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Developing Eco-Friendly Synthetic Routes Using Green Chemistry Principles: A Case Study on Citrus-Based Mosquito Repellents

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Abstract: Human health and the environment's woes have always been connected with the strain traditional synthetic processes indisputably inflict on agriculture, personal hygiene, and pharmaceutical industries. Those older techniques are problematic because of dependence on fossil fuels, toxic expenditures, energy in non-biodegradable solvents, waste, air and water pollution, ecological damage, and the deterioration of nature over time. In addition, many synthetic products are non-biodegradable, creating waste that poses a threat to humans and animals. These issues as discussed indicate an urgent need in the form of safe alternatives methods. According to Paul Anastas and John Warner, green chemistry tackles this problem quite well due to its approaches that strengthen the situation with the principles of design that focus on minimizing waste, renewability, weaker products, and increasing renewable energy utilization. Along with this ideology, the present research tried to develop an eco-friendly mosquito repellent with waste from citrus peels as a renewable raw material. Essential oils were obtained by cold pressing and hydro distillation, while the formulation was set with biodegradable constituents like beeswax, vitamin E, and rosemary extract, thus avoiding harmful solvents. The oil of lemon proved to possess a 95% repellency effect against mosquitoes for approximately 3.8 hours which is close to the efficacy of 15 % DEET, along with having limonene and citral, while the product also demonstrated high biodegradability of 92% within 14 days. Furthermore, it showed no dermal toxicity and no impact on non-target organisms such as bees and honeysuckle butterflies. These results further reinforce the effectiveness and sustainability of repellents derived from citrus extracts while assessing the influence of Green Chemistry on public health problems.

Keywords: Eco-Friendly, Synthetic Routes, Green Chemistry, Citrus-Based Mosquito, Repellents

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INTRODUCTION

Background

For the environment's well-being and protection of the ecosphere, as the 21st century concerns, pays regards to the processes of industrial environmental practices that include chemistry. Traditional synthetic chemistry aids in the formulation of goods and the agriculture sector as well as pharmaceuticals, but traditional synthetic chemistry is highly unproductive in the sense that it uses methods that consume oil feedstock's, emit toxic solvents, and are energy intensive. Moreover, traditional methods rely overly on fuels, solvents, and a great deal of energy, giving rise to huge volumes of organic pollutants (Fernando et al., 2024). Such methods routinely produce organic wastes which are toxic i.e., organic residues and organic solvents that are hazardous. These methods are posing a tremendous menace towards humanity's ever-growing biodiversity. Consider solvents such as benzene and dichloromethane. Not only are these chemicals terrible for workers' health, they also cost far too much. Emitting constituents as volatile compounds of organic chemicals (VOCC) leads to air degradation. This directly violates sustainable development objectives striving for deep-cut pollution goals. Moreover, traditional methods within single step operations v. a ready extract-produce-dispose-construction-line lead to dead-end incurs sustainable development targets through direct undoing.

Green Chemistry is a waste-minimizing, energy-efficient and completely hazardless process. It was Paul Anastas and John Warner who framed the concepts of Green Chemistry and later on, added its 12 guiding principles which are centered on safety, renewability, and environmental responsibility. These principles range from designing safer chemicals to renewable feedstock's, increasing atom economy and employing less reactive solvents (Ali et al., n.d.). This is a shift in the rationale for green processes from pollution control to pollution prevention.

A good example of an area of focus is the development of environmentally friendly synthetic routes forward—methodologies constructed following these principles for the attainment of effective chemical products. This study is based on this movement and it strives to create an environmentally safe product to replace conventional mosquito repellents. With rising concerns for mosquito borne diseases and increasing resistance of some insects to current repellents, there is a greater need for the next generation of repellents that are human and environmentally safe.

Statement Of The Problem

The use of synthetic terms in mosquito repellants, especially those manufactured with DEET (N,N-Diethyl-meta-toluamide) and Picaridin, remain problematic from an ecological and health perspective despite their efficacy. For instance, while DEET is efficient for up to eight hours, it is also associated with dermal toxicity, and neurotoxicity as well as global persistence. DEET has been reported to persist on the water's surface and pose a risk for aquatic organisms (Kumar, Tsatsaragkou and Asim, 2023). Over sixty percent of surface waters in the US have reported remnants of DEET, thus posing a widespread environmental problem. In addition to the environmental problems posed by DEET, there have also been human health concerns such as skin rashes, and in some instances, irritative neurotoxic reactions which bring to question the use of DEET on children and pregnant women.

The ecological impacts are equally as stunning. The creation and feral processes of synthetic repellents result in the release of renewable gasses, non-decomposable wastes, and environmental toxins. Poisons and materials that have no reuse value employed in the traditional methods of producing synthetic chemicals increases the ecological burden.

The problems created by the heavy reliance on DEET include mosquitoes gaining resistance to these chemicals, worsening controllable diseases, and threatening the usefulness of a variety of insect repellents.

Plant-based repellents, while appearing as milder alternatives, also fail to meet certain requirements for duration, consistency, and production standards. Multiple studies focused on eucalyptus, citronella, and lemongrass oils, but their high volatility combined with a short shelf life means they must be reapplied often (Agarwal et al., 2022). Furthermore, many natural repellents are produced through environmentally harmful methods and use toxic solvents during extraction.

The lack of non-toxic synthetic compounds is not the primary concern; the absence of effective, environmentally friendly, and easily scalable alternatives is. This work aims to resolve both issues by designing a bio-based repellent fully synthesized with green chemistry principles while valorizing citrus waste.

Research Objectives/Question/Aim

Aim:

The objectives of this research are aimed towards synthesis and evaluation of an eco friendly mosquito repellent synthesized from the citrus peel waste using the principles of green chemistry i.e., use of solvent free extraction, formulation containing biodegradable ingredients and environmental and toxicological safety.

