Bio Synthesis of Nanoparticles from Bio Waste and Its Application on Anti Corrosion, Antifungal and Paint Applications

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ABSTRACT

This study demonstrates the green synthesis of zinc oxide (ZnO) nanoparticles using pomegranate and orange peel extracts, with pomegranate proving more effective based on a UV-Vis absorption peak at 390 nm. SEM and DLS analyses revealed nanoparticle sizes ranging from 100–250 nm and an average hydrodynamic diameter of 238.7 nm (PDI 0.296). FTIR confirmed the presence of phytochemical capping agents, while XRD validated a hexagonal wurtzite structure. The nanoparticles exhibited strong antifungal activity, with 100 µL of ZnO formulation producing inhibition zones of 12 mm and 15 mm against *Aspergillus flavus* and *Aspergillus niger*, respectively. In corrosion resistance testing, ZnO-incorporated paint showed significantly less rust compared to normal paint after 10 days of salt spray exposure, and the nanoparticle spray visibly reduced rust within 5 minutes. These findings highlight the potential of fruit peel-derived ZnO nanoparticles as eco-friendly, multifunctional agents for antifungal coatings and corrosion prevention, aligning with green chemistry and sustainable waste utilization practices.

KEYWORDS: Zinc Oxide Nanoparticles, Green Synthesis, Antifungal Activity, Corrosion Resistance, Surface Protection.

1. INTRODUCTION

1.1 History

Even though early civilizations were ignorant of the nanoscale characteristics of nanoparticles, their utilization stretches back thousands of years. One of the oldest examples is the Roman Lycurgus Cup from the fourth century AD, which contains gold and silver nanoparticles that cause it to change color in response to light. Similar to this, European craftspeople in the Middle Ages unwittingly employed nanoparticles in stained glass windows, where minute metal particles interacted with light to create vivid hues. In 1857, Michael Faraday experimented with colloidal gold to examine its optical properties, marking the beginning of the scientific investigation of nanoparticles. However, the ability to view and work with materials at the nanoscale was only made possible by developments in electron microscopy in the 20th century. Nanoparticles are an important topic of current research because of the revolutionary applications in a variety of domains, such as materials science, electronics, and medicine, that have resulted from the formal development of nanotechnology in the late 20th and early 21st centuries.

1.2 Bio-Waste Utilization for Synthesizing Nanoparticles

As the need for environmentally friendly and sustainable nanomaterial synthesis grows, biological waste specifically fruit peels is being investigated as a potential substitute for physical and chemical processes. Polyphenols, flavonoids, alkaloids, and organic acids are among the many bioactive substances found in fruit peels, which are frequently thrown away as waste. By serving as stabilizing and reducing agents throughout the nanoparticle manufacturing process, these natural substances replace the requirement for dangerous chemicals. Among the many benefits of this green synthesis method are its affordability, environmental sustainability, and biocompatibility. Metal nanoparticles like zinc oxide (ZnO) have been effectively synthesized from the peels of a variety of fruits, including bananas, oranges, pomegranates, and mangos. When metal precursors interact with the phytochemicals found in the peels, a process known as bio-reduction takes place, producing nanoparticles that are more stable and useful. The use of fruit peel extracts to create nanoparticles has shown promise in environmental cleanup, agriculture, and medicine. Strong antibacterial, antioxidant, and catalytic qualities make them useful for crop protection, wastewater treatment, and medication delivery. In addition to encouraging waste valorization, using bio-waste for nanoparticle synthesis reduces the ecological impact of nanotechnology and is consistent with green chemistry principles. As research progresses, fruit peel-derived nanoparticles' commercial applications can be further enhanced and their contribution to a circular economy can be further explored by improving synthesis settings.

1.3 Synthesis of NPs via Green Synthesis Method

In place of traditional chemical and physical processes, the ecologically friendly process known as "green synthesis" of nanoparticles (NPs) uses biological sources such plant extracts, microbes, and bio-waste. This process produces nanoparticles in a sustainable and economical manner by doing away with the need for hazardous chemicals and unfavorable environmental conditions. Plant biocomponents such proteins, alkaloids, polyphenols, and flavonoids serve as organic stabilizing and reducing agents during the production of nanoparticles. Because of its ease of use, accessibility, and quick reaction speeds, plant-based synthesis is frequently chosen over other biological sources. Stable nanoparticles are created in this method when phytochemicals in plant extracts combine with metal salt precursors. Similarly, through their metabolic processes, microbes such as bacteria and fungi can convert metal ions into nanoparticles, creating distinct nanostructures. Further supporting the idea of waste valorization are bio-waste products, such as fruit peels and agricultural residues, which act as environmentally beneficial reducing agents. Green-synthesised nanoparticles have a wide range of uses in environmental science, agriculture, and medicine. They are appropriate for medicine administration, water purification, and crop protection because to their antibacterial, antioxidant, and catalytic qualities. By reducing environmental risks and improving biocompatibility, bio-based nanoparticle synthesis is more in line with green chemistry principles than conventional synthesis techniques. The goal of ongoing research is to enhance the production and functionality of nanoparticles for commercial applications by optimizing synthesis settings and investigating novel biological sources.

