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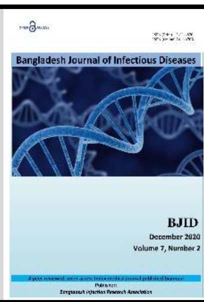


Effectiveness of Coffee Plant Extracts and Green Nanoparticles for Mosquito Control of the Dengue Vector Aedes aegypti: A Comprehensive Review

Yousef Abdulwahab[1,2], Mohammed Al-Shmery[2], Ahyar Ahmad[3], Isra wahid[4], Paulina Taba[5]

[1]Department of Medical Laboratories, Faculty of Medical Sciences, Taiz University, Taiz, Yemen; [2]Department of Medical Laboratories, Faculty of Medical Sciences, Al-Saeed University, Taiz, Yemen; [3]Department of Chemistry, Faculty of Mathematics and Natural Sciences, Hasanuddin University, Makassar, Indonesia; [4]Department of parasitology, Faculty of Medicine, Hasanuddin University, Makassar, Indonesia; [5]Department of Chemistry, Faculty of Mathematics and Natural Sciences, Hasanuddin University, Makassar, Indonesia

Abstract

This comprehensive review examines the efficacy and environmental impact of coffee plant extracts and green nanoparticles as biocontrol agents for mosquitoes. Mosquitoes pose a significant public health threat by transmitting diseases such as malaria, dengue, Zika, and yellow fever. However, the use of insecticides for mosquito control raises concerns about the development of resistance and environmental and human health impacts. As an alternative, biocontrol strategies that utilize natural predators, parasites, and pathogens have gained attention. Coffee plant extracts have shown larvicidal, ovicidal, and repellent properties against mosquitoes, whereas green nanoparticles, particularly copper and silver nanoparticles, exhibit insecticidal activity. These alternatives offer advantages such as environmental friendliness, reduced resistance risks, and targeted mosquito species control while minimizing harm to non-target organisms. However, challenges exist in the mass production and distribution of biocontrol agents as well as their susceptibility to environmental factors. Ongoing research is aimed at developing more effective biocontrol agents for mosquito-borne disease prevention. This review provides valuable insights into the potential of coffee plant extracts and green nanoparticles for mosquito control, their efficacy, and the environmental considerations associated with their use. [*Bangladesh Journal of Infectious Diseases, December 2024;11(2):172-195*]

Keywords: Coffee plant; green nanoparticles; copper nanoparticles; mosquito control; environmental impact

Correspondence: Yousef Abdulwahab, Department of Medical Laboratories, Faculty of Medical Sciences, Al-Saeed University, Taiz, Yemen; **Email:** youdefahmef@gmail.com; ORCID: https://orcid.org/0009-0009-4019-5141

Introduction

Mosquitoes belong to the family Culicidae and are known to transmit various diseases, including malaria, dengue fever, Zika virus, and Chikungunya. *Aedes aegypti* and Aedes albopictus are the two most common mosquito species in Indonesia and are responsible for transmitting diseases such as chikungunya, Zika, and dengue fever. Vector control plays a crucial role in preventing the spread of these diseases[1]. Mosquito larvae primarily breed in standing fresh water, although some species can utilize brackish water or specific conditions in flowing streams. Different mosquito species have different habitat preferences, including stream pools, rainwater pools, tree holes, and plant leaf axils[2]. The behavior of Aedes mosquitoes, particularly Aedes aegypti, has been extensively studied. They are highly anthropophilic and tend to bite daily. *Aedes aegypti* is adaptable and can breed in various habitats, including urban areas. These mosquitoes are attracted to humans and exhibit multiple bites before egg-laying. The behavior of *Aedes aegypti* and Aedes albopictus mosquitoes can vary, with differences in resting behavior, feeding activity, and activity patterns[3].

Methodology

Literature Search: A systematic search was conducted using online databases like PubMed, Scopus, Web of Science to identify relevant studies published up to [2023]. Keywords such as "coffee plant extracts," "green nanoparticles," "mosquito control," "efficacy," and "environmental impact" were used to retrieve relevant articles.

Selection Criteria: Articles were screened based on predefined inclusion and exclusion criteria. Inclusion criteria included studies that assessed the efficacy and/or environmental impact of coffee plant extracts and green nanoparticles for mosquito control. Articles focusing on other biocontrol agents or unrelated topics were excluded.

Data Extraction: Relevant data from selected articles were extracted, including study design, experimental methods, mosquito species targeted, concentrations or formulations of coffee plant extracts or green nanoparticles used, efficacy measures, environmental impact assessments, and any adverse effects reported.

Efficacy Assessment: The efficacy of coffee plant extracts and green nanoparticles in mosquito control was evaluated based on larvicidal, ovicidal, adulticidal, repellent, or other relevant measures reported in the included studies. The effectiveness of these biocontrol agents against different mosquito species and life stages was analyzed.

Environmental Impact Evaluation: The environmental impact of coffee plant extracts and green nanoparticles was assessed by examining their potential effects on non-target organisms, such as beneficial insects or aquatic organisms. Studies reporting on the persistence, degradation, and potential accumulation of these agents in the environment were analyzed.

Data Synthesis and Analysis: The findings from the included studies were synthesized and analyzed to provide an overview of the efficacy and environmental impact of coffee plant extracts and green nanoparticles for mosquito control. Any limitations or gaps in the existing literature were identified

Mosquito Control

Mosquito control involves eliminating breeding sites and targeting larvae and adults. Recent studies have shown that environmental modifications, larviciding, and biocontrol is effective in reducing mosquito populations. New approaches, such as sound-based mosquito traps, are emerging as valuable tools for mosquito control[4]. Insecticides play a crucial role in combating pests with a diverse range of available options. In the past, alternative methods, such as plant extracts and sulfur, have been used. The development of synthetic insecticides during World War II has led to affordable and efficient options. Pyrethroids replace hazardous compounds and are specifically screened to minimize their impact on non-target organisms and ecosystems[5]. Emerging compounds are required to have novel modes of action, reduced resistance risks, and environmental friendliness. Innovative insecticide classes, including uncouplers, oxadiazines, diacylhydrazines, and compounds derived from natural sources, offer promising prospects for effective control[6]. Although chemical insecticides play an important role in agriculture, they must be used carefully to minimize negative impacts on human health and the environment. Studies have shown negative effects on butterfly survival, feeding, and bee populations as well as increased toxicity of pesticide mixtures to aquatic organisms[7]. Therefore, the use of chemical insecticides should be balanced with potential risks by employing the lowest effective dose and targeted application to avoid harm to non-target organisms.

Insecticide Resistance

Insecticide resistance refers to the ability of certain insect populations to survive exposure to insecticides designed to kill them. This resistance can occur because of genetic mutations or adaptations in the insect's physiology, rendering the insecticide less effective in controlling their population. The problem of insecticide resistance has become widespread and poses a significant challenge to mosquito control[8]. To combat this issue, it is crucial to regularly monitor mosquito populations for their resistance to different types of insecticides. By implementing integrated management strategies, including mechanical control, sanitation, and educational actions to reduce breeding sites, we can lessen the reliance on chemical control methods. By diversifying the types of insecticides used and regularly rotating them, the development of resistance can also be mitigated [9]. There are several mechanisms by which mosquitoes develop insecticide resistance. These mechanisms include target site insensitivity, increased detoxification enzyme activity, and reduced penetration of the insecticide into the mosquito's body; insecticide resistance not only affects mosquito control efforts, but also has significant implications for agriculture. Insecticide resistance in agricultural pests can lead to reduced crop yields and increased economic losses for farmers [10]. Mosquitoes are a major public health threat, transmitting a wide range of diseases including malaria, dengue, Zika, and yellow fever. The widespread use of insecticides to control mosquitoes has led to the development of resistance as well as environmental and human health concerns. Biocontrol strategies offer promising alternatives to insecticides, using natural predators, parasites, and pathogens to suppress mosquito populations.