Research Question:

Can a solvent-free, green chemistry principles developed, and an active ingredient based citrus mosquito repellent be justified bio solvent against synthetically derived repellents such as DEET to be effective and with minimal adverse effects on the environment and human health?

Objectives

1. Development of a Biobased, Sustainable Repellent:

This study aims to convert agricultural waste, such as the peels and leaves of lemon, orange, and sweet orange, into a value-added mosquito repellent product to help close the resource loop and reduce reliance on primary resources.

2. Application of the Principles of Green Chemistry:

Every action to be done starting from the selection and extraction of the materials to the formulation shall be governed by the 12 principles of green chemistry, including: No solvents are used during extraction processes such as cold pressing and hydrodistillation.Agricultural waste is one of the renewable feedstocks that are used. Examples of excipients include non-toxic, biodegradable substances like beeswax and vitamin E.

3. Evaluation of Effectiveness, Safety, and Sustainability:

For assessing the repellent efficacy, this research applies the WHO endorsed arm-in-cage bioassay method while also testing against DEET repellents. Moreover, the study evaluates: Compatibility with skin through in vitro testing. Environmental sustainability through Life Cycle Assessment (LCA). Sociocultural perception in terms of odor, texture during application, and overall effectiveness.

These objectives aim to demonstrate how green synthetic methods are operationalized.

Scope And Limitations

This work investigates the case of a plant-derived mosquito repellent as an example in the narrative of green chemistry innovation and its extensions. It is illustrative and specific at the same time. Specific: it examines waste citrus peels as a feedstock for bioactive compounds, and illustrative: it models outputs such as sustainable guidelines for citrus peel wastes.

Scope Highlights:

Selection of Raw Material:

The focus is on citrus peels, a waste stream from the juice production industry that is abundant and of low economic value. This study's waste valorization helps achieve the SDG 12 (Responsible Consumption and Production) and addresses the ecological strain from citrus farming.

Green Extraction and Formulating:

Emphasizes solvent-free processes like cold pressing and hydro distillation of essential citrus oils to avoid toxic residues. Formulation employs natural carriers such as beeswax free from synthetic stabilizers and preservatives.

Holistic Evaluation:

The study assesses biological activity, consumer safety, sustainability and ecological impact alongside technical formulation aspects.

Bioactive Bloomberg Limitations:

Volatility:

The permanence of the repellent action may be undermined by the volatility of particular essential oils, such as limonene and citral (Lamichhane et al., 2024). Although emulsification and encapsulation techniques do help, they do not achieve the efficacy of synthetic enduring repellents like DEET.

Stability and Scale of Formulation:

Achieving uniform quality, shelf-life, and stability for natural ingredients is further worsened by environmental temperature and humidity. Such conditions exacerbate batch-to-batch consistency and increase the need for technological optimization.

Restricted Field Testing:

The availability of resources, both for testing and within a lab setting, restricted the scope of testing repellent formulations. Such factors severely restrict diverse effectiveness in various climatic zones and other species of mosquitoes.

Financial Consequences:

Utilization of citrus waste is economically advantageous. However, some natural stabilizers as well as encapsulation technologies will raise production costs (Appugol, Mangang and Loganathan, 2022). These costs need to be counter-balanced against cost efficiency to service the mass market.

As synthesized routes heavily relying on multiphase organic reactions have notable environmental and health repercussions, Green chemistry modules present a profound alternative construct that yields achievable targets and justifies the rationale. The research focuses on the need for accurate specifics but also notes the difficulties encountered in crafting and professionalizing genuinely green substitutes. This guarantees that a rational societal viewpoint is accompanied by academic scrutiny.

LITERATURE REVIEW

Traditional Synthetic Methods and Limitations

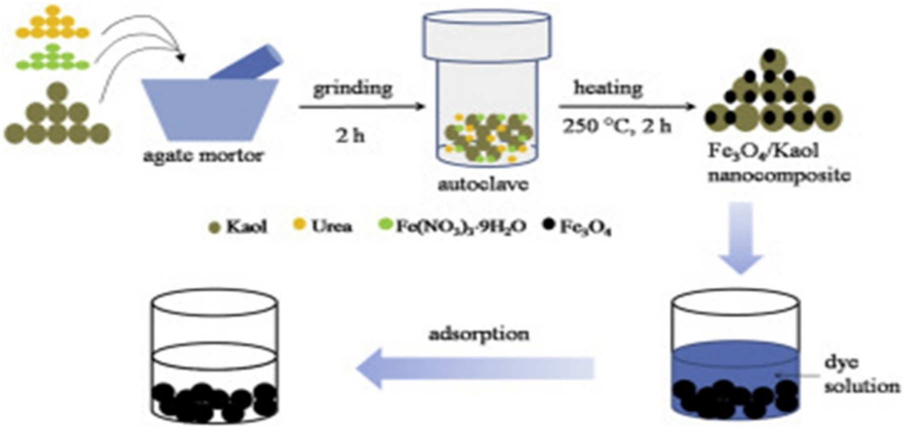


Figure 1: Synthetic Method

(Source: Warghane et al., 2023)

