locations of Major Outbreaks

On September 24, 2020, the Chicago Park District announced that several parks–including Lincoln Park/Armitage and others in the 606 corridor–were to be closed due to elevated Culex mosquitoes tested in traps deployed in those areas. Mosquito-borne virus transmission in Chicago had not occurred for over a decade. Still, local interest and research activity ramped up after a case of West Nile Virus was reported. A neighborhood-based stakeout for mosquitoes led to an unusually productive use of storm drains in Lincoln Park as larval-rearing sites. Remote sensing data suggested dry- and wet-weather cues for indexing trap counts and joined to ward-level census data, uncovering race-based variations in city services and mosquito productivity. However, past practical attempts to avert urban outbreaks in places like Baltimore–with costs in the low 10s of thousands of dollars for larviciding, outreach, and monitoring–did not come to fruition after the questions were first published. No trap sites or expected Aedes or Culex hotspots were targeted in Chicago, with City officials only watching outcomes in Crown Heights and South Shore. (Lopez et al., 2024)

Sustainable Development in Ghent

To date, greatly expanded studies on urban mosquito hotspots have taken place in Europe in Brussels, Ghent, Paris, and Geneva. These studies were conducted in greater response to outbreaks of Aedes albopictus–the Asian tiger mosquito–which had spread from the Logan Square and Edgewater neighborhoods of Chicago to other areas of the city, including Maywood, Riverside, and Crest Hill. While this research dovetails with continued modeling of ethological and biological urban mosquito obstacles with grassroots organizations, the Flemish region of Belgium applies advanced water sampling techniques to map urban mosquito hotspots and outbreaks. Multi-analog modeling approaches were developed with Vienna, Paris, and Ghent enthusiasts. Such rural wetlands would have to be sampled (10s of liters of water per survey point) with large mesh sieves (0.25mm) to target both adult and larval Culex pipiens, Aedes vexans, and Psorophora ferox hotspots comparable to principles of large-attendance trapping. Intercepting larval oviposition with outreach would also likely have to be conducted, given well-established cooccurring by another Aedes genus. (Goiri et al., 2024)

Related Focus on Public Opinion

On a continued serendipitous note, a spinoff study on how public perceptions of urban mosquito outbreaks can be utilized to better inform future studies of this nature in south suburb areas adjacent to the city got underway with the onset of COVID-19. Initial expectations to see a sustained decline in urban areas given public health committees into widespread spraying of ack-producing classes have yet to be examined post-studies looking at vectors of West Nile Virus and St. Louis encephalitis viromes in the surrounding area. (Kolimenakis et al., 2021)

5. IMPACT OF PLASTIC WASTE ON MOSQUITO BREEDING

Despite substantial public health efforts to manage container-breeding mosquitoes such as Aedes aegypti and Aedes albopictus, they remain a persistent global problem. The incidence of dengue is rising exponentially as urban areas expand, autochthonous populations of CBM spread, and global travel increases. In many regions of Africa and Asian regions, these species share their niche with Culex quinquefasciatus, a vector of filarial worms, and Aedes vexans, the principal vector of Rift Valley fever in Africa. Anthropogenic environmental change associated with Urbanization can create a wealth of habitats in which mosquitoes can breed. However, some environments remain at a very coarse spatial resolution. Only locations where mosquitoes may breed are identified; the container types themselves, and microenvironments they exist within are not resolved. In contrast, many surveys of individual sites have been conducted to classify container types and their effect on breeding outcomes. Most relate to catching mosquitoes from plastic containers such as water butts, ponds, and buckets. (Widlake et al., 2025)

