Sustainable Mosquito control: The role of Nanotechnology in essesntial oil Delivery system

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Abstract:

This review aims to explore the use of nanotechnology in enhancing mosquito repellency by examining the nano-formulations of essential oil-based repellents. The objective is to assess the efficacy, safety, stability, and long-lasting protection provided by these nano-formulations. A comprehensive review of the literature was conducted to gather information on the various nano-formulations employed to improve mosquito repellency. The review considered studies that evaluated the performance of nanoencapsulation, nanosuspensions, nano-emulsions, and nanoparticles in terms of solubility, stability, controlled release, and skin adhesion of essential oil-based repellents. Nano formulations provide prolonged protection, increase the efficacy of active ingredients, and reduce the need for frequent reapplication. Furthermore, the targeted delivery enabled by nanotechnology minimizes exposure to non-target organisms and reduces environmental impact. The incorporation of biodegradable polymers in nano-formulations enhances their eco-friendly nature. Nano formulations of essential oil-based repellents show great potential in enhancing mosquito repellency. The advancements in nanotechnology have addressed the limitations of conventional repellents by improving their performance and durability. However, further research is needed to optimize formulation parameters, assess safety, and evaluate long-term effectiveness. Integration of nanotechnology with mosquito repellents holds promise in reducing the burden of mosquito-borne diseases and improving public health.

Keywords: Mosquito repellency, nanotechnology, essential oil-based repellents, efficacy

1. Introduction

Mosquito-borne diseases pose a significant global health challenge, affecting millions of people each year. Mosquitoes are vectors for diseases such as malaria, dengue fever, Zika virus, chikungunya, and West Nile virus, among others [1]. These diseases not only cause immense suffering and loss of human life but also have a substantial economic impact on affected regions. The mosquito control methods primarily rely on the use of chemical insecticides and repellents. However, the overuse and misuse of these synthetic compounds have led to the development of resistance in mosquito populations and raised concerns about their environmental and human health impacts [2]. In recent years, there has been growing interest in developing alternative mosquito repellents using natural compounds, particularly essential oils. Essential oils are volatile liquids that are derived from different plant components and have a variety of biological attributes, including the ability for repelling insects [3]. They have a number of benefits over synthetic chemicals, including as being sustainable and renewable, biodegradable, and maybe having lower toxicity towards non-target organisms. Many cultures have long used essential oils for their ability to repel insects, demonstrating their potential efficacy [4]. There are certain difficulties with using essential oils as insect repellents, though. Due to their high volatility, essential oils evaporate quickly and have a short duration of effect. When exposed to external variables, they may also be susceptible to degradation, which reduces their stability and efficiency. Due to these drawbacks, scientists are investigating novel methods to improve the effectiveness and durability of insect repellents based on essential oils. Nano-formulation development is one such tactic [5]. In order to increase the delivery and stability of active substances, including essential oils, nano-formulation entails encapsulating them within nanoscale carriers. Liposomes, nanoemulsions, and solid lipid nanoparticles are examples of nano-encapsulation techniques that provide controlled release mechanisms, higher stability, and improved skin adhesion [6]. These characteristics may prolong and increase the effectiveness of the mosquito-repellent activity. In nano-formulations, controlled release methods offer a prolonged release of active substances, extending their repulsive effects. To ensure the selective release of repellents at certain mosquito entrance points and increase their effectiveness, targeted delivery systems might be used [7]. This strategy makes it possible to lower the amount of active substances that are needed, potentially reducing any negative impacts on both human health and the environment. For the creation of successful nano-formulations, active components must be carefully chosen and optimised. The chemical makeup and repelling properties of essential oils obtained from various plant sources vary. Additionally, repelling synthetic chemicals can be added to nano-formulations [8]. A crucial factor is choosing the safest and most effective active ingredients based on their toxicity profiles, regulatory approvals, and efficacy as repellents. Analysing nano-formulations' physicochemical characteristics and functionality is crucial. The stability and bioavailability of the formulation can be understood through particle size studies, and interactions with biological membranes can be influenced by surface charge measurements [9]. The formulation's capacity to hold onto active chemicals is indicated by its encapsulation efficiency and loading capacity. The assessment of the regularity and structure of the formulation is made possible by morphological analysis. The nano-formulation's ability to tolerate environmental conditions and sustain its repellent function over time is ensured by stability assessment [10].