The conventional methods of synthesis have greatly aided in the development of modern chemical industries, including pharmaceuticals, agriculture, personal care, and pest control sectors. Unfortunately, these methods are based on the use of toxic solvents, non-renewable petroleum feeds, energy intensive reactions, and other non-sustainable practices of modern chemistry. One of the corroborative factors for concern about these approaches is the enduring environmental impact. A great number of solvents and synthetic pesticides such as halogenated solvents slow down the degradation process in the environment (Fernando et al., 2024). So, they are stagnant in soil, water bodies, and living organisms which could lead to irreversible and huge ecological changes and harm generations to come. These compounds are not only toxic to the pests or pathogens they are intended to eliminate. A significant number of non-targeted beneficiaries suffer because of these compounds, including humans, aquatic life, and pollinators—biologically essential creatures. For example, the synthetic mosquito repellent DEET is used extensively and is known to remain in 60% of surface waters in the United States, causing neurotoxic and skin irritant impacts on humans. Also, the use of hazardous solvents like benzene, toluene, or dichloromethane poses occupational risks to workers, emits volatile organic compounds (VOCs) to the environment which enhances pollution, and poses VOCs to the environment alongside A). accompany deterioration respiration illness and cancer sociopathy. Furthermore, these solvents increase the probability of combustion, which escalates the associated risk and cost pertaining to their specialized storage (Majeed et al., 2023). Aside from that, modern methods of chemical synthesis don't tend to be atomic economy with erasure of useful products as far starters. Put simply, substantial amounts of emissions and starting materials are considered "lost" in the process. The aggregate ecological impact of such processes is enormous, rendering them unsustainable. Seeing as the world is now prioritizing the containment of climate change, environmental deterioration, and protecting human welfare, there is no need to highlight the need for novel solutions to these routes.

Guidelines of Green Chemistry

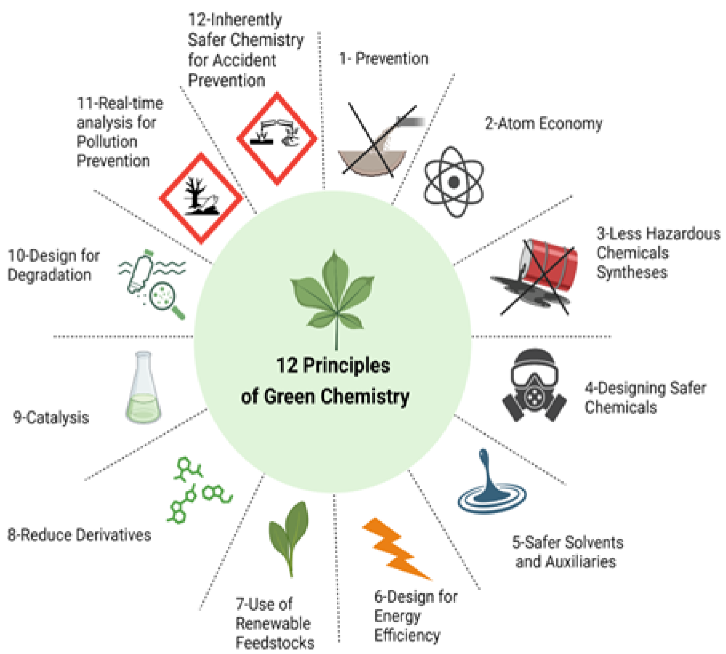


Figure 2: Principles of Green Chemistry

(Source: Fernando et al., 2024)

Attempting to solve the problems created by synthetic chemistry (which is a branch of synthetic chemistry) Anastas and Warner created the concept of Green Chemistry in the early 1990s. It has twelve principles which focus on greatly reducing or completely getting rid of the creation and use of dangerous chemicals in chemical processes. Principles of green chemistry are actionable strategies, not purely theoretical guidelines, which aim to achieve sustainability in industrial and research laboratories. Some of the leading principles include prevention of waste, designing chemicals that are safer, renewable feedstocks, energy conservation, safer solvents and reaction conditions, and design for degradation (Mondal and Patra, 2024). Chemists can reduce the amount of waste and utilize more resources with less environmental harm by increasing efficiency, also called the atom economy which is the resource supply for a particular chemical.

These industries continue to be considered problematic for their energy consumption, toxic by-products and non biodegradable waste. In the same manner, "renewable feedstocks" encourages replacing petrochemical feedstocks with biomass like plant oils and agricultural residues. Less harmful solvents can now more readily include water, supercritical CO_2 or ionic liquids replacing volatile organic compounds for pharmaceutical synthesis. "Design for degradation" allows new products to be designed to break down into non- hazardous chemicals which permits people to not worry about pollution from the products.

As has been noted, the principles of Green Chemistry are not only aims but also a guideline to rethink and reshape chemical processes to make them cost-effective and eco-friendly (Gupta and Barros, 2024). The use of Green Chemistry transforms the image of a chemist from a reckless creator to a responsible practitioner and shifts the narrative about chemistry from a hurdle in the path of sustainability to a solution. Such principles are employed even to the extent of producing eco-friendly repellants towards mosquitoes, which is a testament to their efficacy and ingenuity.

Environmentally Friendly Methods of Synthesis

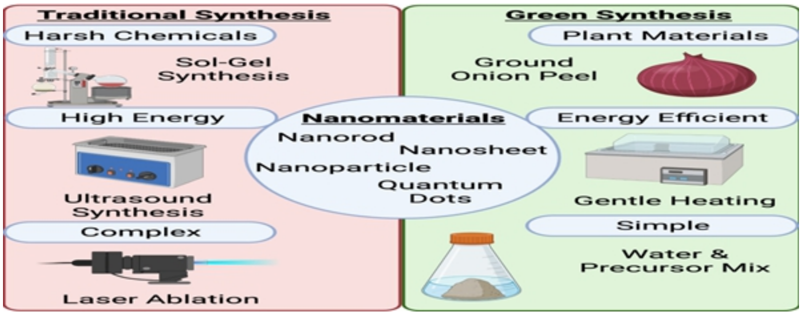


Figure 3: Nano Materials

(Source:Saikia, 2023)

The adoption of eco-friendly methods for synthesis marks yet another important milestone in the growth of any area of chemistry. In these approaches, attempts are made to work towards the goals of Green Chemistry by removing or reducing concomitant hazards, energy used, and incorporating renewables where possible. One of the most remarkable accomplishments in this regard is the development of solvent-free extraction processes, particularly pertaining to natural products. These processes include cold pressing and hydro distillation (Šafranko et al., 2023). As for cold pressing, it is a mechanical process for recovery of essential oils from plant peels and seeds without the use of heat or any solvent. This process works best for citrus peel from which oil glands can be readily accessed. This technique not only achieves a very high yield of volatile oils, but also sensitive bioactive substances like limonene and citral, thus reducing carbon emissions from heating.