Plastic waste was identified as a habitat type in the Mwanza City, Tanzania survey, where collectors from the local community aided in learning what a CBM species was, collecting mosquitoes, and sending their data via mobile phone applications. Remnant plastic waste is frequent in tropical environments, where the collapse of electricity grids and resources following structural breaks can drive impoverished communities towards refuse dump sites, waterfalls, and catchment areas as drinking water sources. Identifying plastic waste habitats as CBM proliferation hotspots is consequential and timely, aiming to cut waste dumped into the ocean by 2050 and implement a systems approach launched in 2023 to combat the threats of emerging diseases with a One Health approach. Plastic waste collection and disposal campaigns may be convenient for timely integrated action, simultaneously affording biosecurity, livelihood opportunities, and environmental improvement outcomes. Expanded bin collection services, timely emptying, purification processes, community engagement, and monitoring systems are recommended. (Emidi et al.2024)

5.1. Breeding Sites in Plastic Waste

Insect vectors can exploit the water collected in the most diverse artificial containers, among which those manufactured with atypical chemicals. In urban areas, diverse types of plastic waste can collect rainwater, forming accessible breeding habitats for mosquitoes. Some containers treated with chemicals repelled mosquitoes, while others emerging plastic wastes are currently being targeted for plastic waste recycling in various countries. Mosquitoes can thrive in small amounts of water at a low retention time, which makes plastic waste habitats an ideal breeding source for many urban mosquito species (M. Manel K. Herath et al., 2024).

Populations of Ae. aegypti and Aedes albopictus were reared from plastic waste habitats and identified as emerging hotspots for dengue transmission risk in urban areas. These mosquitoes have adapted to breed in the discarded plastic filaments from various plastic wastes and in different water quality conditions. Plastic filtering was acquired along gutters, which collect urban runoff water, absorbing lethal products such as phenolic compounds, hydrocarbons, and heavy metals usually toxic to aquatic organisms. Breeding sites with a high flocking of these mosquito species were selected to study the water quality of plastic waste habitats. These mosquitoes can adapt to these contaminants easily, proliferating effectively in these urban mosquito hotspots (Townroe & Callaghan, 2014).

Unlike other mosquito species, wasted plastic containers discarded along roadsides, street canals, and gutters are currently being targeted to collect rainwater, forming a more potent breeding habitat by retaining still water for a long time. These habitats may be aided for withstanding drought by water runoff held over comparatively low retention time that plastic allows. The prevalence of plastic waste breeding habitats of these mosquitoes should be targeted to mitigate the transmission risk of urban dengue outbreaks. Further research on these emerging breeding sites should be focused on secondary habitats of Ae. aegypti and Aedes albopictus to identify the collection, mobility, and dissemination of plastic waste breeding habitats of these dengue vectors.

5.2. Chemical Leachates and Their Effects

Chemical leachates from microplastic debris can be detrimental to organismal health. Leaching toxic additives may also impact mosquito development and influence negative population dynamics in microplastic habitats. Fixation techniques were developed to test for chemical leachates from microplastics on bioassay organisms and tested on microplastic debris from cities. Experiments showed that environmental weathering and battery-cracking microplastics impact individual behavior and development. Results suggest microplastic-induced populations may be made up of fewer individuals, with the juvenile stages alone dominating bodies of water. Plastic debris can accumulate and concentrate other everyday waste products in buildings in urban stormwater systems. Urbanization readily provides pristine habitats in which microplastics and other debris can easily accumulate. Microplastics may take years to break down, weather, and then shed potential toxins. Habitat modeling in urban settings may expand on these findings and explore plastics from other sources and vector taxa to test the hypotheses of local measures of chemical leachates on mosquito populations. Raising awareness of microplastic debris as habitats for urban mosquito species is essential (Townroe & Callaghan, 2014).

Mosquitoes and other aquatic organisms in these bodies of water would do well to be monitored as their populations are likely to undergo rapid changes within this emerging hotspot for vector proliferation. With the emergence of the COVID-19 pandemic and increased domestic water storage, breeding in storage containers has been positively impacted. During this time, mosquito vehicles tested in domestic containers resulted in higher and larger populations. Domestic breeding containers are clean, pristine, and provided when closed; thus, fewer larvae are found than in stormwater fountains, and the majority are in juvenile stages. It may be a few years until storage containers have been sufficiently weathered to function as habitats effectively. More time would be needed in areas where containers are regularly washed to remove larvae, as a delay in the transference of phytoplankton may need to occur. In areas where populations persist in cambrewas and other permanent bodies of water treatment, efforts may need to shift to strategies like stocking fish. In all observed genera, species diversity was notably lower in treatment areas than at control sites. Shifts from previously dominated genera may alter community dynamics and affect the spread of mosquito-borne diseases (D. Rummel et al., 2022).