It is essential to assess the practical utility of nano-formulations for repelling mosquitoes. The effectiveness of the formulations as repellents against various mosquito species can be evaluated using standardized testing procedures such as arm-in-cage or Y-tube olfactometer tests. Analogies with traditional repellents can shed light on the possible benefits of nano-formulations in terms of effectiveness and durability [11].

Studies on duration and persistence aid in determining how well the formulation protects against mosquito bites over the long term. The creation of nano-formulated insect repellents must take into account safety issues and environmental effect analyses. Assessments of the formulation's toxicity to people and non-target species, like bees and aquatic life, shed light on any potential dangers. Testing for skin irritability and compatibility ensures that the formulation is safe for human usage [12]. The potential ecological effects of nano-formulation can be determined by analyzing its environmental destiny and biodegradability. To evaluate the overall efficacy and safety of nano-formulated insect repellents, a thorough risk-benefit analysis is required [13]. Innovative strategies and ongoing research efforts are needed to overcome formulation issues such as achieving optimal encapsulation efficiency, stability, and controlled release. It can be more successful overall to combine nano-formulated repellents with other mosquito control measures like insecticide-treated bed nets and vector surveillance. Future research should focus on creating innovative active compounds with enhanced repellant qualities and safety characteristics [14]. To make it easier to translate these innovations into useful mosquito control solutions, regulatory considerations, and commercialization channels need to be investigated.

2. Nano-formulation Approaches for Mosquito Repellents:

Worldwide, diseases caused by mosquitoes continue to pose serious risks to public health. To stop disease transmission and lessen the burden of mosquito-borne conditions, it is essential to develop efficient insect repellents [15]. Traditional insect repellents frequently contain synthetic chemicals that can be harmful to the environment and human health. The creation of nano-formulations as a cutting-edge method for making insect repellents has garnered growing interest in recent years. Active substances, such as molecules that repel people, are encapsulated in nanoscale carriers (figure 1.0) through the process of nano-formulation, which offers superior stability, controlled release, and efficacy [16]. The many nano-formulation techniques employed for insect repellents, such as nano-encapsulation techniques, controlled release systems, and targeted delivery strategies, are explored here.

3. Nano-encapsulation Techniques

In order to effectively shield and transport the chemicals, nano-encapsulation procedures require the encapsulation of active components into nano-sized carriers. For mosquito repellents, a number of nano-encapsulation strategies have been investigated, including liposomes, nanoemulsions, and solid lipid nanoparticles [17].

3.1. Liposomes: The vesicular structures known as liposomes are composed of lipid bilayers and can include both hydrophilic and hydrophobic active ingredients. They have advantages including controlled release, biocompatibility, and preservation of the encapsulated chemicals. To offer sustained release and lengthen the duration of the repellent action, liposomes have been used to encapsulate essential oils and synthetic repellents [18].

3.2. Nanoemulsions: Nanoemulsions are stable, isotropic systems formed of oil droplets dispersed in water or the opposite, and are stabilised by surfactants or co-surfactants. They offer better solubility, controlled release, and stability characteristics. Research has been done on encapsulating synthetic and essential oils repellents in nanoemulsions, which offer enhanced stability and long-lasting repellent characteristics [19].

3.3. Solid Lipid Nanoparticles (SLNs): Lipid-based nanoparticles known as SLNs are created by dispersing solid lipids in an aqueous phase. They offer advantages such as regulated release, active component protection, and biocompatibility. SLNs have been researched as carriers for encapsulating repellent compounds in an effort to increase the stability and potency of insecticides. These substances provide a prolonged release [20].

4. Controlled Release Systems for Mosquito Repellents: Controlled release methods are essential for increasing the effectiveness and durability of insect repellents. They make it possible for active chemicals to be released gradually, resulting in a long-lasting repelling effect. To induce the regulated release of repellant chemicals in nanoformulations, several techniques have been used [21].