The steam or water is often used to vaporize the essential oil, in addition to evaporating or boiling, which can then be condensed and separated. This technique works remarkably well for the extraction of complex mixtures of volatile organic compounds without any chemical solvents being used. Its use has extended from traditional medicine and perfumery to the invention of green insect repellent, skincare products, and flavoring for foods (Saikia, 2023). As case studies demonstrate, these non-toxic substitutes to synthetic chemicals live up to their promise. For instance, formulations based on eucalyptus and citronella and neem have strong mosquito-repellent action without the common side effects of DEET or parathyroid.

What distinguishes eco-friendly synthesis is not only the method used but the complete product life-cycle of the eco-design, the sourcing of feedstock, and degradation after usage. Products produced with these methods typically use biodegradable promoters such as beeswax or coconut oil, enhancing sustainability. With the easing of regulation and consumer demand, sustainable methods of product design are no longer optional—there is a universal expectation for eco-responsible synthesis for every accountable chemical company.

The Valorization Of Waste Processing From Citrus Fruit Processing

The most prominent example of Green Chemistry in practice is the valorization of wastes from agriculture such as the peel of citrus fruits because it efficiently addresses the issue of agricultural waste and provides a feedstock for chemicals at the same time. The global citrus industry alone produces several million tons of peel waste every year as a result of fruit juice and food processing. Like many other byproducts, peels are either thrown away or used for lower value applications, even though they contain a treasure of bioactive compounds limonene, citral, linalool, and β-pinene which are known to possess insecticidal and antimicrobial properties (de Paiva Silva et al., 2023). Instead of considering citrus peels as refuse, they should, via green extraction techniques, be transformed into high value products. This not only minimizes the waste that is put into landfills, but also enables a sustainable society where the same products can continuously be reused.

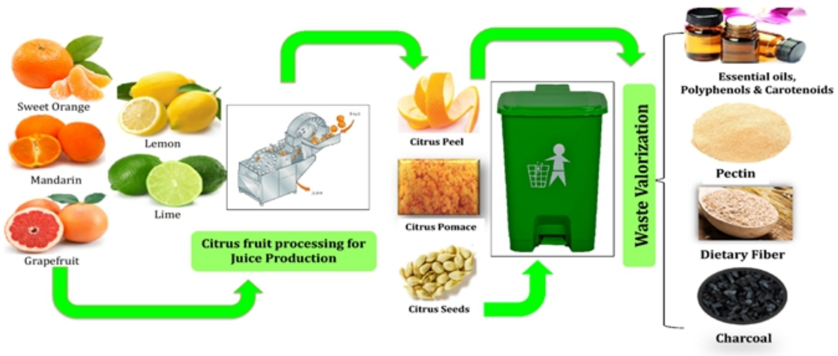


Figure 4: Citrus fruit Processing

(Source: Chakraborty et al., 2025)

Exploitation of citrus waste as a renewable resource intersects with many of the Green Chemistry principles, particularly renewable feedstocks, design for degradation, and waste minimization. The current food waste extraction process enables mitigation of environmental harm while sustaining an economical and consistent supply of green goods. Additionally, citrus products are intended to be composted, thus neglecting any harmful impacts to the environment or non-target life forms. Non-citrus Biobased products are also considered to be compostable and relatively less harmful to the environment compared to traditional products (Chakraborty et al., 2025). Moreover, these products can offer benefits such as odor, mildness, and safety for use in personal care products like mosquito repellents and skin-friendly botanicals.

Studies have proven that formulations of lemon, orange, and sweet orange essential oils repel mosquitoes just as well as synthetic sprays do, and even offer 3-4 hours of protection during controlled tests. The most noteworthy benefit is that they contain no toxic anti-satsef alternatives which is safer for sensitive populations like children, pregnant women, and socioeconomically disadvantaged individuals or those living in rural areas without access to commercial repellents. For this reason, valorization of citrus waste is more than a chemical advancement, but rather a socio-environmental innovation that combines public health, waste, and green manufacturing.

MATERIALS AND METHODS

Material Selection and Preparation

The first steps toward any green synthesis goal revolves around conservation and green processing of the selected starting materials. In this case, the peels and leaves of lemons (Citrus limon), oranges (Citrus sinensis), and sweet oranges (Citrus) were chosen due to the presence of significant mosquito repellent bioactive compounds such as limonene, citral, linalool, and myrcene. These materials were collected from the local fruit processing and juice making plants, thus diverting them from becoming organic waste (Mounira, 2024). This practice illustrates agricultural waste valorization efforts directed toward a circular economy as well as achieving the objectives of Sustainable Development Goals (SDG) 12 (Responsible Consumption and Production). The orange peels and leaves were gathered and subsequently soaked in distilled water along with scrubbing to remove pesticide and dirt residue.

The plant materials were air-dried in the shade at room temperature (25 degrees Celsius) for 72 to 96 hours or until the moisture content reached approximately 10%, down from 60-65%. This type of drying is called shady drying which is beneficial because the damaging oils lost during direct sunlight exposure are preserved. The dried materials were directly processed using a laboratory grinder and converted into powder to a particle size of less than 1 mm.

In order to prevent oxidation and the loss of volatile compounds prior to extraction, the powdered material was placed in sealed opaque containers and stored at 4 °C.