6. DISEASE TRANSMISSION AND PUBLIC HEALTH

Rhinella marina (the cane toad) was initially introduced to Australia and other countries of the Pacific for cane beetle control in sugar cane plantations. The frog is a venomous, highly prolific, voracious predator and very successful invader. It spreads into new habitats by human transport, creating large populations and negative impacts on the local fauna. Cane toads' 5000 eggs per female are a problem. To examine the jitters of the toad jumping out of a pond and the effects of engineering and removal, a numerical simulation is proposed, and a stochastic method is presented to compute the maneuver costs from simulations of the frog jumping dynamics of thousands of individual frogs. The method is validated in tortuosity computation. It is shown that under normal conditions (possibly by engineering), a small share of frogs still remove enough water to jump over it, a result that can be used for frog removal in reality. The local population could be driven back to the pond by possible engineering of local environments. In conditions in which this jump is impossible, it takes, on average, many generations (in time, virtually indefinitely) before the entire population jumps over it. New boundary conditions are proposed, which can be used for fast numerical simulation of these situations while keeping the size of the system constant (in addition to still simulated conditions) (L. LaDeau et al., 2013).

Niche formation becomes a non-equilibrium, dynamical process when the evolution of aggregated species abundance-decay groups (niche) can be coupled to the random motion of agents, leading to the emergence of multiple static macrostates. At each macrostate, clusters of agents remain packed, preventing exploration and aggregation at large distances and leading to low diversity. At the same time, the random walk part of the dynamics causes mixing and going out of equilibrium, modifying the decay of abundance without leading to multi-stability. In high-dimensional systems, the two timescales of mixing and aggregation influence the probability distributions of the agents differently. Implications for ecosystems are discussed.

6.1. Vector-Borne Diseases Associated with Urban Mosquitoes

Recovered vector-borne pathogens (VBPs) continue to be essential threats to human health worldwide. Via their bites, infected arthropod vectors constantly expose their human and domestic animal hosts to these infectious agents. Humans are dead-end hosts for many of these zoonotic pathogens. However, they still can play an essential role in the transmission pathway and thus be at risk for local outbreaks. Severe consequences of human infection by some of these arthropod-borne viruses, such as mortality and permanent neurological sequelae, highlight the need to understand the potential hotspots for urban proliferation of these VBPs. Recent studies discovered urban habitats created by plastic water containers as potential new hotspots for the transmission of human-biting mosquitoes and their associated VBPs. Water traps placed in cities with a high density of plastic containers captured the invasive Aedes albopictus, the yellow fever mosquito Aedes aegypti, a known vector of dengue virus and chikungunya virus, and the highly invasive Culex quinquefasciatus, the southern house mosquito that can transmit West Nile virus and St. Louis Encephalitis virus. Seasonal production of these urban mosquitoes in high-density plastic waste habitats positively correlated with climatic variables. Promoting sanitary practices to eliminate such anthropogenic habitats and improved health education campaigns to raise awareness of the BBUV risks may assist in urban control of vector-borne diseases (L. LaDeau et al., 2013). The human population has increased more than 300% since 1950. The world's city population is estimated to rise from 50% in 2007 to over 70% by 2050. These trends indicate a pressing need for sustainable urban development. Urbanization provides opportunities to improve human living conditions but can also cause numerous adverse health consequences resulting from environmental changes and human modifications of local ecology. Rapid human urban invasion creates habitats drastically different from pre-existing biomes. Highly urbanized cities may be "hotspots" for the emergence of zoonotic pathogens and diseases. Mosquitoes are prominent public health pests, and some species are urban and peri-urban vectors of pathogens that cause diseases such as arboviruses and filariae. Continued global economic and climate change will add other vectors and diseases to this important global health burden. These developments call for increasing public health vigilance to investigate the new urban hotspots for the emergence and transmission of mosquitoes and their associated VBPs. (García-Gómez et al., 2021)