4.1 Matrix Systems: Active compounds are contained within a matrix in matrix systems, which controls how quickly they are released through diffusion or erosion. To offer sustained release and lengthen the duration of the repellent effect, resistant compounds have been encased in polymeric matrix, such as biodegradable polymers [22].

4.2 Microencapsulation: Active compounds are enclosed in a barrier during the microencapsulation process, which controls their release over time. Lipids, polymers, or other materials could be used to create microcapsules. They have been researched for their potential to encapsulate repellent ingredients, provide sustained release, and lengthen the duration of repellent's effects on mosquitoes [23].

4.3 Nanogels: Cross-linked polymer networks known as nano gels can swell and compress in response to outside stimuli. They have been investigated for use as mosquito-repellent controlled release systems that allow the triggered release of repellent substances in response to specific environmental cues, like temperature or pH [24].

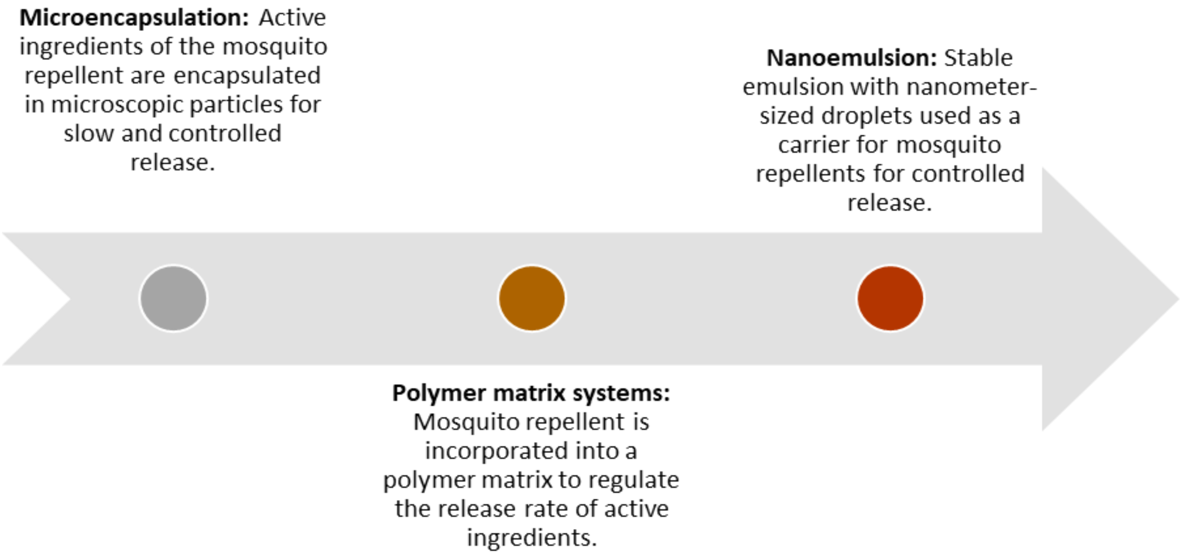

Figure 1.0 Various formulation for controlling release of repellent

5. Targeted Delivery Strategies

By localizing and delivering repellent chemicals to mosquito entry points, targeted delivery systems are essential for improving the efficiency of mosquito repellents. These methods make use of nanoformulations, which have a number of benefits over conventional repellant formulations [25]. Surface modification, nanostructured materials, and microencapsulated fabrics have all shown promise in enhancing the effectiveness of insect repellents among the different methods investigated for targeted delivery. By adding specific ligands or functional groups to the surface of nano-carriers, one can enable selective binding to mosquito receptors or improve adhesion to the skin [26]. The nano-formulated repellents can directly interact with the mosquitoes upon contact by including ligands that are appealing to mosquitoes or have an affinity for mosquito receptors, boosting the localized distribution and enhancing the repellent effects. The effectiveness of repellant substances can be considerably increased by this focused binding, which can also decrease their dispersion in the environment [27]. Nanostructured materials, like nanofibers or nanosponges, present an additional method for the targeted administration of insecticides. These materials' favorable surface area-to-volume ratios and distinctive structural characteristics enable the regulated release of repelling substances [28]. In order to prevent mosquitoes from entering a space, nanostructured materials can be coated with repellent substances and applied to windows, doors, or external surfaces. The repellent compounds are gradually released by the nanostructured materials, guaranteeing that the active ingredients are released steadily and successfully repel mosquitoes in the area [29]. The overall effectiveness of the insect repellents is increased by the controlled release method, which offers a prolonged and maintained repellent effect. Microencapsulated fabrics offer yet another method for the targeted delivery of insecticides [30]. This method involves applying microscopic capsules that contain repellent substances to fabrics, such as textiles or garments.