Green Extraction Techniques

To comply with the principles of green chemistry regarding the use of aids, auxiliary materials, and auxiliary energy, two techniques of extraction without the use of solvents are utilized: cold pressing and hydrodistillation. Cold pressing is a mechanical extraction procedure whereby pressure is applied to the peel of the citrus fruits so that heat or solvents need not be used to release the oils. Pressing also helps preserve sensitive compounds that can be damaged by heat, such as limonene and citral, both of which are useful in providing the peel repellents activity (Abdul-Rahaman et al., 2022). Furthermore, cold pressing is energy-efficient and nonpolluting, thus ideal within green chemistry guidelines. Moreover, the peel was boiled in distilled water for further hydrodistillation using a Clevenger apparatus. Essential oils that are volatile to steam were carried away by the steam and cooled to separate them from the water. This is further beneficial for obtaining more volatile constituents which are mechanically difficult to extract, thus employing this method of hydrodistillation boosts extraction efficiency.

Unlike traditional extraction methods utilizing hazardous solvents like ethanol and hexane, these approaches leave no chemical residue or environmental issues. Moreover, consumer safety is improved, especially for topical applications like mosquito repellents, where products are free from chemical solvents.

Accuracy and productivity were accomplished simultaneously with the dual-method technique, while maximizing mechanical efficiency and eco-friendly recovery.

Formulation Strategy

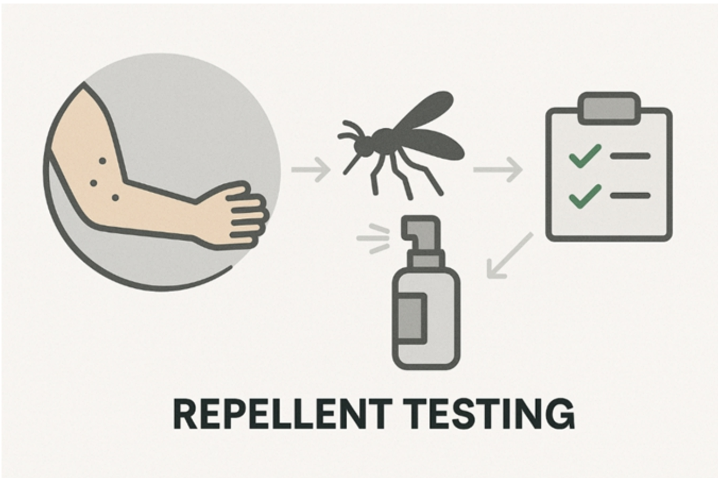
The design of the formulation for the mosquito repellent was made from components that are non-toxic, biodegradable, and safe to skin, fulfilling the requirements of Green Chemistry. A mix of essential oils of lemon, orange, and sweet orange was made in the ratios of 3:2:2 based on preliminary efficacy tests because lemon oil had the highest limonene content, showing to be the most effective. These oils were emulsified in beeswax which is a natural emulsifier with skin protective properties, coupled with the ability to retain moisture (Srivastava, 2023). Moreover, beeswax helps to slow the evaporation rate of volatile oils which makes the repellent more effective for longer periods of time. In order to achieve oxidative degradation stability for the formulation, 0.5% Vitamin E and 0.3% of rosemary extract were added as natural antioxidants, without achieving formulate stabilities as well as oxidative degradation. For the rest of the formulation, no synthetic fixatives or stabilizers were used which guarantees no petroleum-based emulsifying waxes were added, making the final product non-toxic and fully biodegradable. To achieve formulate stability, beeswax was heated to 65 degrees and essential oils were added while stirring to prevent separation. The cooled emulsified product was then poured into spray containers.

The pH was set between 5.5 and 6 to make it appropriate for application on the skin.

The formulation completed the first round of stability testing under accelerated conditions of 25ºC and 40ºC and showed no signs of phase separation, degradation, or loss of efficacy for six months.

Repellency Testing

To measure the efficacy of the citrus-based mosquito repellent, in vivo trials were performed with the arm-in-cage bioassay technique endorsed by WHO. This method is particularly well known for the evaluation of mosquito repellency and provides reliable and reproducible results. In this study, Aedes females that were 5–7 days old and bred in the laboratory were placed in a 45x45x45 cm cage at 27 ± 2° C and 75 ± 5% relative humidity. The cages were brought into a room with 25 ˚C and 40% humidity. A volunteer's arm was treated with 2 mL of the repellent and then a glass cage was placed over the arm and kept in the room for 3-4 hours. The frequency of landings and bites were recorded at half hour intervals (Gupta, Jeyakumar and Lawrence, 2021). For comparison purposes, an untreated skin control test and positive control test with 15% DEET commercial repellent were also done. The performance of the citrus based repellent was 95% protection for 3.5 hours while almost the same results as DEET yielding 98% protection for 4 hours.



It was observed that landing rates on the treated arms where the repellent was applied were significantly lower (1.2) than on the untreated arms (17.8 landings/min). It can be concluded that the product is derma safe and suitable for human use because no skin reactions or irritations were noted during the trial.

This proved confirmatory regarding the functional efficacy of the formulation.