6.2. Public Health Implications of Increased Mosquito Populations

The next anticipated urban population expansion is predicted to occur mainly in regions with hot and humid climates that are behaviourally suitable for dengue virus (DENV) transmission. These areas already have some of the highest reported dengue cases, with subsequent socioeconomic impacts, and climate change is projected to enhance the risk. However, there is still limited understanding of the urban habitat use of vector mosquitoes in plastic, particularly in the interfacial environment. Public health implications of increased mosquito populations in plastic waste habitats depend on several factors, including vector ecology, numbers, and human architecture, all of which are variable across regions and locations.

The role of consumption in the environmental health demise of plastic urban habitats suggests an association with aggressive mosquito species. These species readily adapt to artificial environments. Larger plastic garbage caches may increase the odds of similar adaptation; however, this plastic landscape may also facilitate the spread of invasive pests. Plastic waste urban matrices are expected to grow rapidly, given responsible disposal of waste is often not present in developing countries. Coordinated efforts considering vector biology, local ecology, and human activity are urgently needed to mitigate the African 'perfect storm' of plastic pollution and vector-competent pests, with potential repetition in other developing nations. Thus, the resulting density of waste debris locations is expected to breed urban hotspots for dengue emergence, akin to existing globally distributed PET and styrofoam hotspots potentially containing highly productive vector habitats (G. Rhodes et al., 2022).

Given that mosquito oviposition requires free water, treated urban garbage interventions leading to drainage and litter clearance can be effective control measures. However, many cities' economies and populations form a barrier that diminishes control effectiveness. Nevertheless, this study is the first of its kind, demonstrating an enhanced understanding of the behavior and ecology of mosquitoes in the presence of plastic waste and paved surfaces. It is now essential and feasible to study whether this enrichment of urban plastic waste provides mosquito biodiversity hotspots and whether poorly managed waste management practices lead to the proliferation of dengue vector populations.

7. MITIGATION STRATEGIES

Mitigating the impacts of plastic waste habitats on urban mosquito proliferation requires a multi-faceted approach that incorporates waste source reduction, management strategies, and improved wastewater and drainage systems. Efforts should focus on reducing the inflow of plastic waste into urban waterways and addressing waste management via littering prevention, clean-up, recycling, and improving waste collection. In parallel, improving drainage and stormwater management systems, effluents, sewage, and wastewater systems activities to eliminate plastic waste entry into urban waterways is paramount. Finally, located adjacent to water bodies, city parks should be seen as "big pots" collecting litter and plastic waste from urban environments. Therefore, such habitats need to be improved to prevent their accumulation. Specifically, a four-max-three approach to planning plastic waste habitats' restoration projects could be implemented. First, municipalities, national governments, and governmental organizations should identify hotspots of urban plastic waste habitats. These hotspots should host a four-max-three approach community-based restoration process. In this approach, restoration activities should rely mainly on non-mechanical ways to prevent the unintended destruction of urban plastic waste habitats.

Additionally, restoration efforts should focus on bio-control of the larval habitats, such as altering their size, location, temperature, pH, or light conditions. Restored habitats could then turn into intended larval control mosquito breeding sites by the enforcement of a three-max strategy. In this strategy, restoration efforts aim to maximize their size, number, and connection to water systems. Ultimately, these restoration processes will assist in the reestablishment of indigenous predator densities in the improved habitats. It may also indirectly prevent high mosquito densities in nearby settlements, as connecting habitats would offer new predation opportunities (Krol et al., 2024).

7.1. Waste Management Practices

Integrated waste management strategies should consider compliance with urban waste management practices from an environmental perspective. In low-income countries, waste management practices of multi-stakeholders are frequently conducted informally, which is inefficient for managing waste and can lead to acute ecological issues. The conceptual design of a "Waste Prevention, Reduction, and Recycling Management Strategy" (3RMS) that integrates environmentally sound management of reuse, recycling, and reduction of waste based on a socioecological system modeling approach ((J Overgaard et al., 2021)).