The microencapsulated repellents are released in a targeted and sustained manner when the fabric is exposed to moisture, such as sweat [31]. This regulated release ensures ongoing protection against mosquito bites and lessens the amount of repellent that comes into direct contact with the skin, which is beneficial for people with sensitive skin. Additionally, the repellent compounds' early breakdown is prevented by microencapsulation, increasing the stability and shelf-life of the repellents [32].

The enhanced stability and extended shelf-life of mosquito repellents made using nanotechnology are two of their main benefits. Nano-carriers that include repellant substances shield them against environmental conditions including oxidation and volatilization that can cause the active components to degrade [33]. Because of their increased stability, repellent chemicals work longer and offer more comprehensive protection from mosquito bites. Another key benefit of repellents made with nanotechnology is controlled release. A sustained and persistent repellent effect is maintained by the progressive release of the encapsulated repellent chemicals over time [34]. By maintaining an effective concentration of repellent chemicals at the target region, this controlled release mechanism improves their repellent efficiency and lessens the need for frequent reapplication. The controlled release also maximizes the utilization of repellant substances while minimizing their negative effects on the environment. Strategies concentrate the repellent effects on the mosquito entry points selectively, minimizing the dispersion of repellent components in the surroundings [35]. With a more focused approach, less repellent is needed and there is less chance of having an adverse effect on ecosystems and organisms that are not the target. These techniques maximize the effectiveness of the repellents by delivering the repellent compounds right to the mosquito entrance points, guaranteeing that the bulk of the active chemicals reaches the desired targets [36,37].

6. Selection and Optimization of Active Ingredients

The ability of essential oils obtained from various plant sources to ward off mosquitoes has long been acknowledged. These oils are complex combinations of volatile substances that have the ability to repel insects like mosquitoes [38]. They have a number of advantages over synthetic substances, including being natural, biodegradable, and possibly having less hazardous effects on both people and the environment. When choosing essential oils for formulations that repel mosquitoes, it's important to take into account their repellent efficacy, stability, availability, and safety profiles. Numerous essential oils, including citronella, lemongrass, eucalyptus, lavender, and peppermint oils, among others, have demonstrated mosquito-repelling properties [39]. Each essential oil has a distinct chemical composition that helps to give it repelling qualities. A number of elements need to be taken into consideration in order to employ essential oils as effective mosquito repellents. First, the method and quality of essential oils' extraction can affect how effective they are at repelling pests [40,41]. To ensure the presence of bioactive components, high-quality essential oils derived through procedures like steam distillation or cold-press extraction are suggested. For essential oils to continue acting as repellents over time, their stability is necessary. Due to things like exposure to light, heat, and air, essential oils are susceptible to deterioration [42]. To maintain their stability and effectiveness, suitable formulation, packaging, and storage methods are required. It's important to take into account both the accessibility and durability of essential oils.