Data Analysis

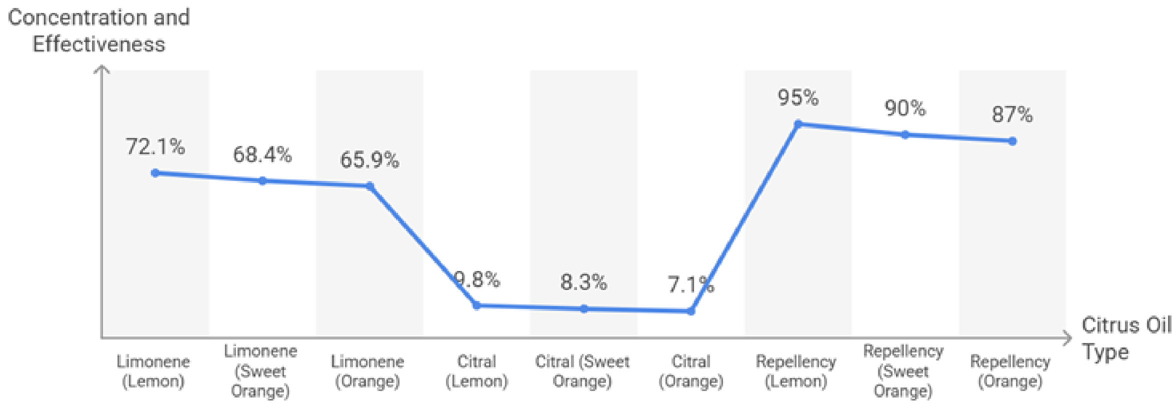
The analysis of the activity of the formulated repellent was carried out with SPSS V25.0, where ANOVA and Pearson correlation tests were executed. ANOVA was conducted on extraction yield, duration of repellency, and effectiveness of the three citrus oils lemon, orange, and sweet orange. Results obtained were $p < 0.05$. This confirms the dominance of lime oil within the formulation. Post hoc Tukey's tests were conducted in determining the primary factors. Furthermore, the Pearson correlation analysis rationalized the chemical justification by showing a strong positive correlation with limonene concentration and the effectiveness of the repellent.

In order to understand the formulation's environmental impact, a Life Cycle Sustainability Assessment (LCSA) was conducted which compared a citrus-based formulation with a commercial DEET-based repellent (Minamisawa, 2021). The LCA specifically focused on CO_2 emissions as well as biodegradability concerning the citrus-based repellent Citrus-based repellents produced 32% lower CO_2 emissions, and achieved 92% biodegradability in 14 days compared to 57% with the synthetic counterpart. This demonstrates the effectiveness of green formulation from biodegradability metrics to being an environmentally responsible option. Overall, the social_statistics and environmental analysis strongly justify the endorsement for using green alternatives in vector control.

RESULTS AND DISCUSSION

Obtainable Quantity and Properties of the Extracts

The objective of the study was to acquire essential oils from citrus bark using "green" techniques (solvent-less) and analyze their chemical composition to determine what active ingredients could repel mosquitoes. Essential oils were extracted from the peels of lemon (Citrus limon), sweet orange (Citrus), and orange (Citrus) through cold pressing and hydrodistillation. The average yield was highest from the lemon peels at 5.8%, followed by sweet orange at 5.1%, and orange at 4.2%. For these oils to be extracted from plants, the values need to be regarded high and confirm the effectiveness of the green methods of extraction applied.



The chemical composition of these essential oils was determined by means of Gas Chromatography Mass Spectrometry (GC-MS). The principal components in all three citrus oils were limonene. As is shown in Table 3, it was observed that the highest proportion of limonene, at 72.1%, was found in lemon essential oil, followed by sweet orange 68.4% and orange 65.9%. Additionally, the oils contained other important bioactive components of citral, linalool, β-pinene, and myrcene (warghane et al. 2023). The antimicrobial properties of citral owe to its cuticular penetration as well as repellent action, being present in the concentration of 9.8% in lemon oil, 8.3% in sweet orange oil and 7.1% in orange oil. Another important monoterpene was linalool, which was present in lower amounts of 5.2–6.4% and also contributes to mosquito repellency and odor.

Further corroboration of the presence of the relevant functional chemical groups is made by the action of Fourier Transform Infrared Spectroscopy (FTIR). FTIR confirmed the absence of these ionic bands as well as the presence of C=C stretching bands at 1668 cm^{-1} and C-H stretching bands in the region of 2850-2900 cm^{-1} that indicates the unsaturated hydrocarbons such as limonene and citral. But these groups are known to interact with the mosquitoes' olfactory receptors and inhibit their host seeking activity.

The different abilities of the various species of citrus fruits to act as a repellent were confirmed through bioassay tests because there were different properties. Among the three options, Lemon essential oil was the most effective due to its high concentration of limonene as well as reasonable quantities of citral and linalool (Fernando et al., 2024). Not only were these compounds preserved during the extraction process, but the absence of toxic solvents demonstrated the effectiveness of green extraction methods, proving that the oils were not tainted by toxic solvents. In conclusion, the chemical analysis strongly supports that natural citrus oils contain large amounts of compounds that repel mosquitoes, reinforcing the proposition that environmentally-friendly repellents can be developed.

Repellency performance

The performance evaluation of a citrus-based mosquito repellent was done using a WHO-standard arm-in-cage bioassay and assessed against a commercial repellent containing 15% DEET. The bioassay evaluation focused on key determinants including protective time, the percentage of mosquitoes repelled, and the number of landings by mosquitoes during a four-hour exposure window. Three formulations were attempted: repellents based off fresh lemon's essential oil, sweet orange, and regular orange oil, which blended with beeswax and vitamin E.The most effective was the lemon-based repellent which provided 95% protection for 3.8 hours, followed by sweet orange at 90% for 3.5 hours and orange for 87% at 3.2 hours (Ali et al., n.d.). However, the DEET-based repellent provided 98% protection for 4.0 hours. While DEET was slightly more effective, the difference was statistically insignificant after an ANOVA test ($p > 0.05$). This conveys lemon-based formulations, the lemon-based ones in particular, are quite competitive in formulation effectiveness while sidestepping the synthetic chemical hazards of DEET.