Various biocontrol strategies have been developed.

Predators: Predatory fish, such as Gambusia affinis and Poecilia reticulata, are widely used to control mosquito larvae in aquatic habitats. Other predators such as bats, birds, and dragonflies also play a role in mosquito control.

Parasites: A number of parasitic organisms, including nematodes, fungi, and bacteria, can infect and kill mosquitoes. For example, the nematode Romanomermis culicis is a highly effective parasite for mosquito larvae.

Pathogens: Certain bacteria and viruses can be used to control mosquitoes. For example, Bacillus thuringiensis var. israelensis (Bti) is a selective mosquito larvicide widely used in public health programs.

Biocontrol strategies have several advantages over the use of insecticides. They are generally more environmentally friendly and are less likely to lead to resistance. Biocontrol agents can also be targeted to specific mosquito species, which can help reduce their impact on non-target organisms. However, biocontrol strategies also face challenges. One challenge is that some biocontrol agents are difficult to mass-produce and distribute. Another challenge is that biocontrol agents can be affected by environmental factors such as temperature and pH[11]. Despite these challenges, biocontrol strategies are an increasingly important part of mosquito control. Several research projects are underway to develop new and more effective biocontrol agents.

Mosquito Controlling Plants and Their Derivatives

Plant extracts are utilized to create mosquito control products such as repellents, larvicides, and adulticides. These products deter mosquitoes from biting and kill mosquitoes at different stages of their life cycle. Common mosquito repellent plants include citronella, eucalyptus, lavender, lemongrass, peppermint, and thyme. These plants can be used in various ways, such as by applying their essential oils to the skin, burning dried leaves or stems, or growing plants around homes and gardens[12]. Certain plants, such as neem, garlic, chili pepper, turmeric, and ginger, exhibit larvicidal properties against mosquitoes. Extracts derived from these plants can be applied to water bodies where mosquito larvae breed. Plants such as pyrethrum, chrysanthemum, lantana, catnip, and mint have adulticidal properties. These extracts can be used to develop sprays, coils, and other products that are effective in killing adult mosquitoes. Ongoing research is focused on developing new mosquito control products using plant extracts. For instance, a combination of neem and citrus oils has been found to be effective in repelling and killing mosquitoes[13]. Another study discovered that a compound derived from garlic plants was effective in killing mosquito larvae [14]. Plant extracts are a promising alternative to synthetic insecticides for mosquito control. These extracts can be used to create effective and environmentally friendly mosquito control products.

***Coffee Arabica* Plant:** *Coffee Arabica*, native to Ethiopia, is the oldest and most popular species of coffee worldwide, contributing to approximately 60.0% of the world's coffee supply. It thrives in high-altitude regions, between 3,000 and 6,000 ft above sea level, and requires a mild climate with moderate rainfall. Plants have a slow growth rate, taking approximately three to four years to reach maturity. *Coffee Arabica* beans are renowned for their high-quality and intricate flavor profiles. They are often described as having a smooth chocolatey taste with hints of caramel, fruit, and nuts. Flavor characteristics can vary based on the growing conditions, processing methods, and roasting levels.

These beans are a rich source of antioxidants and other beneficial compounds that protect the body against free radicals, which can lead to diseases, such as cancer and heart disease. *Coffee Arabica* beans also contain caffeine, which is a stimulant that enhances alertness and energy levels. Apart from its use as a beverage, *Coffee Arabica* has also been utilized for medicinal purposes. Its extract exhibits anti-inflammatory and antimicrobial properties and has been shown to be effective in treating skin conditions, such as eczema and psoriasis.

Findings from the literature[15-16] on *Coffee Arabica* include the following:

- *Coffee Arabica* beans are good sources of antioxidants.
- *Coffee Arabica* extract possesses anti-inflammatory and antimicrobial properties
- The *Coffee Arabica* extract exhibited insecticidal and antimicrobial properties.
- *Coffee Arabica* extract has been effective in treating skin conditions, such as eczema and psoriasis.
- There is a potential for *Coffee Arabica* to reduce the risk of type 2 diabetes

Coffee Arabica offers numerous health benefits and diverse applications. It is a sought-after crop owing to its high-quality coffee beans and medicinal properties[15,16].

Biochemical Composition of *Coffee Arabica*

Coffee Arabica is a complex mixture of over 800 biochemical compounds, including caffeine, antioxidants, and other beneficial compounds. The biochemical composition of *Coffee Arabica* varies depending on the variety of coffee beans, growing conditions, and processing methods. Caffeine is one of the most important biochemical compounds found in *Coffee Arabica*. Caffeine is a stimulant that can improve alertness and energy levels. It is also known to have several other health benefits such as reducing the risk of type 2 diabetes and Parkinson's disease[17]. Other beneficial biochemical compounds found in *Coffee Arabica* include[18]:

Chlorogenic acids: Chlorogenic acids are antioxidants that have been shown to have a number of health benefits, such as reducing blood pressure and improving blood sugar control.

Trigonelline: Trigonelline is a compound that gives coffee a characteristic aroma. Trigonelline has also been shown to have several health benefits such as improving cognitive function and reducing the risk of type 2 diabetes.

Melanoidins Melanoidins are compounds formed during roasting. Melanoidins have been shown to have several health benefits such as reduced inflammation and improved gut health.

Coffee Arabica's biochemical composition offers a rich array of compounds with potential health benefits and contributes to its distinctive characteristics.

Mosquito Larvicidal and Repellent Activity of Coffee Plants

Coffee plants have been shown to have larvicidal and repellent activities. This is because of the presence of various compounds in coffee plants, such as caffeine, quinic acid, and chlorogenic acids.

Table 1: Coffee Plants Exhibit Larvicidal and Repellent Properties Against Mosquitoes

Study	Title	Methods	Results	LC50
19	Spent Coffee Grounds and Novaluron Are Toxic to *Aedes aegypti* (Diptera: Culicidae) Larvae	Not reported	Complete mortality was observed after 48 h of exposure to 50 g/L	50 g/L
20	Larvicidal effect of some traditional Saudi Arabian herbs against Aedes	Not reported		4.34 g/L
21	aegyptilarvae, a vector of dengue fever	Not reported	the light roasted used coffee grounds at the concentration of 125 mg/mL was the best in	Not reported

Study	Title	Methods	Results	LC50
			inhibiting the larvae survival.	
22	The Comparative Study of Arabica Used Coffee Grounds and Temephos in Controlling the *Aedes aegypti* Larvae	Laboratory study using Aedes albopictus larvae	Coffee grounds repelled gravid female mosquitoes and inhibited larval development	Not reported
23	Coffee and its waste repel gravid Aedes Albopictus females and inhibit the development of their embryos	Laboratory study using *Aedes aegypti* larvae	caffeine and coffee grounds blocks development and causes death of *Aedes aegypti* in the larval stage.	Not reported
24	Attractiveness of bioinsecticides caffeine and used coffee grounds in the choice of oviposition site by *Aedes aegypti* (Diptera: Culicidae)	Laboratory study using *Aedes aegypti* larvae	Coffee grounds were effective in killing *Aedes aegypti* larvae and inhibiting their development	33.66 g/L
25	Efficacy of coffee grounds as a bio-larvicide against *Aedes aegypti* (L.)	Laboratory study using *Aedes aegypti* larvae	The fumigant formulation was found to effectively control 100% of the adult mosquitoes	Not reported

This table 1 summarizes the key information from each study.