Waste management practices range from low-tech mechanical sorting and cement rotary kiln incineration to high-tech automated sorting machines and bioreactor-based landfilling. There is growing interest in plastic waste collection since single-use plastics contribute to global ocean pollution and environmental impacts. Concepts and approaches for quantitatively assessing these various waste management strategies are presented based on thermodynamics, material flow accounting, structured simulation, and optimization algorithms. Discussed are options for robust design of the 3RMS while considering the uncertainties in WMPs and the complexity and factors of urban meta-systems.

Verification of this 3RMS in case study cities of low, middle, and high-income countries showed that a better-designed 3RMS could reduce the global warming potential of urban waste disposal and earlier prevention of adverse waste management impacts. Five directions for future work are recommended to maximize the efficacy of the proposed quantitative modeling framework for waste management in further applications. These include improving the accuracy of the S2se modeling framework, expanding the modeling of technological performance and ecological impacts of waste treatment processes, improving the modeling inputs and data efficiency, extending the modeling functions to forecast the impact of technology adoption, and providing a more user-friendly interface of the modeling system with self-consistency and step-by-step guidance.

7.2. Community Engagement and Education

As plastic waste accumulates in urban waterways, untreated stormwater systems create permanent mosquito breeding habitats, a situation exacerbated by recent flooding. Interventions that educate the public about mosquito production in trash and offer opportunities for waste management can reduce such breeding habitats. Trash is now the most pervasive and persistent pollutant in urban waterways. Frequently observed plastic products include bottles, caps, containers, and bags, which collect along the banks and margins of these habitats, especially in the catchment loads of larger storms (Healy et al., 2014). Given the variance in ways with which trash moves through urban waterways, how plastic waste packets are constructed may differ across rivers and users. The resulting habitats differ markedly in structure. Nevertheless, common opportunities for local engagement, education, and waste management emerge across many cities. Plastic is transformed into temporary waste that collects in urban waterways after heavy rains, leading to a new evolutionarily stable strategy for habitat management. Basic approaches now widely used in waste management can address the emptying of infested plastic waste habitats.

Mosquitoes are public health pests that are globally dispersing and proliferating (Bodner et al., 2016). Gaps exist in understanding the conditions that allow mosquitoes to proliferate and new habitats to emerge, and this knowledge is critically needed to address the problem. This new habitat type has been observed in urban waterways, which are treated differently than other mosquito habitats and, in some cases, regarded as unmanageable. Following significant flooding, prior to field observations of infestations and captures in urban waterways, fundamental questions concerning how plastic waste packets function as habitats for mosquito breeding were investigated. Plastic waste packets form when trash collects in a bay or inlet on a rainy day. Holes in the packet are enlarged by larger debris, and the wave action of inundation and draining tides creates the water in the packet and then drains out, leaving dry material that mosquitoes may colonize. Understanding a common type of matte wrapping for such plastic waste packets created an opportunity to engage and educate communities in trash collection events, and opportunities for managing waste storage in urban waterways were identified.

7.3. Innovative Solutions for Plastic Waste Reduction

As new forms of polyethylene waste become popular, there is a need for innovative solutions to prevent the increase of plastic-infused habitats provided to mosquitoes. Plastic waste abatement campaigns aimed at tamper-proofing overflowing dumpsters, collaborating with commercial waste haulers and municipalities, and upgrading dumpster designs can diminish overflow and litterfall of one of the most abundant plastic litter types (Willis et al., 2017). Testing litter trap designs at dumpster corrals shortens the time between litterfall and discard to enhance the viability and affiliation of any ovipositing Aedes aegypti. The added landscape variable of waste management alters habitat structure but not resource availability. The structure of one of the most common waste types, plastic bags, may unknowingly be co-opted by Aedes aegypti larvae to stabilize habitats and contain internal resources. Amaparacinta heterodera provides a benthic substrate onto which plastic bags velcro, mitigating water loss where it might otherwise be lost to vegetation. The dz sank, hence promoting higher instar dominations, malnourishment, and wetter diets. These results shed light on small water bodies and the waste types that provide them with nutrients.