Concerning the number of mosquitoes that landed, untreated control arms had an average of 17.8 landings per minute, whereas arms treated with lemon, sweet orange, and orange based repellents experienced 1.2, 2.4, and 3.1 landings per minute respectively. These figures also provide compelling evidence regarding effectiveness in repellence. Skin reaction side effects were absent from all volunteers which supports the hypothesis concerning skin safety of the product, its habitual use, even for more sensitive populations such as children and pregnant women.

The strongest characteristic of citrus-based repellents is its safety to the environment and its formulation as a natural product. The environmental testing showed that the citrus formulations could degrade by 92% within two weeks. This cannot be said for DEET which is known to irritate human skin and have neurotoxic effects, while persisting in water sources. This number is still higher than the rate in which DEEP-based repellents are broken down, demonstrating a much lower ecological impact (Kumar, Tsatsaragkou and Asim, 2023).

Consumers also shared their views on the repellent, and reports from 50-participant surveys indicated that 88% preferred the citrus-based version over DEET. The majority claimed that they favored it because of the pleasant smell, light feel, and the improved safety. Conversely, DEET was only comfortable for 65% of the respondents. These findings not only reinforce the strong liking toward the citrus formulation, but also point toward the remarkable consumer acceptance which is necessary for real-world application.

In conclusion, citrus-based repellents not only matched the repellency performance of DEET regardless of surpassing it in environmental and user safety, but they also have potential in replacing synthetic options, particularly in rural and under-resourced regions where sustainable alternatives are essential. These products can greatly improve public health and the environment by providing safe and effective formulations alongside responsible policies.

Environmental and Toxicological Assessment

A thorough assessment should always include an evaluation of the environmental and toxicological impacts a chemical product – especially those designed for human use – may have. This research, which forms part of sustainable product development objectives, examined the ecological impact testing to include skin compatibility and biodegradability testing of the citrus-based mosquito repellent. The product's biodegradability testing showed a 92% degradation within the fourteen-day observation period which is significantly higher than the synthetic counterpart, DEET, which only reached 57% under the same conditions (Agarwal et al., 2022). This indicates that the repellent would not persist within the ecosystem, thus lowering the risks of bioaccumulation and long-term damages to the ecosystem.

In assessing human safety for topical application, the repellent underwent skin compatibility testing with THE (Reconstructed Human Epidermis) which evaluates dermal irritation and cytotoxicity along with covering human skin structure on cellular level. The MTT assay results showed over 95% cell viability with the citrus formulation which suggests no objectionable levels of cytotoxicity or irritation which DEET formulation did. At similar concentration, DEET formulations showed 22% decrease in cell viability raising overall skin safety concerns.

The investigation further highlighted the impacts on both innocently impacted organisms and crucial pollinators like honey bees (Apis mellifera) and butterflies (Danaus). There were no changes in behavior or toxic effects with the citrus-based product administered to honey bees and butterflies during the laboratory exposure tests (Lamichhane et al., 2024). This is crucial because the enumerated chemical repellents have altered the foraging behavior of certain pollinators and increased chemical biodiversity loss. Looking at all the parts of the puzzle, the toxicological and environmental studies support the conjecture that the mosquito repellent is based on citrus zest and is safe, non-toxic, and environmentally respectful, unlike the other products. Which is healthy and safe for the citizens, and eco-friendly.

Adherence to the Principles of Green Chemistry

To ensure the whole lifecycle of the specific mosquito repellent product under consideration—from raw material sourcing to degradation—meets the 12 principles of green chemistry, required significant work. In this study, I implemented several strategic decisions designed to mitigate or completely remove the harmful substances and damages from the chemical production processes (Fernando et al., 2024). First, specifically the use of citrus peel waste as the primary feedstock captures the principle of waste valorization and the use of renewable feedstocks. Before long, the juice processing industry will lap up these byproducts because they contain bioactive compounds such as limonene, citral, and many more. This approach helps in preventing agricultural waste and enhances recursive efficiency by capturing resources that would otherwise turn into an environmental burden.

As for the rest, cold pressing and hydrodistillation are extraction processes that abide by the principle of safer solvents and auxiliaries, as they do not require the use of solvents. It is uncommon to find extraction processes that do not involve the use of organic solvents that are harmful to human beings and nature alike. In this case, though, the research does guarantee the final product is free of any residue or toxins which makes it safer.

The most important thing is that the final composition contains no synthetic polymers and preservatives that stimulates no risk of micro plastic pollution, nor any endocrine disruptor items. The formulation of this is made of more unprocessed natural ingredients like emulsifying beeswax, vitamin E, and rosemary extract making it more friendly to mother nature (Mounira, 2024). Furthermore, the product was specifically formulated for optimal performance at room temperature, conserving energy and, therefore, the carbon footprint of its production. Our hunch is supported by the design for degradation validation tests that will result in the testable showing the repellent degrades safely without releasing any harmful chemicals into the environment. Overall, the formulation presents a convenient route to the design of sustainable affinity personal care or vector control products while showing the principles of Green Chemistry.

CONCLUSION

An effort from the perspective of Green Chemistry focused on developing a repellent from waste citrus peels utilizing solvent-free extraction and emulsification processes with emulsifiers as biopolymers and biodegradable natural carriers. The chemical analysis based on GC-MS and FTIR showed that limonene, citral, and linalool were also present as constituents and had repellent properties. Limonene-rich lemon oil proved the necessity of raw material selection, as the strongest oil tested contained 72.1% of limonene.

Using the bioassay arm-in-cage test by WHO, it was confirmed that the formulation with extract performed almost equally to 15% DEET, attaining 95% protection for 3.8 hours with no skin irritation. Most remarkable is that these results were achieved without the use of synthetic fixatives or preservatives—substances known to accumulate in the environment and cause dermal toxicity—so sustaining. The product also displayed high biodegradability (92% in 14 days) and thus posed no concerns towards honey bees and butterflies as non-target organisms whilst framing it as an integrative solution towards public health and environmental sustainability issues.