Thanasoponkul et al[19]: Exposure to 50 g/L of spent coffee grounds resulted in complete mortality of *Aedes aegypti* larvae after 48 hours. LC50 = 50 g/L.

Sharawi[20]: Traditional Saudi Arabian herbs exhibit larvicidal activity against *Aedes aegypti* larvae, with an effective concentration of 4.34 g/L. LC50 = 4.34 g/L.

Tangtrakulwanich et al[21]: Light roasted used coffee grounds at a concentration of 125 mg/mL showed the best inhibition of larvae survival. LC50 = Not reported.

Satho et al[22]: Coffee grounds repelled gravid Aedes albopictus females and inhibited larval development. LC50 = Not reported.

Monteiro Guirado et al[23]: Caffeine and coffee grounds blocked larval development and caused death in Aedes aegypti. LC50 = Not reported.

Aditama and Zulfikar[24]: Coffee grounds effectively killed *Aedes aegypti* larvae and inhibited their development. LC50 = 33.66 g/L.

Nakano[25]: The fumigant formulation derived from coffee grounds effectively controlled 100% of the adult mosquitoes. LC50 = Not reported.

Nanotechnology

Nanotechnology involves manipulating substances at the atomic and molecular levels, and has applications in various industries. Nanomaterials have unique properties owing to their high surface area and are used in healthcare, energy, and manufacturing sectors. Examples include the use of nanoparticles for targeted drug delivery in healthcare, development of solar cells and batteries in energy, and creation of materials with unique properties in manufacturing.

Potential future applications include nanobots for medical procedures, molecular computers for advanced computing, and self-healing materials[26].

Nanomaterials can be classified based on their origin, dimensions, and structural configuration.

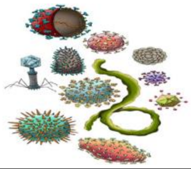
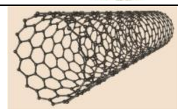
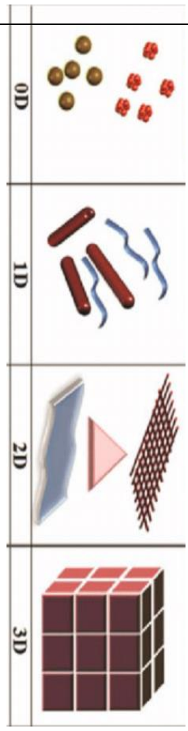
Origin-based classification distinguishes between natural and engineered nanomaterials. Dimension-based categorization classifies nanomaterials based on their size and morphology as 1D nanowires, 2D nanosheets, 3D nanostructures, and 0D nanoparticles.

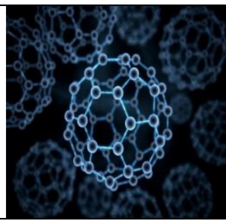
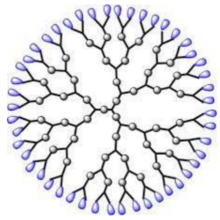
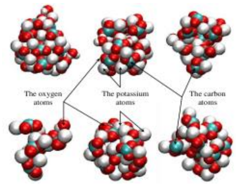
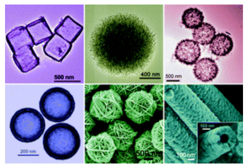
Structural-configuration-based classification categorizes nanomaterials based on their composition and organization, including crystalline nanomaterials, amorphous nanomaterials, core-shell structures, and composite nanomaterials[27]. Nanotechnology is a rapidly advancing field with significant potential, and it is important to consider both the benefits and risks associated with its application. Understanding the latest developments in nanotechnology is crucial for understanding its impact on various industries and society as a whole.

Significance and Applications

The classification of nanomaterials is crucial for their effective application in various fields. It aids in the design of targeted drug delivery systems in medicine by engineering nanoparticles to transport medications to specific locations in the body. In the field of electronics, categorization aids the construction of nanoscale devices with accurate measurements and optimal electrical characteristics. In addition, the classification of nanomaterials plays a significant role in energy generation and storage, contributing to the development of highly effective solar cells, supercapacitors, and batteries. Furthermore, it advances materials science and industrial processes by facilitating the development of new materials and improving production methods.

Table 2: Class of Nanomaterials

Classification	Type	Shapes	Examples	Photo
Based on origin	Natural Nanomaterials	Nanomaterials which are present naturally in nature	Virus, Clay, Natural Colloids, Fullerenes, Graphene	
Based on origin	Artificial Nanomaterials	Engineered nanomaterials prepared by well-defined mechanical and fabrication process	Carbon Nanotubes, Quantum Dots	
Based on dimension	0-D	Nanomaterials have dimensions in all the 3 directions	Metallic Nanomaterials (Silver, Gold, Copper), Quantum Dots	
Based on dimension	1-D	In such structures one dimension of the nanomaterials is outside the nanometer range.	Nanowires, Nanotubes, Nanorods	
Based on dimension	2-D	These nanostructures have two dimensions outside the nanometer range.	Nanofilms, Nanowalls, Nanosheets	
Based on dimension	3-D	All dimensions of 3D nanostructures are outside the nanometer range.	Bulk Materials Composed of Individual Blocks Within the Nanometer Scale	

Classification	Type	Shapes	Examples	Photo
Based on structural configuration	Carbon Based Nanomaterials	These nanomaterials are ellipsoids, tubes hollow sphere, fullerenes, nanotubes.	Ellipsoids, Tubes Hollow Sphere, Fullerenes, Nanotubes	
Based on structural configuration	Dendrimers	These nanostructures are highly branched. They are highly symmetric, monodispersed and spherical compounds.	Highly Branched, Highly Symmetric, Monodispersed and Spherical Compounds	
Based on structural configuration	Composites	They are multiphases solid nanostructures in which at least one of the phases have one, two or three dimensional within the nanoscale	Multiphases Solid Nanostructures	
Based on structural configuration	Metal Based Materials	These nanomaterials are made of metals which include nanogold, metal oxides, nano silver, quantum dots etc	Nanogold, Metal Oxides, Nanosilver, Quantum Dots	

Overall, the categorization of nanomaterials is vital for their successful utilization in various fields[28]. Class of Nanomaterials: As indicated in Table (2), nanomaterials are divided into groups according to their origin, size, and structure.