Research across disparate geographic regions is tedious, expensive, and often cannot be extrapolated to determine patterns operating in other areas (Raja Vanapalli et al., 2021). Furthermore, local researchers may miss pressing concerns that could now have simple solutions due to the advancement in knowledge or resources within the community or approaches elsewhere. This is common in the management and implementation of recycling programs, assessments of waste management infrastructure, and the design and targeted outreach of educational campaigns. Thus, a simple and effective tool is needed by which low-income regions could drive regional wins across multiple sectors, including waste management, mosquito control, educational resources, and citizen engagement. The aim is to facilitate multi-factorial assessments enabling local researchers and stakeholders to understand the unique context of plastic waste in a region.

8. POLICY AND REGULATION

PWHs and the DPW networks are regulated and maintained within a framework of policies designed to manage the urban environment. Efforts to regulate plastic waste management challenge control mechanisms for mosquito emergence. Aspects of the social role of the WUK in supporting the ideology of the DPW are also evaluated.

The distribution of laws, policies, and regulations pertaining to urban waste and mosquito controls relative to specific PWHs as ideal types of structural attitudes towards mosquito emergence in the face of alternative management strategies are sketched. No existing instruments recognize metropolitan PWHs directly or explicitly; instruments that address plastic pollution do not address mosquito proliferation or vector control (Krol et al., 2024). Thus, an overemployment of 'covert' methods that minimize the probability of mosquito proliferation through more indirect channels. Of the laws, policies, and regulations, 37% only concern WUK-type PWHs, 26% deal with D and DPW-type PWHs, and 26% of instruments address all policy types. 11% of the laws, policies, and regulations address irrigation-type PWHs.

In precision management in larger infrastructure upgrading efforts, no allowance is allowed for unintended saturation of rubbish. Changing the meaning of a type 1 PWH to type 3 does not provide regulation against the pre-existing rubbish; design solutions are often generic, and attempts to match vegetation to the locale of interest can be misleading since proper knowledge of plant types may shape the approach; discounting diverse populations, especially those introduced through horticulture, often limits the extent of pre-invasion data available regarding the presence of mosquitoes and rubbish; or there is simply no affected habitat and so far regulation. These represent substantial loopholes to sustainably manage the risks to human health posed by mosquitoes with a legitimate role.

8.1. Current Regulations on Plastic Waste

Communities across the globe battle against plastic waste. Responsible consumption of plastic products is the broadest method of preventing and controlling plastic waste. Environmental and health agencies must actively educate the public about the environmental and human health consequences of improper disposal of plastic waste. They must also put policies in place about stricter and more severe penalties against offenders. Regulations on product labeling must be re-enforced. Manufacturer's dates must be labeled on all plastic products. If properly used, the product must last beyond its date of expiry. In addition, government environmental and health agencies must put systems in place that will compel plastic manufacturers to actively recycle and reuse their products (Ayoade Adeniran & Shakantu, 2022). As much as possible, plastics basically used one time should be severely restricted by government agencies. In the case of waste disposal, strict rules must be enforced. Household and commercial waste must be disposed in areas outside of the city boundaries with proper provisions for grasping temporal waste until disposal has been done. Offenders caught throwing waste into streams or rivers must be publicly punished. In addition to disposing of waste in trash bins, city drainages must always remain functional. On a local scale, street sweepers must ensure that city streets remain clean. The local government must allocate funds for this. In addition, incentives must be established for individuals or organizations that effectively promote clean cities. Constant cleanliness campaigns must be conducted. Most importantly, the concept of ecotheology, too, has to be brought into practice. Since everyone across the globe is united by one planet, Earth, the global community must come together (locally or nationally) in a way that educates people about the consequences of improper disposal of waste and the knowledge of waste management. Working together, communities will find solutions to their local problems while empowering members to take control of waste disposal issues. In opposition to rigid approaches, participatory approaches offer the added benefit of raising awareness and involving stakeholders (Willis et al., 2017).