There may be a limited supply of some essential oils or they may come from plant species that are in danger of extinction. Making ensuring that the sourcing and production of essential oils adhere to sustainable standards and do not worsen the environment is crucial [43]. In addition to essential oils, synthetic compounds with repellent activity have been extensively studied and utilized in mosquito repellents [44]. These compounds are often derived from chemical classes such as DEET (N,N-diethyl-meta-toluamide), picaridin, IR3535 (3-[N-acetyl-N-butyl]-aminopropionic acid ethyl ester), and ethyl butyl acetylamino propionate (IR3535). Synthetic compounds offer advantages such as a prolonged duration of protection and higher repellent efficacy against a wide range of mosquito species [45]. Considerations should be made while choosing synthetic chemicals for mosquito repellents, including repellent effectiveness, safety, stability, and regulatory approvals. One of the most popular and efficient synthetic repellents, DEET offers mosquitoes long-lasting protection. However, some people may have skin irritation or other negative consequences from DEET, which has prompted researchers to look towards substitute synthetic substances [46]. As a DEET substitute, picaridin, a synthetic substance made from the natural substance piperine, has grown in favor. It has a comparable amount of effectiveness against mosquitoes and is less prone to irritate the skin. Other synthetic substances with repellent properties that are suitable for human use include IR3535 and ethyl butyl acetylamino propionate [47]. For synthetic chemicals to continue to function as repellents throughout time, stability is necessary. The chemicals' potency can be diminished by factors including degradation brought on by exposure to oxygen, heat, and light. To ensure the stability and endurance of synthetic components in mosquito-repellent compositions, proper storage and formulation methods should be used. When choosing synthetic chemicals for insect repellents, regulatory permissions and guidelines should be taken into account. Adherence to these rules is essential to guarantee the safety and legality of mosquito repellent products as different nations may have various legislation regulating the use of certain substances [48].

In order to guard against these diseases, mosquito repellents are made to stop mosquitoes from landing on or biting human skin. Several methods of action, such as masking smells, repellent compounds, and interference with insect sensors, contribute to the efficiency of mosquito repellents [49].

6.1. *Masking* scents: Masking or modifying the smells released by the human body is one way that insect repellents work. Mosquitoes seek for their hosts by using the carbon dioxide (CO2) and other chemical molecules that humans generate as clues. Repellants can hide the alluring human odors and make it challenging for mosquitoes to recognize and zero in on their targets by emitting aromas that are either pleasant or overbearing to mosquitoes. Mosquitoes can be repelled by natural repellents like citronella oil, which is made from the leaves of plants of the Cymbopogon genus. Similarly to this, mosquitoes' capacity to sense human odors can be hindered by the essential oils of plants like lavender, eucalyptus, and peppermint, which successfully mask the alluring smell [50].

6.2 Interference with mosquito sensors: Mosquitoes use a variety of sensory cues, such as visual, olfactory, and thermal signals, to find and bite their hosts. Certain insect repellents try to interfere with these sensory cues, making it challenging for mosquitoes to locate and feed on people [51].

6.2.1. Visual disruption: Some insecticides repel mosquitoes by constructing a visual barrier that confuses or repels them. These goods frequently take the form of mats or coils designed to repel mosquitoes by emitting smoke or vapor. Because of the smoke's optical obstruction, mosquitoes are unable to identify people [52].

6.2.2. Olfactory interference: Mosquitoes use their sense of smell to find the compounds that people release into the air. Mosquito repellents that interfere with their smell receptors can prevent them from locating human hosts. Natural plant-based repellents like citronella and lemongrass can also disrupt the mosquito's olfactory system in addition to the previously mentioned DEET and picaridin [53].

6.2.3. Thermal camouflage: Mosquitoes are capable of detecting the heat and thermal signatures given off by warm-blooded creatures, such as humans. The goal of some cutting-edge repelling technologies is to reduce the temperature difference between the human body and the environment in order to achieve thermal camouflage. This makes people less attractive to mosquitoes, which makes it more difficult for them to find their hosts [54].