The Elements Metal and Metal Oxide

The use of metal nanoparticles (NPs) in various fields, including medicine, diagnosis, environmental cleaning, catalysis, antibacterial agents, electronics, cosmetics, biotechnology, packaging, and coatings, holds great promise. Copper nanoparticles (CuNPs) are particles smaller than 100 nm that can be applied in lubricants, polymers, metallic coatings, inks, and skin care products, enhancing the performance of lithium-ion batteries and exhibiting potential in medicine, drug delivery, cancer treatment, and insecticide use[29]. Silver nanoparticles (AgNPs) are gaining attention in biomedicine owing to their antibacterial, therapeutic, and catalytic properties. They are used in various applications, such as textile engineering, water purification, dental resin composites, ion exchange fibers, and medical equipment surface coatings to prevent microbial colonization and biofilm formation. Gold nanoparticles (AuNPs) are valuable in bio-applications, such as labeling, delivery, heating, and sensing[30,31]. Metal oxide nanoparticles (NPs) have emerged as a novel class of materials in the pharmaceutical industry and other health-related applications. These NPs are biocompatible, enabling the immobilization of enzymes and selective sensing of biomolecules. Various metal-oxide NPs, including CuO, NiO, ZnO, MnO2, Fe2O3, TiO2, and CeO2, have been extensively studied for their electrochemical detection capabilities[32].

Synthesis of NPs

Nanoparticles (NPs) can be synthesized using two main approaches: bottom-up and top-down methods. In the bottom-up method, nanomaterials are constructed by assembling atoms, molecules, or nanoclusters using biological and chemical techniques. Common bottom-up methods include sol-gel, spinning, pyrolysis, chemical vapor deposition (CVD), and biosynthesis[33]. On the other hand, the top-down method involves reducing bulk materials to obtain nanoscale particles through physical and chemical techniques. Techniques, such as nanolithography, thermal decomposition, laser ablation, mechanical milling, sputtering, and pyrolysis, are commonly used. However, these methods may introduce surface defects, internal stress, and contamination of the resulting nanoparticles. They can also be costly because of their high temperature and pressure requirements[34].

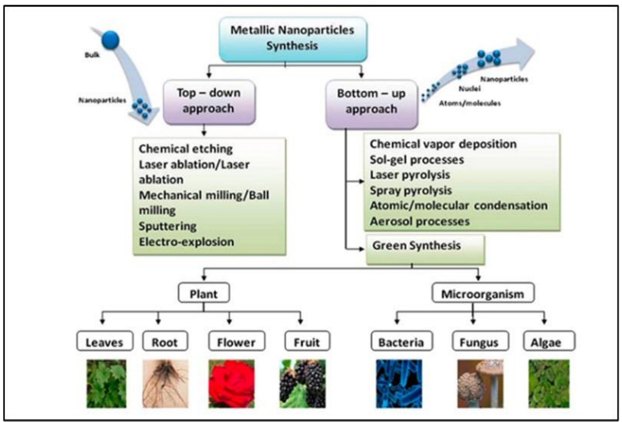


Figure 1: Schematic of various approaches for the synthesis of NPs adapted from[33].

In contrast to the top-down approach, the constructive method offers advantages in terms of producing high volumes of nanoparticles with a more uniform chemical composition and fewer surface imperfections at a lower cost. However, it is important to consider the potential hazards associated with the chemical synthesis of nanoparticles, such as carcinogenicity, genotoxicity, cytotoxicity, and general toxicity. Therefore, there is a growing focus on developing "green" nanoparticles using the principles of green chemistry, which prioritize eco-friendliness, energy efficiency, and convenience[35].

The 12 principles of green chemistry serve as guidelines for designing and conducting chemical processes that minimize environmental impact. These principles include waste prevention over cleanup, maximizing the use of all atoms in the starting materials, using and generating less hazardous substances, designing safer chemicals, choosing safer solvents and auxiliaries, designing energy-efficient processes, utilizing renewable feedstocks, minimizing unnecessary derivatives, utilizing catalysis for safer reactions, designing products that degrade harmlessly, employing real-time analysis for pollution prevention, and creating inherently safer chemical processes[36].

Synthesis of NPs from Biological Sources

Nanoparticles (NPs) can be synthesized using biological sources such as plants, microbes, and proteins. Plant-mediated synthesis of nanoparticles offers several advantages, including the availability of readily accessible plant extracts, biocompatibility, minimal contamination, large-scale production capability, cost-effectiveness, and the use of phytochemicals as reducing and stabilizing agents[37]. The intracellular synthesis of NPs by plants occurs through the process of bioaccumulation, where plants take up metal ions at a faster rate than they are eliminated. This accumulation can lead to the production of reactive oxygen species (ROS), which plants counteract through detoxification. Phytochelatins, Metallothionein, cysteine-rich and oligopeptides, enzymatic antioxidant systems, phenolic compounds, and flavonoids play essential roles in sequestering metal ions and maintaining ROS homeostasis[38]. Extracellular synthesis of NPs using plant extracts offers advantages, such as avoiding the use of toxic chemicals and stringent aseptic conditions required for microorganism-mediated synthesis. Plant extracts act as natural capping agents and stabilize the nanoparticles. This process is simple, efficient, cost-effective, and rapid. Different parts of plants, including the roots, stems, leaves, flowers, pods, latex, and bark, have been utilized for NP synthesis. Metallic salts dissociate into anions and cations, with the cations forming hydroxyl complexes. Crystallite growth occurs when hydroxyl complexes become supersaturated and capping agents from plant extracts hinder the growth of high-energy atomic planes. Reducing agents donate electrons to convert metal ions into nanoparticles, while stabilizing agents prevent nanoparticle aggregation and promote the production of smaller nanoparticles. Plant extracts contain polyphenols, amino acids, polysaccharides, organic acids, and proteins, which facilitate the formation of metallic nanoparticles by suppressing the superoxide-driven Fenton reaction [37].

Phytochemical-mediated synthesis of NPs

Phytochemicals, including alkaloids, polyphenols, terpenoids, antioxidants, glutathione, quinone, amino acids, organic acids, alcoholic compounds, sugars, proteins, and polysaccharides, play a crucial role in the synthesis of nanoparticles (NPs) mediated by secondary metabolites. Flavonoids are particularly prominent in the orchestration of NPs synthesis.

Table 3: Various Plant Used in The Synthesis NPs and Their Applications

Botanical Names	NPs	NP size (nm)	Application	Ref.
Anacardium occidentale	gold	10 to 60	Antimicrobial,Anticancer	40
Dracocephalum kotschyi	gold	5 to 21	Anticancer	41
Euphorbia fischeriana Root	gold		Antioxidant	42
Camellia sinensis	silver	4 to 50	Antibacterial	43
Ferula gumosa, Ferula latisecta, Leaf	silver	20 to 80	Antibacterial	44
Musa acuminata colla L. flower	silver	Nanoclusters	Antibacterial, Antifungal	45
Trianthema portulacastrum Extract	Zinc oxide	25 to 90	Cytotoxic, Cytotoxic, Antibacterial, Antifungal, Antioxidant	46
Punica granatum Extract	Zinc oxide	32.98 to 81.84	Cytotoxic Antibacterial	47
Tecoma castanifolia Extract	Zinc oxide	70 to 75	Antiseptic, Antioxidant, Antitumor	48
Ocimum tenuiflorum Extract	Copper oxide	20 to 30	Antibacterial	49
Moringa oleifera Extract	Copper oxide	35 to 95	Antifungal	50
Eichhornia crassipes Leaves	Copper oxide	28	Antifungal	51
Gloriosa superba Leaves	Copper oxide	5 to 10	Antibacterial	52
Artocarpus heterophyllus Extract	Titanium dioxide	15 to 20	Cytotoxic, antibacterial, anticancer	53
Citrus sinensis fruit	Titanium dioxide	20 to 50	Antibacterial, Cytotoxic, Anticancer	54