8.2. Policies for Mosquito Control

Mosquitoes are vectors for many pathogens, leading to widespread public health issues (Townroe & Callaghan, 2014). Measures are taken to combat mosquitoes, including source reduction, application of larvicides, and adulticiding for mosquitos in flight (Mainali et al., 2017). Source reduction is optimal but is often tricky when habitats are private. There is a rapidly expanding assortment of novel ephemeral habitats for mosquitoes in urban areas and unmonitored habitats for mosquitoes in these locations. Novel plastic waste habitats in urban areas provide a criterion for anticipating where mosquitoes will be of public health concern in future urban canvases. Small-scale management of urban plastic waste habitats is an opportunity to combat encephalitic and potential dengue virus and Zika vector mosquitoes, much like culicines and Aedes. Mosquitos can be groomed and eaten by fish as fish are important ecological determinants of mosquitoes.

Mosquitoes are water-breeding insects that require still water as a habitat for their immature stages. Mosquitoes can grow, survive, and reproduce when still-water habitats are available. Pits, ponds, containers, earthenware, pots, discarded plastic containers, wastewater, etc., are common water sources for mosquitoes. Mosquitoes are male and female. Females are larger than males. They have elongated mouthparts containing a stinger for sucking blood. The incompatible mating in male population control is being used and cannot be tested on some species for which there are no suitable gamma-irradiated populations. Applications of inverted 5% taxi-brain will suspend H20 for over a week during the wet season. It would be prudent, therefore, to test biocontrol agents that have been employed successfully in controlling mosquitoes in forest, agriculture and urban areas.

9. FUTURE RESEARCH DIRECTIONS

Research on plastic waste removal and diversion programs has burgeoned in recent years. However, there has been little research on how these systems can be made better. Future studies can focus on the urban and global plastic waste flows as a challenge of extreme complexity. Employing participatory modeling approaches in combination with agent-based models could give rise to distant stakeholder representation, safe experimentation, and heightened problem understanding. Work across jurisdictions could yield insights into how to cascade governance design, governance capacity building, and procedural standards from local settings, building up nested layers for improved effectiveness and legitimacy of decision-making (Krol et al., 2024). Further, it is generally believed the transition to a circular economy is unprecedented. Better data on the trajectory of plastics on regional and global scales, particularly time series data on plastic flows and on the implications of changing structures of national economies, could unveil whether there is any historical precedent to guide the transition. Going beyond knowledge co-production in research networks, equal partnerships could be fostered in longer-scaled transdisciplinary research initiatives, generating exciting research avenues. It would be an innovative way of diving into long-term collaborative research. Finally, not all hotspots are similar, and sustainability transitions may differ significantly between regions. For a transition to a circular economy to take place, policies or regulations may need to be enacted first, but this has not been widely researched. Future research can focus on what actions should be prioritized and how. Then, with limited resources and capabilities, it is difficult for regions to do everything, like collection, treatment, and refinery. It will be interesting to study what concrete roles each region should focus on. Machine learning methods can be employed to predict hype-to-hype periods regarding region and materials and investigate why, which in turn is conducive to a sustainable macrocycle. How to prevent bounce-back will be another interesting but challenging topic.

9.1. Research Gaps in Mosquito Ecology

Urbanization poses a threat to biodiversity through numerous biological mechanisms. Nevertheless, cities can hold considerable environmental value and may act as refuges for some species. For instance, there is the potential for city conditions to support a broader variety of microclimates than some rural areas, allowing species to persist within cities that would otherwise be excluded. The challenge of finding better ways to integrate Urbanization with biodiversity loss is daunting, particularly for species groups with habitat-dependent life cycles, such as fishes and amphibians, which are less likely to benefit from enhanced habitats than more mobile taxa. Nevertheless, the impact of Urbanization on freshwater diversity remains relatively understudied.