While mosquito repellents can be quite efficient at cutting down on bites and the spread of disease, no repellent offers 100% protection (shown in table 1.0). The effectiveness of repellents can be impacted by mosquito behavior, species variation, and individual factors. In order to minimize mosquito bites and lower the risk of mosquito-borne diseases, it is advised to use repellents in conjunction with other preventive measures such as donning protective clothes, using a bed net, and removing mosquito breeding areas [55]. To ensure their best functioning, selecting effective repellents needs to take into account a number of factors. The effectiveness of the repellant, the length of the protection, safety, user acceptance, and environmental impact are some of these criteria. The capacity of a substance to stop mosquitoes from biting is known as its repellent efficacy. It is determined by comparing the landing and bite rates of mosquitoes on treated and untreated skin [56]. High-efficiency repellents show a notable decrease in mosquito bites. Another important aspect to take into account when choosing repellents is the length of the protection. It affects how long the repellent is still able to keep mosquitoes at bay. Less frequent reapplication is required with longer-lasting protection, which is convenient for consumers. When choosing repellents, safety must come first, assuring that they do not present health concerns to people. Both synthetic and natural substances are subjected to safety evaluations, such as tests for dermal toxicity, skin irritancy, and skin sensitization [57]. To reduce the risk of negative impacts, products should follow safety standards and recommendations. The widespread use and potency of repellents are significantly influenced by user acceptance. User pleasure is influenced by elements including flavor, texture, and convenience of use. Users are more inclined to embrace repellents that are well-tolerated, enjoyable to use, and suitable for a variety of skin types. It's important to take into account how repellents affect the environment. This involves evaluating their potential for accumulation in ecosystems, persistence in the environment, and toxicity to non-target animals. Repellants should ideally have no negative environmental impact and biodegrade quickly.

Table 1.0: Comparative Analysis of Essential Oils as Mosquito Repellents

S. No	Essential Oil	Repellent Efficacy	Duration of Protection	Mechanism of Action	Ref.
1.	Citronella	High	Moderate	Masking effect and disruption of mosquito olfactory receptors	[58]
2.	Lemongrass	Moderate	Short	Interference with mosquito host-seeking behaviour	[59]
3.	Eucalyptus	High	Moderate	Repellent effect and inhibition of mosquito feeding	[60]
4.	Lavender	Moderate	Short	Disruption of mosquito olfactory receptors and deterrent effect	[61]
5.	Peppermint	Moderate	Short	Interference with mosquito host-seeking behavior	[62]

7. Mechanism of Action:

7.1. Citronella: Citronella oil is well-known for its mosquito-repellent properties. It exerts its repellent effect through a masking effect and the disruption of mosquito olfactory receptors. Mosquitoes are attracted to human odours such as carbon dioxide and lactic acid. Citronella oil masks these odours, making it difficult for mosquitoes to locate their hosts. Additionally, citronella oil interferes with the mosquito's olfactory receptors, reducing their ability to detect human scents and deterring them from biting [63].

7.2. Lemongrass: Lemongrass oil is another essential oil with mosquito repellent activity. It works by interfering with mosquito host-seeking behavior. The strong aroma of lemongrass oil confuses and repels mosquitoes. When individuals apply lemongrass oil, the scent overwhelms the mosquito's ability to locate and feed on the host, effectively preventing mosquito bites [64].

7.3. Eucalyptus: A potent insect repellent, eucalyptus oil effectively deters mosquitoes. It serves as a deterrent and prevents mosquitoes from feasting. The distinct chemicals in eucalyptus oil, including citronellal and p-menthane-3,8-diol (PMD), are what give it its anti-mosquito abilities. These substances prevent mosquitoes from detecting and locating their hosts, which reduces their behaviour during landing and feeding [65].

7.4. Lavender: The ability of lavender oil to deter mosquitoes is average. It primarily functions through olfactory receptor disruption in mosquitoes. Mosquitoes are confused and repelled by the aroma of lavender oil, making it less likely that they would approach and attack people who are wearing it. Lavender oil also functions as a deterrent, making the environment unfavourable for mosquitoes and preventing them from landing on treated locations [66].

7.5. Peppermint: Mosquitoes are believed to be repelled by the energising aroma of peppermint oil. Similar to lemongrass oil, peppermint oil obstructs the behaviour of mosquitoes looking for hosts. Since human smells are obscured by peppermint oil's potent aroma, mosquitoes have a tougher time finding and feeding on their hosts.

Peppermint oil efficiently wards off mosquitoes by causing a sensory overload for them [67]. Table 2.0 includes comparative analysis of different types of mosquito repellents.