Table 4: Various Algae Used in The Synthesis NPs and their applications

Algae	NPs	Size (nm)	Applications in Agriculture	Ref.
Ulva armoricana	Ag	12.5	Antibacterial	55
Chlorella vulgaris	Ag	40 to 90	Catalyst for the synthesis of quinolines	56
Neodesmus pupukensis	Au and Ag	5 to 34	Antioxidant, antimicrobial	57
Gelidiella acerosa	Au	5 to 117	antibacterial, antioxidant	58
Tetraselmis indica	ZnO	20 to 40	Fabric, cosmetic, biomedical, food wrapping	59
Padina boryana	Pd	11	Antibacterial, anticancer	60
Macrocystis pyrifera	CuO	2 to 50	N.M	61
Botryococcus braunii	Cu and Ag	10 to 70 (Cu), 40 to 100 (Ag)	Antimicrobial	62

Table 5: Various Fungi Used in the Synthesis NPs and Their Application

Fungi	NPs	Size (nm)	Applications in agriculture	Ref.
Phanerochaete chrysosporium	ZnO	50	Antimicrobial	63
Trichoderma harzianum	Ag	21	Antioxidant, antibacterial	64
Rhizopus oryzae	MgO	20	Germicide, Insecticidal, and Tanning	65

Fungi	NPs	Size (nm)	Applications in agriculture	Ref.
			Treatment	
Morchella esculenta	Au	16	Biomedical	66
Aspergillus sydowii	Ag	1-24	Fungicidal and antiproliferative action to HeLa cells	67
Aspergillus flavus	Cu	2-60	Biomedical	68
Ganoderma lucidum	Ag	15-22	Antimicrobial, antiseptic, antimycotic	69
Periconium species	ZnO	16-78	Germicide and antioxidant	70
Fusarium solani	Au	40-45	Antitumor	71
Trichoderma harzianum	Ag, CuO	5-18	Biotechnological method	72

Table 6: Various Bacteria Used in the Synthesis NPs and Their Application

Bacteria	NPs	NP size (nm)	Application	Ref.
Actinobacter species	Au	5–500	Antimicrobial, fungicidal, nano compost	73
Haloferax volcanii	Au	*10*	Antiseptic activity, Nano biosensors	74
Deinococcus radiodurans	Au	*43*	*Antibacterial action*	75
Acintobacter species	Au	*15*	*Antioxidant action*	76
Escherichia coli	Ag	100	stimulant of plant growth, antibacterial action, and antifungal action	77
Bacillus licheniformis	Ag	18–63	Fungicidal effect	78
Pseudomonas deceptionensis	Ag		antibacterial action and bio film suppression	79
Pseudomonas fluorescens	Ag	5-50	Antibacterial activity pesticide	80
Sporosarcina koreensis	Ag	varied	Antibacterial action	81
Acinetobacter sp.	Ag	10	Fungicidal - biofilm inhibition	82
Pseudomonas rhodesiae	Ag	20-100	Antibacterial action	83
Streptomyces capillispiralis *Streptomyces zaomyceticus* *Streptomyces pseudogri*	Ag	23-63 11-36 11-44	Antibacterial action Antifungal action Larvicidal	84
Haloalkaliphilic Streptomyces	Ag	16	Antibacterial action Antifungal action	85
Streptomyces griseus	Cu	5-50	fungicides	86
Lactobacillus casei	Cu	30–75	Plant fertilizer	87

Table 7: Summarizes the Common Techniques That Used for Characterizing Nanoparticles

Techniques	Instruments	Size Distribution	Agglomeration State	Shape	Surface Area	Chemical Composition
Spectroscopy Techniques[92]	Visual ultraviolet spectroscopy					
	X-ray Diffraction					
	FTIR analysis					
Microscopy Techniques[93]	(Scanning Electron Microscopy) SEM					
	(Transmission Electron Microscopy) TEM					
	(Scanning Probe Microscopy) SPM					

Specific functional groups, such as carboxyl, sesquiterpenes, amide groups, alkynes, and hydroxyl groups in monoterpenoids, interact with plant extracts, such as those from Acacia mearnsii bark, resulting in the formation of silver nanoparticles[39]. Nanoparticles are produced using microbiological techniques. Numerous microorganisms, including prokaryotes and eukaryotes, algae, fungi, bacteria, and actinomycetes, have been used to synthesize NPs both intracellularly and extracellularly (Table 4).

Characterization of NPs

Nanoparticles (NPs) have emerged as a new class of materials with applications ranging from medicine to electronics. However, their unique properties, such as their small size and high surface area, can also pose challenges in terms of characterization. Characterization of NPs typically involves assessing their size, shape, surface area, polydispersity, and stability Various diagnostic methods have been used to study the produced NPs based on different features such special functional classes, light scattering and absorption potentials, and so on. In most cases, UV-visible spectroscopy is utilized to confirm the stability and synthesis of NPs[88]. The features of NPs, including composition and concentration, surface characteristics, surface functional groups, and atomic organization, are measured using Fourier - transform infrared (FTIR) spectroscopy[89]. The location, size, and morphology of NPs can be seen by transmission electron (TEM), scanning electron microscopy (SEM), and atomic force microscope (AFM)[90]. The crystalline structure is determined via X-ray diffraction (XRD)[91].

Nanoparticles NPs from *Coffee Arabica* plants: *Coffee Arabica* plants have been utilized for the green synthesis of various nanoparticles (NPs) with diverse applications. Saha et al. [94] employed green coffee bean extract to synthesize bismuth nanoparticles (BiNPs), which exhibited a spherical shape with diameters ranging from 20 to 40 nm. Nadagouda et al[95] reported the green synthesis of silver nanoparticles (AgNPs) using roasted dry Coffea arabica seed extract, resulting in AgNPs with sizes ranging from 20 to 60 nm and a face-centered cubic symmetry. AL-Hashimi[96] observed strong antimicrobial activity of AgNPs synthesized using roasted dry Coffea arabica seed extract.

Chien et al[97] demonstrated the use of coffee extract as a green reductant for synthesizing AgNPs on carbon microspheres. Abdelmigid et al[98] successfully synthesized zinc oxide nanoparticles (ZnO NPs) using coffee ground extracts, which exhibited antibacterial properties and lower cytotoxicity compared to chemically synthesized NPs. Haridas et al[99] utilized *Coffee Arabica* leaf extracts (CAE) for the eco-friendly synthesis of AgNPs as biosensors, demonstrating excellent sensing performance for amino acids. Yust et al[100] explored the use of spent coffee grounds (SCGs) for the green synthesis of gold and silver NPs, effectively utilizing SCG extracts as reducing agents. Abel et al[101] developed a green deposition method for synthesizing ZnO NPs using coffee leaf extraction, resulting in highly crystalline cubic-shaped NPs. Other authors focused on the green synthesis of copper oxide nanoparticles (CuO NPs) using coffee extracts as reducing agents, which exhibited photocatalytic degradation activity[102]. Other writers produced iron oxide nanoparticles (Fe2O3-NPs) using coffee seeds aqueous extract, resulting in cubic-shaped particles with sizes ranging from 23.2 nm to 37.5 nm[103].