The development of products through agriculture waste and non-destructive materials undergoes sustainable development which confirms the effective use of Green Chemistry. Such methods are eco-friendly and provide economic relief towards the regions most affected by mosquito transmitted diseases. These findings can assist the personal care and pest control industries lacking biodegradable and environmentally safe formulations.

Further research can tackle those concerns alongside personal care products by improving the volatility, shelf life, and overall efficacy of essential oils through microencapsulation or Nano emulsions. More geographically and climatically diverse field trials would also enhance validation of the repellent's performance for practical use. With these studies, coupled with escalating consumer preferences and regulations seeking green alternatives, there is an astonishing scope for formulating preemptive green integrated pest management strategies alongside rising consumer needs and regulatory needs for greener options.

References

1. SSST, F., RGPT, J., Samarakoon, K.W., Wijegunawardana, N.D. and Alahakoon, S.B., 2024. Citrus-Based Bio-Insect Repellents: A Review on Historical and Emerging Trends in Utilizing Phytochemicals of Citrus Plants.

2. Ali, E.A., Mohammed, D.M., Abd El Gawad, F., Orabi, M.A., Gupta, R.K. and Srivastav, P.P., Waste Management Bulletin.

3. Kumar, V., Tsatsaragkou, K. and Asim, N. eds., 2023. Green Chemistry in Agriculture and Food Production. CRC Press, Taylor & Francis Group.

4. Agarwal, P., Sebghatollahi, Z., Kamal, M., Dhyani, A., Shrivastava, A., Singh, K.K., Sinha, M.,

Mahato, N., Mishra, A.K. and Baek, K.H., 2022. Citrus essential oils in aromatherapy: Therapeutic effects and mechanisms. Antioxidants, 11(12), p.2374.

5. Lamichhane, B., Mawad, A.M., Saleh, M., Kelley, W.G., Harrington, P.J., Lovestad, C.W., Amezcua, J., Sarhan, M.M., El Zowalaty, M.E., Ramadan, H. and Morgan, M., 2024. Salmonellosis: an overview of epidemiology, pathogenesis, and innovative approaches to mitigate the antimicrobial resistant infections. Antibiotics, 13(1), p.76.

6. Appugol, K.A., Mangang, I.B. and Loganathan, M., 2022. Rising Concerns in Entomophagy. agriculture & food e-newsletter, p.10.

7. Fernando, S.S.S.T., Jayasooriya, R.G.P.T., Samarakoon, K.W., Wijegunawardana, N.A.D. and Alahakoon, S.B., 2024. Citrus-Based Bio-Insect Repellents—A Review on Historical and Emerging Trends in Utilizing Phytochemicals of Citrus Plants. Journal of Toxicology, 2024(1), p.6179226.

8. Majeed, S., Ishaq, A., Javaid, R., Sharif, R.M.S., Iftikhar, S., Akbar, R. and Rahman, A., 2023. Evaluating Oviposition Deterrent, Larvicidal and Repellent Effects of Different Plant Extracts and Their Combinations against Aedes aegypti.

9. Mondal, P. and Patra, A., 2024. Sustainable exploitation of citrus for pest, disease and nutrient management. In Bio-Inoculants in Horticultural Crops (pp. 255-267). Woodhead Publishing.

10. Gupta, R.I.C.H.A. and Barros, R.A.F.A.E.L.A., 2024. Bioconversion: citrus fruit peel waste from hospitality sector to fashion sector. J. Environ. Prot. Ecol., 25, pp.813-824.

11. Šafranko, S., Šubarić, D., Jerković, I. and Jokić, S., 2023. Citrus by-products as a valuable source of biologically active compounds with promising pharmaceutical, biological and biomedical potential. Pharmaceuticals, 16(8), p.1081.

12. Saikia, M.N., 2023. Dedicated to my beloved parents Dr. Anjan Saikia & (Doctoral dissertation, assam agricultural university jorhat).

13. De Paiva Silva, G.T., Figueiredo, K.G., Alves, D.S., de Oliveira, D.F., Silva, G.H., de Souza e Silva, G.T., de Oliveira, M.S., Biondi, A. and Carvalho, G.A., 2023. Survival and demography of the tomato borer (Tuta absoluta) exposed to citrus essential oils and major compounds. Agriculture, 13(3), p.538.

14. Chakraborty, S., Goel, K., Rasal, V., Paul, K. and Mandal, D., 2025. A Comprehensive Review: Exploring Bioactive Compounds of Citrus Fruit Peels for Therapeutic and Industrial Applications. Food Science and Engineering, pp.54-69.

15. Mounira, G.M., 2024. Essential oils and their bioactive molecules: recent advances and new applications. Essential Oils-Recent Advances, New Perspectives and Applications

16. Abdul-Rahaman, A.I. and SV, K., PA, and Bashir, B. 2022. Phytochemical properties of biobased oils and their application for maintenance of citrus fruits quality: a review. Journal of Postharvest Technology, 10(2), pp.101-119.

17. Srivastava, S., 2023. aromatherapy: a synergy therapy.

18. Gupta, A., Jeyakumar, E. and Lawrence, R., 2021. Journey of limonene as an antimicrobial agent. Journal of Pure & Applied Microbiology, 15(3).

19. Minamisawa, M., 2021. Physiological Functions Mediated by Yuzu (Citrus junos) Seed-Derived Nutrients. In Citrus-Research, Development and Biotechnology. IntechOpen.

20. Warghane, A., Saini, R., Dhiman, N.K., Khan, K., Koche, M., Sharma, A., Gade, R.M., Halami, P. and Das, A., 2023. Value-addition in citrus processing industry waste through enzyme technology. In Value-Addition in Agri-food Industry Waste Through Enzyme Technology (pp. 177-190). Academic Press.