Table 2.0: Comparative Analysis of Synthetic Compounds as Mosquito Repellents

S. No	Synthetic Compound	Repellent Efficacy	Safety Profile	Regulatory Approvals
1.	DEET	High	Caution advised	Widely approved
2.	Picaridin	High	Generally safe	Widely approved
3.	IR3535	Moderate	Generally safe	Widely approved
4.	Ethyl Butylacetylaminopropionate	Moderate	Generally safe	Widely approved

Due to their excellent potency and prolonged protection, synthetic chemicals are frequently employed in insect repellents. Comparative study of synthetic substances used as insect repellents [68]:

7.5.1. DEET (N, N-Diethyl-meta-toluamide): One of the most popular synthetic ingredients in mosquito repellents is DEET. It has a high level of repellent effectiveness and offers strong defence against mosquito bites. DEET is renowned for its long-lasting protection, providing prolonged hours of mosquito repulsion. However, it is advisable to use caution when using it as some people may have skin irritability or allergic responses. DEET has undergone significant research and received global regulatory authority approval for use [69].

7.5.2. Picaridin (KBR 3023): Another synthetic substance included in insect repellents is called picaridin. It has a high level of repellent effectiveness and provides protection for a fair amount of time. Compared to DEET, picaridin is usually thought to be less likely to irritate skin. For people who might be sensitive to DEET, it offers an alternative choice. For usage as a mosquito repellent, picaridin has obtained extensive regulatory clearances [70].

7.5.3. IR3535 (Ethyl Butylacetylaminopropionate): The synthetic substance IR3535 has a mediocre ability to repel mosquitoes. Compared to DEET and picaridin, it offers protection for a shorter period of time. The majority of people tolerate using IR3535 well and consider it to be generally safe. It has received regulatory approval for use in formulations of insect repellents [71].

7.5.4. Ethyl Butylacetylaminopropionate: The synthetic substance ethyl butylacetylaminopropionate is another one that keeps mosquitoes away. It has a mediocre ability to repel and provides protection for only a brief time. It is typically safe to use and well accepted by most people, just like IR3535. The use of ethyl butylacetylaminopropionate in insect repellent products has acquired regulatory approval [72,73].

8. Safety Considerations and Environmental Impact

When assessing mosquito repellents' efficacy and acceptability for usage, it's crucial to take safety concerns and the influence on the environment into account. Although insect repellents are necessary for preventing the spread of diseases carried by mosquitoes, it is important to guarantee their safety for human usage and reduce any potential negative environmental impacts. This section will go over the safety concerns and environmental impact of mosquito repellents, including risk-benefit analysis, skin compatibility, toxicity assessment, and environmental fate [74]. To evaluate their possible toxicity to people, mosquito repellents are subjected to stringent safety evaluations. These assessments consist of tests for eye irritation, skin sensitization, and acute and long-term toxicity. To assess possible dangers, many exposure pathways, including ingestion, inhalation, and skin contact, are taken into account [75]. To ensure human safety, these studies assist determine safe exposure levels and the highest permitted concentrations of active components in repellant compositions. To govern the use of repellents and safeguard the general public's health, regulatory organisations like the Environmental Protection Agency (EPA) establish safety standards and guidelines. Clinical trials, epidemiological research, and post-marketing surveillance are used to gather safety data to keep track of any negative health consequences on people [76]. It is important for individuals to follow the instructions and precautions provided by manufacturers to minimize the risk of adverse reactions. The use of mosquito repellents can have unintended consequences on non-target animals, such as wildlife, beneficial insects, and aquatic life. In order to determine the potential ecological impact of repellents, field investigations and laboratory testing are used to determine the toxicity of repellents to non-target organisms [77]. These studies look at how repellents affect non-target creatures' survival, development, behaviour, and reproduction. Regulating bodies establish policies and limitations on the use of repellents in environmentally sensitive areas after taking into account potential dangers to non-target creatures. Manufacturers and formulators are urged to create insect repellents that are still effective against mosquitoes while being less hazardous to non-target creatures [78]. Skin Compatibility and Irritation Testing: Skin compatibility is a crucial factor in safety evaluations for insect repellents. Since the skin is the main point of contact when applying repellents, any negative reactions may have a substantial influence on user compliance and general safety [79]. Repellents are put through extensive testing to see how well they work on skin and whether they can irritate, sensitise, or trigger allergic reactions. To ascertain the possibility of unfavourable skin reactions, these procedures also involve patch testing on volunteers who are humans. Additionally, research is done to evaluate the possibility of phototoxicity or photosensitivity, particularly for repellents containing certain synthetic chemicals [80]. In order to verify that repellents are safe for topical application and reduce the risk of skin irritation or other unfavourable skin reactions in users, skin compatibility tests are an invaluable tool. To encourage safe and effective use of repellents on the skin, it is critical for manufacturers to provide clear directions for use and precautions [81]. In order to reduce the long-term effects of mosquito repellents on ecosystems, it is crucial to take into account their environmental destiny and biodegradability. Studies are done to determine how long repellent active components last, how they change over time, and how they behave in different environmental compartments such soil, water, and air [82].