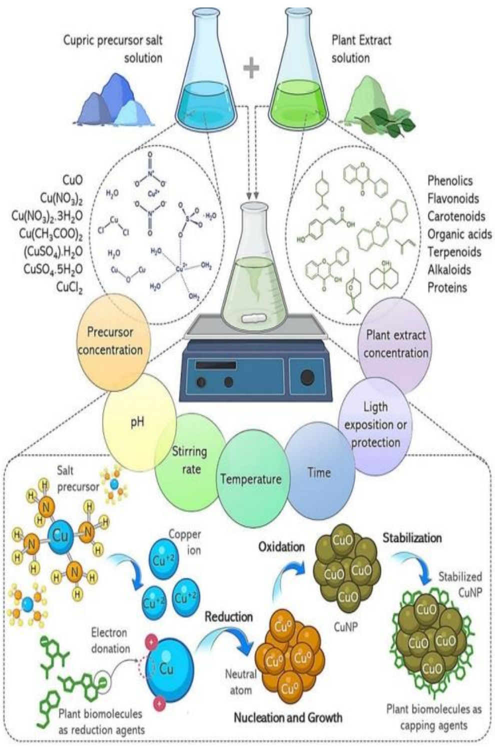


Figure II: shows the process of nanoparticle biosynthesis using metallic copper precursor salts and plant extracts. The compounds in the extracts reduce copper ions, leading to the formation of copper nanoparticles that are stabilized by interacting with other plant compounds[111].

Table 8: of CuNPs synthesized using some plant extracts

Plant	Precursor	NPs Characteristics	Applications	Ref.
Azadirachta indica Hibiscus rosa-sinensis, Murraya koenigii, Moringaoleifera, and Tamarindus indica	CuO	Particles are spherical and range in size from 9.8 to 10.77 nm.	antioxidant activity and cytotoxicity	113
Kigelia africana	Cu(CH3COO)2	The study does not report the morphology or size of NPs, it focuses only on antimicrobial activity.	Antimicrobial activity	114
Centella asiatica	CuCl2 ·2H2O MnO2	Cu/MnO2 nanocomposites, size range 10-30 nm.	High catalytic activity for the reduction of inorganic and organic dyes	115
Camelia sinensis	CuCl2.	Agglomerated form with an average size of 60 ± 6 nm.	Dye degradation against Antibacterial activity	116
Ageratum houstonianum	CuCl	Size around 80 nm, agglomerate, and not specific shape. NPs behave as a semiconductor.	Antiviral action	117
Ehretia acuminata	CuCl 2H_2O	NPs of 500 nm. The. shape was not reported. Green NPs and phytochemicals were coated on a cotton textile surface.	Antiviral	118
Aloe vera	Cu(NO3)2-3H2O	Monoclinic phase, average particle size of 20 nm	Bactericidal against fish pathogens	119
Galeopsis herba	Cu(NO3)2-3H2O	Size of 5-10 nm with spherical shape	High antioxidant activity and catalytic activity	120
Hagenia abyssinica	Cu(NO3)$_2$.3H2O	Spherical, hexagonal, triangular, cylindrical, and prismatic shapes. Size range of 10-50 nm	Antibacterial	121
Cinnamomum zelanicum	Cu(NO3)2-3H2O	Spherical morphology with size of 19.55 to 69.70 nm	Cardioprotective against isoproterenol-	122
Berberis vulgaris	Cu(NO3)2-3H2O		Positive effect on various physiological and biochemical characteristics of Solanum lycopersicum seedlings	123
Carum carvi	Cu(NO3)2-3H2O	Regular and homogenous spherical distribution	Antimicrobial activity	124

Plant	Precursor	NPs Characteristics	Applications	Ref.
		with 12.4 nm size		
Syzygium alternifolium	CuSO4-5H2O	Spherical, 2-69 nm	Antiviral	125
Falcaria vulgaris	CuSO4-5H2O	Spherical, 20 nm	Nematicidal, antibacterial	126
Orobanche aegyptiaca	CuSO4-5H2O	Spherical, <50 nm	Antioxidant, antifungal, antibacterial, wound healing	127
Gnidia glauca, Plumbago zeylanica	CuSO4-5H2O	Variable size, 5-93 nm	Antidiabetic	128
Eucalyptus camaldulensis	CuSO4-5H2O	Spherical, 41-65 nm	Antibacterial	129
Prunus nepalensis	CuSO4-5H2O	Spherical, 35-50 nm	Anticancer	130
Nigella sativa	CuSO4-5H2O	Size 98.23 nm	Antiobesity	131]
Zingiber officinale	CuSO4-5H2O	Crystalline, 60 nm	Antibacterial	132
Haplophyllum tuberculatum	Cu(NO3)2 3H2O	Amorphous particles, 85 nm	Nematicide	133
Krameria sp.	(CuSO4) 5H2O	Spherical NP's, 6.16 nm	Antioxidant, antimicrobial	134

On the other hand some scientist synthesized gold, silver, and selenium nanoparticles (Au, Ag, and Se NPs) using coffee bean extract under hydrothermal conditions, which exhibited bactericidal activity and low antioxidant activity[104]. Other scholars. created alumina nanoparticles using coffee extracts via a microwave-assisted method, resulting in spherical NPs with an average size of 50-200 nm[105]. some authors successfully synthesized iron nanoparticles (FeNPs) using coffee waste residues, which showed effectiveness in degrading chlorinated volatile organic compounds[106]. Other experts generated a cafestol–chitosan–ZnO NP system from coffee, which exhibited antibacterial properties against both Gram-positive and Gram-negative strains [07]. some authors used coffee bean extract as a natural oxidant for the green synthesis of metallic iron nanoparticles (n-Fe), which were effective in the removal of Orange II dye[108]. Other scholars successfully manufactured catalyst materials on coffee ground-derived carbon with desirable physical and electrochemical properties[109].

Copper Nanoparticles

Copper nanoparticles (CuNPs) have diverse applications in catalysis, electronics, energy storage, sensing, and biomedical fields. CuNPs can be synthesized using chemical reduction, electrochemical deposition, or green synthesis methods[110]. They possess desirable properties such as high electrical conductivity, catalytic activity, antimicrobial properties, and tunable optical characteristics[112]. These qualities make them suitable for various applications. However, challenges related to stability, toxicity, and scalability must be addressed for their successful implementation. Further research is needed to optimize synthesis techniques, understand potential impacts, and explore new applications. With ongoing advancements, CuNPs have the potential to revolutionize industries and contribute to technological progress in the future.

Copper NPs synthesized from *Coffee Arabica* plants: CuO nanoparticles were synthesized using coffee powder extract and copper sulphate pentahydrate. The nanoparticles exhibited spherical shapes with diameters ranging from 15 to 30 nm, as confirmed by XRD, UV-Vis, TEM, and SEM analyses. These CuO nanoparticles showed an inhibitory effect on testosterone levels in human serum, suggesting their potential role in hormone regulation[135]. In another study, copper oxide nanoparticles were synthesized using coffee extracts as reducing agents. These biosynthesized nanoparticles demonstrated promising photocatalytic activity in degrading Methylene blue dye[102]. Coffee bean extracts were used for cost-effective synthesis of nanoparticles. Although the antioxidant potency of these nanoparticles was reduced compared to air-oxidized nanoparticles, they still exhibited free-radical scavenging activity and were biocompatible with human dermal fibroblasts.