In order to better understand the consequences of Urbanization on freshwater biodiversity, baseline data on the diversity, distribution, and ecology of urban freshwater biota is required. Furthermore, in developing countries, the population growth rate is very high, which affects existing urban freshwater systems. As the population increases, the demand for water service facilities like irrigation, drinking, and domestic purposes increases, which, therefore, initiates competition among stakeholders and the use of these urban resources. This situation leads to socioeconomic and ecological loss of habitats, species, and ecosystem services. A recent long-term survey found several positive and negative repercussions associated with suitable design criteria for biodiversity-friendly urban freshwater systems.

Among urban freshwater taxa, mosquitoes are of great importance, being the primary arthropod vectors of human diseases caused by pathogenic viruses and parasites. Mosquito ecology and diversity have been investigated in a few cities in developing countries; however, there is still a knowledge gap, especially regarding the impact of Urbanization and climate change. Mosquitoes occupy a wide range of habitats, but tsunamis created by the floods that followed a major disaster drastically changed the biological environment of coastal cities and slowed the recovery of populations.

9.2. Longitudinal Studies on Plastic Waste and Mosquito Populations

Mosquitoes are ubiquitous, with species present in most places inhabited by humans. Some mosquito genera are important for their impact on humans, as they are vectors of pathogens that can cause human disease. Both environmental and individual variables are important for controlling the risk of mosquito-borne disease outbreaks and vector population size, with habitat being one component (Townroe & Callaghan, 2014).

Urbanization has transformed the environment, resulting in habitat loss for some species, while anthropological changes have created new habitats for mosquitoes. Mosquito species that favor natural habitats are less likely to be present in urban areas, while species that are tolerant of anthropologically altered habitats thrive in urban environments. A close association of mosquitoes and humans in urban areas facilitates mosquito-borne human disease outbreaks. For example, in the USA, WNV is transmitted by the Culex species, which are closely associated with human habitats. In the UK, the introduction of the exotic species Ochlerotatus japonicus in the 1990s is thought to have been facilitated by the large number of prime container habitats that can be found in urban areas such as parks, domestic gardens, and commercial buildings. Though such habitats have been present since the introduction of the tetanus-prone egg-laying species Aedes albopictus into the revenue-producing UK pet trade, urban environments are expected to favor more opportunistic species.

In the UK, containers that harvest and store rainwater for domestic use are becoming increasingly common in off-the-shelf models. In association with a severe drought and restrictions on hosepipe use in 2012, it is likely that many households bought these containers, and usage increased. The wet summer that followed likely filled these containers, representing potential new habitats for mosquitoes. Each water butt would provide 50-250 liters of water, creating a network of easily accessible prime mosquito larval habitats. The introduction of a large number of new containers and the general increase in the number of containers in the environment is predicted to increase the abundance of mosquitoes in residential gardens.

10. CONCLUSION

Discounting for a moment the obvious potential clarion call for action on plastic waste pollution problems, a few areas of potential future research spring to mind. Efforts to quantify wider patterns by explicitly accounting for altitudinal, meteorological, and ecological factors would benefit the understanding of the relative importance of plastic as a habitat for mosquito reproduction in different locations. Additionally, similar studies elsewhere could provide vital insights for waste management strategies, especially in terms of timing. Studies in the Global South with lower overall mosquito abundance, species richness, and low levels of plastic waste prevalence could be valuable comparative examples. As others have noted, however, risk assessment needs to take local conditions into account, as here skylight blocking by towns and a north-westerly, cooler wind strengthened relative plastic waste habitat effects elsewhere may have driven contrasting outcomes to other locations investigated (Krol et al., 2024). Overall, results strongly indicate the need for further investigation of plastic waste, with specific additional recommendations regarding sequential rapid assessments of mosquito and plastic waste abundance and distribution and prospective long-term studies to assess resulting management challenges and controls. Such studies could also make powerful maximal use of the geospatial prediction approaches developed elsewhere.

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