These investigations support the evaluation of repellents' general environmental persistence as well as their potential for bioaccumulation in living things. Testing for biodegradability is done to see how easily repellents can decompose in the environment. In a perfect world, repellents would breakdown into harmless byproducts with little environmental persistenc [83]. To assess the overall efficacy and safety of insect repellents, a detailed risk-benefit analysis is required. This investigation examines the potential health concerns linked to illnesses spread by mosquitoes as well as the advantages of employing repellents to stop such illnesses [84]. The effectiveness of repellents, their safety profiles, the frequency and severity of diseases spread by mosquitoes in particular areas, and potential negative impacts on human health and the environment are all evaluated as part of the risk-benefit analysis. Making judgements on the usage of insect repellents is made easier by regulatory bodies, healthcare experts, and individuals thanks to this analysis [85].

9. Challenges and Future Perspectives

Developing and evaluating novel nano formulations based on essential oil mosquito repellents presents several challenges. These include the complexity of formulation, ensuring stability and longevity of the formulations, optimizing the concentration of active ingredients, and ensuring safety and skin compatibility [86]. The formulation process requires expertise in nanotechnology and formulation science to effectively encapsulate hydrophobic essential oils within nanoparticles or other nanostructures. Additionally, maintaining the stability of the formulations and preventing the degradation of essential oils over time is crucial for sustained repellent efficacy. Finding the optimal concentration of active ingredients in the nano formulations is essential to balance efficacy and minimize potential adverse effects [87]. Furthermore, ensuring the safety and skin compatibility of the nano formulations is a critical aspect that involves thorough testing for skin irritation, sensitization, and systemic toxicity [88]. Researchers can explore innovative approaches such as nanoemulsions, solid lipid nanoparticles, and liposomes to improve stability, controlled release properties, and bioavailability of the repellent formulations. Combination approaches involving essential oils and other active ingredients or technologies can lead to synergistic effects, broadening the spectrum of repellency and enhancing efficacy against various mosquito species [89,90]s.

10. Conclusions

Utilising nano formulations with insect repellents containing essential oils offers a lot of potential to improve mosquito control strategies. However, there are several challenges that need to be overcome by ongoing research and innovation, including formulation complexity, stability problems, the ideal concentration of active ingredients, and safety considerations. The efficiency of mosquito repellents can be increased in a number of ways with the help of nano formulations, which present exciting opportunities. The regulated release of essential oils made possible by nanoparticle encapsulation prolongs the effectiveness of the repellent and provides long-lasting insect protection. Researchers can increase the stability and the longevity of the repellent compositions by optimising particle size, surface properties, and content.

Essential oils can have synergistic effects when combined with other active components in nano formulations, affecting several facets of mosquito physiology and behaviour to stop the emergence of resistance. Specific nanoparticle features enable targeted delivery systems, which enable accurate and localised distribution of repellents to mosquito-prone locations, maximising effectiveness while minimising environmental impact. Safety concerns are of the utmost importance, necessitating extensive testing and evaluation to guarantee biocompatibility, non-toxicity, and environmental friendliness. Adopting eco-friendly practises, such as employing naturally occurring oils and eco-friendly nanomaterials, is consistent with green chemistry concepts and sustainability objectives.

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Conflicts of Interest

The authors declare no conflict of interest.

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