Additionally, the nanoparticles demonstrated antiproliferative effects on MCF7 breast cancer cells, especially the copper sulfate-oxidized nanoparticles[136]. Cupric oxide nanoparticles were successfully synthesized using coffee powder extracts through the sol-gel method at various calcination temperatures. Characterization techniques confirmed the formation of single-phase copper oxide nanoparticles with a monoclinic crystal structure[137]. In a different study, copper nanoparticles were synthesized using a green method that utilized a solution of green coffee bean extract as both a reducing and stabilizing agent. These nanoparticles exhibited excellent stability with average particle sizes ranging from 5 to 8 nm. They also acted as efficient and recyclable catalysts for the rapid reduction of methylene blue[138].

Green-synthesized nanoparticles and mosquitocidal effects

The World Health Organization (WHO) has established guidelines for testing larvicides and pupicides, which involve rearing mosquito larvae and evaluating their susceptibility to these substances. The larvae are hatched from collected eggs in containers filled with water and food, maintained at a specific temperature. The time for hatching and larval development varies depending on the mosquito species. Some researchers also collect larvae from natural habitats for testing purposes[139]. Table 1 summarizes the larvicidal and pupicidal activities of nanoparticles derived from various green sources.

Table 9: Mosquitocidal Activities of Nanoparticles Derived from Various Green Sources.

Plant	Metal Precursors	Shape and Size	Activity and Species	LC50	Ref.
Syzgium cumini	Zn(CH3COO)2, 1mM	Spherical, 50-60 nm	Larvicidal and Ovicidal (Ae. aegypti)	51.94	140
Ficus racemosa	AgNO3, 1 mM	Cylindrical, 250.06 nm	Larvicidal (Cx. quinquefasciatus and Cx. gelidus)	12.00	141
Piper longum	AgNO3, 1 mM	Spherical, 25-32 nm	Larvicidal (Ae. aegypti, An. stephensi and Cx quinquefasciatus)	8.97	142
Holarrhena antidysenterica	AgNO3, 1 mM	Spherical, 32 nm	Larvicidal (Ae. aegypti L. and Cx quinquefasciatus)	93	143
Ammannia baccifera	AgNO3, 1 mM	Triangular and hexagonal, 10-30 nm	Larvicidal (An. subpictus and Cr. quinquefasciatus)	29.54	144
Tridax procumbens	CuSO4, 1 mM	Spherical, 16 nm	Larvicidal (Ae. aegypti)	4.21	145
Grewia asiatica	CuSO4.5H2O, 1 mM	Spherical, 60-80 nm	Larvicidal (Ae. aegypti)	100	146
Annona squamosa	CuSO4, 1 mM	Spherical, 5.99-24.48 nm	Larvicidal (An. stephensi)	170	147
Mangifera indica	TIO(OH)2, 5 mM	Spherical, 30±5 nm	Larvicidal (An. subpictus and Cr. quinquefasciatus)	5.84	148
Momordica charantia leaves	TICI, 5 mM	Irregular	Larvicidal and pupicidal (An. stephensi)	3.43	149
Morinda citrifolia roots	TIO(OH)2, 5 mM	Spherical, oval, and triangular	Larvicidal (An. stephensi, Ae. Aegypti and Cx. quinquefasciatus)	05.03	150]
Vitex negundo, leaves	TiCl4, 5 mM	Spherical	Larvicidal (An. subpictus and Cx.	7.52	151

Plant	Metal Precursors	Shape and Size	Activity and Species	LC50	Ref.
			quinquefasciatus)		
Clausena dentate, leaves	H2SeO, 1 mM	Spherical,	Larvicidal (An. stephensi, Ae. aegypti and Cx. quinquefasciatus)	240.71	152
Ceropegia bulbosa, tuber	H2SeO, 40 mM	Spherical	Larvicidal (An. albopictus)	250	153
Nigella sativa, seed	H2SeO3, 0,01 mM	Clusters,	Larvicidal (Cx. pipiens)	17.39	154
Nilgirianthus ciliates leaves	H2SeO 30 mM	Spherical	Larvicidal (Ae. aegypti)	0.92	155
Opuncia ficus-indica peel	Na2SeO3, 2 mM	Spherical	Larvicidal (Cx. pipiens)	75.41	156
Ulva lactuta seaweed	Zn(CH3COO)2. $2H_2O$	Sponge-like	Larvicidal (Ae. aegypti)	38	157
Myristica fragrans fruit	Zn(NO3)2.6H2O	Semispherical, hexagonal	Larvicidal (Ae. aegypti)	5	158
Cocos nucifera fruits	Pd(OAc)2 1 mM	Spherical, 323 nm (TEM)	Larvicidal and ovicidal (Ae. aegypti)	288.88	159
Citrus limon leaves	PdCl, 1 mM	Spherical, 1.5-18.5 nm (TEM)	Larvicidal (An. stephensi)	10.83	160
Nephrolepis exaltata whole plant	FeCl3.6H2O 0.01 M	Spherical, 30-70 nm (TEM)	Larvicidal (An. stephensi)	25	161
Aegle marmelos, leaves	NiCl2 1 mM	Triangular, 80-100 nm (SEM)	Larvicidal (An. stephensi, Ae. aegypti and Cx. quinquefasciatus)	534.83	162
Cocos nucifera, fruits	Ni (OAc)2 1 mM	Cubical, 47 nm (TEM)	Larvicidal (Ae. aegypti)	259.24	163[
Artemisia vulgaris, leaves	HAuC, 1 mM	Spherical, triangular, and hexagonal	Larvicidal (Ae. aegypti)	74.42	164
Moringa oleifera, leaves	HAuC4.3H2O 1 mM	Spherical, oval, triangular, and pentagonal	Larvicidal (Cx. quinquefasciatus)	8.24	165

The data highlights the focus on metal nanoparticles, particularly silver nanoparticles, for controlling mosquito vectors. Ae. aegypti, Cx. Quiquefasciatus, and An. stephensi were the most frequently tested mosquito species. The tested nanoparticles showed LC_{50} values ranging from 5 to 500 ppm. It is important to note that the tested mosquito species were mostly laboratory strains rather than wild populations.

Aedes aegypti **larvicidal by green synthesis copper NPs:** The larvicidal activity of copper oxide nanoparticles (CuO NPs) synthesized from *Pistia stratiotes* leaf extract was evaluated against *Aedes aegypti* and *Culex quinquefasciatus* mosquitoes. At a concentration of 15 ppm, the CuO NPs resulted in 100% mortality of *Culex quinquefasciatus* larvae. The LC50 and LC90 values for *Culex quinquefasciatus* were determined as 4.23 ppm and 13.67 ppm, respectively. *Aedes aegypti* larvae exhibited 93.0% mortality, with LC50 and LC90 values of 4.23 ppm and 13.67 ppm[166]. *Rubia cordifolia* bark extracts were used to synthesize biocompatible copper oxide nanoparticles (CuONPs) with an average particle size of 50.72 nm. The CuONPs demonstrated significant larvicidal activity against *Aedes aegypti* (65 ± 8.66%), *Anopheles stephensi* (80 ± 13.69%), and *Culex quinquefasciatus* (72 ± 13.04%) mosquito larvae[167]. *Strobilanthes cordifolia* plant extracts were utilized for the eco-friendly production of FeNPs/CuNPs. CuNPs exhibited larvicidal activity against *Aedes aegypti* mosquitoes, resulting in a 65% larval mortality rate.

The LC50 and LC90 values were determined as 6.32 µg/mL and 51.30 µg/mL, respectively[168]. Copper sulphide nanoparticles (CuSNPs) synthesized through sonochemical irradiation exhibited larvicidal effects against *Aedes aegypti* mosquitoes, causing 100.0% mortality within 24 hours at a concentration of 7 ppm. Morphological changes and damage to the larvae's epithelium layer were observed[169]. Silver nanoparticles synthesized using bacterial isolates exhibited larvicidal activity against Aedes aegypti, *Anopheles stephensi*, and *Culex quinquefasciatus* mosquito larvae, causing damage to various internal structures. Histopathological analysis revealed damage to epithelial cells, food bolus, basement membrane, muscles, and midgut segments[170]. Selenium nanoparticles (SeNPs) synthesized using *Nilgirianthus ciliatus* leaf extracts demonstrated strong insecticidal activity against *Aedes aegypti* mosquito larvae, with an LC50 of 0.92 mg/L. Histopathological analysis revealed damage to the midgut and caeca regions [155]. Zinc oxide nanoparticles (ZnO NPs) synthesized using Indigofera tinctoria leaf extracts exhibited significant larvicidal activity against Aedes aegypti.

The nanoparticles caused destructive changes in larval body tissues, particularly in fat cells and the midgut[171]. Nickel metal organic frameworks (Ni-MOFs) showed larvicidal properties against *Aedes aegypti* mosquitoes, causing structural alterations in treated larvae. Tissue fragmentation, damage to epithelial cells, and organ collapse were observed[172]. Studies on larvicidal effects and biochemical outcomes of nanoparticles reported changes in enzyme levels. Copper nanoparticles derived from Annona muricata, *Azadirachta indica*, and *Pongamia glabra* extracts reduced total protein levels in *Aedes aegypti* and Aedes albopictus larvae. Fungal-synthesized titanium dioxide nanoparticles increased glucose levels in *Aedes aegypti* mosquitoes, while silver nanoliquids reduced total body glucose levels in *Phenacoccus solenopsis* insect larvae [173–175].Silica nanoparticles decreased alkaline phosphatase enzyme levels in Culex pipiens larvae, while syzygium aromaticum chitosan nanoparticles increased enzyme activity in Culex pipiens mosquitoes[176,177]. There have been several studies indicating that the increased toxicity of insecticides and nanoparticles can lead to elevated levels of the Aspartate aminotransferase (AST) enzyme in mosquito larvae. Halawa et al. [178] found that chlorpyrifos and *Bacillus thuringiensis israelensis* treatment resulted in increased AST enzyme levels in Culex pipiens larvae. Sugeçti and Büyükgüzel[179] demonstrated that the application of oxfendazole in *Galleria mellonella* insect larvae induced oxidative stress, leading to elevated AST enzyme levels. Durairaj et al[180] observed that chitosan-based silver nanoparticles decreased the LDH enzyme levels in Culex and Anopheles larvae. Conversely, Tunçsoy et al[181] found increased LDH levels in *Galleria mellonella* insects treated with copper oxide nanoparticles.

In summary, nanoparticles can enter cells, interact with cellular components such as sulfur-containing proteins and phosphorus-containing DNA, and cause denaturation of organelles and enzymes. These interactions can disrupt the cell membrane, the proton motive force responsible for cellular energy production, and lead to loss of cellular function and cell death[182].

Impact of Nanoparticles on DNA Damage In Insects

Nanomaterials can induce DNA damage in cells, primarily through the generation of reactive oxygen species (ROS). Transition metal ions released from nanoparticles can catalyze reactions that produce highly reactive hydroxyl radicals (OH•), leading to DNA damage[183]. While genotoxicity data on nanoparticles in insects is limited, studies have shown their potential to cause DNA damage in various organisms. High concentrations of Cd telluride quantum dots were found to accumulate in tissues and cause DNA damage in *Elliptio complanate*[184]. Exposure to Ag nanoparticles resulted in cellular and DNA damage, as indicated by the expression of stress-related genes in Japanese medaka. Also Zebrafish treated with Ag nanoparticles exhibited DNA damage, including double-strand breaks and activation of the p53 gene[185]. Higher concentrations of zero-valent nano iron induced DNA damage in the sperm of *Mytilus galloprovincialis*[186]. CuO nanoparticles and Ag nanoparticles were shown to induce DNA damage in hemolymph cells of *M. galloprovincialis*, with the extent of damage increasing over time[187]. In Drosophila melanogaster, the presence of Ag nanoparticles led to the accumulation of reactive oxygen species, triggering apoptosis, DNA damage, and activation of antioxidant pathways[188].

Ecotoxicity of NPs on Non-Target Organisms

Artemia species, also known as brine shrimp, are highly tolerant to a wide range of salinity levels and are commonly used to assess the toxicity of chemicals and pollutants in aquatic environments. They serve as biomarkers for evaluating environmental toxicity. A recent study examined the effectiveness of a green copper nano-pesticide derived from M. robertsii on A. nauplii and A. salina. The copper nanoparticles (CuNPs) showed reduced toxicity compared to mosquito larvae and stored grain pests. The LC_{50} and LC_{90} values for A. nauplii ranged from 166.731 to 450.981 µg/mL, while for A. salina, they ranged from 293.901 to 980.153 µg/mL. These findings suggest that CuNPs have potential as safe and effective pesticides in aquatic environments [147]. Another study investigated the production of copper oxide nanoparticles using Spinacia oleracea leaf extract and their impact on Artemia salina. The study found that the cytotoxic effect of copper oxide nanoparticles increased with higher concentrations (250, 500, 1000, 2000, 6000, and 10,000 g/mL) on both cysts and live organisms of A. salina[189.]

Conclusion

In conclusion, our comprehensive review highlights the potential of coffee plant extracts and green nanoparticles as effective and environmentally friendly biocontrol agents for mosquito control. Mosquitoes are a significant public health threat, and the use of chemical insecticides has limitations and environmental concerns. Coffee plant extracts, with their larvicidal, repellent, and adulticidal properties, offer promising alternatives. Additionally, the integration of nanotechnology, specifically metal and metal oxide nanoparticles, shows potential for targeted control. However, further research is needed to evaluate the safety and efficacy of these approaches and consider their environmental implications. By combining diverse strategies and minimizing reliance on conventional insecticides, we can develop sustainable mosquito control methods that protect public health while preserving the environment.

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ORCID
Yousef Abdulwahab https://orcid.org/0009-0009-4019-5141
Mohammed Al-Shmery: https://orcid.org/0000-0001-6311-2534
Ahyar Ahmad https://orcid.org/0000-0002-0913-4721
Isra wahid https://orcid.org/0000-0002-6642-1401
Paulina Taba https://orcid.org/0000-0001-7327-5505

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