1.4 Fungal Growth on Walls

High humidity, inadequate ventilation, and excessive moisture can all contribute to the prevalent problem of fungus growth on walls. On surfaces like walls, ceilings, and wooden buildings, fungi like mold and mildew may grow quickly and flourish in moist environments. The perfect conditions for the germination and growth of fungal spores are provided by leaks, condensation, or water seepage. Fungal growth can have a musty smell and frequently manifest as black, green, or white spots. Stachybotrys (sometimes called black mold), Aspergillus, and Penicillium are prevalent indoor fungus species that can be harmful to one's health, particularly for those who have allergies or respiratory conditions. When spores from the fungi are breathed, they can induce allergic reactions, skin irritation, and breathing problems.

1.4.1 Antifungal Activity of Zinc Nanoparticles (ZnNPs)

The distinct physicochemical characteristics of zinc nanoparticles (ZnNPs), such as their high surface area-to-volume ratio, nanoscale size, and increased reactivity, have made them potent antibacterial agents. The production of reactive oxygen species (ROS), damage to the integrity of fungal cell membranes, and blockage of vital metabolic pathways are some of the processes that are thought to be responsible for their antifungal effectiveness. Fungal cell walls are impacted by ZnNPs, which causes increased membrane permeability, intracellular content leakage, and ultimately cell death. The main mechanism by which ZnNPs inhibit fungal growth is oxidative stress-induced cytotoxicity, in which ROS, including hydroxyl radicals (•OH) and superoxide anions (O_2^-), cause DNA damage, protein denaturation, and lipid peroxidation. The Zn^{2+} ions that are produced from the nanoparticles can also disrupt electron transport chains, interfere with enzyme activity, and prevent fungal cell proliferation. In fungus, several mechanisms work together to cause cell death akin to apoptosis. ZnNPs have shown potent antifungal action against a variety of harmful fungi, such as Fusarium species, Aspergillus niger, and Candida albicans. As biocompatible antifungal agents, zinc nanoparticles (ZnNPs) help reduce crop fungal infections and lessen the need for synthetic fungicides. In order to fight fungal infections with the least amount of damage to human cells, zinc nanoparticles (ZnNPs) are used in pharmaceutical formulations, antifungal coatings, and wound dressings. The biocompatibility and environmental friendliness of ZnNPs have been improved by the use of green synthesis techniques that make use of plant extracts, biopolymers, and microbial pathways. However, to maximize antifungal efficacy while reducing potential toxicity, it is still essential to optimize nanoparticle size, surface charge, and functionalization. Continuous studies in material science and nanomedicine are improving ZnNP formulations for specific antifungal uses, providing a safe and efficient substitute for traditional antifungal drugs.

1.5 Corrosivity

The propensity of a substance, typically a chemical, to harm or even destroy materials it comes into touch with particularly metals, skin, or other surface is known as corrosivity. Because extremely corrosive materials can degrade structures, produce leaks, or pose safety issues, it is a crucial consideration in sectors that deal with chemicals, pipelines, and storage tanks. Chemical interactions, frequently including moisture, oxygen, acids, or salts, cause corrosion. Corrosivity measurement aids in the selection of suitable materials, inhibitors, or protective coatings to guard against damage and guarantee long-term durability.

1.5.1. Anti-Corrosivity of Zinc Nanoparticles

Zinc nanoparticles (ZnNPs) are very useful in protective coatings because of their well-known anti-corrosive qualities. Because of their ability to produce dense barrier layers at the nanoscale, they keep corrosive chemicals, oxygen, and moisture from getting to the metal surface underneath. In order to prevent corrosion of the base metal, ZnNPs also offer sacrificial anodic protection, which involves preferred oxidation. Their capacity to self-heal is an additional benefit; the zinc ions that are liberated from the nanoparticles can aid in fixing small surface flaws, increasing durability. Because of these characteristics, ZnNPs are widely utilized to extend the life of metal structures in sectors like construction, automotive, and marine. In order to improve corrosion resistance, mechanical strength, and environmental sustainability, researchers are still investigating novel formulations that incorporate zinc nanoparticles (ZnNPs) into sophisticated coatings.

1.6. Incorporation of Nanoparticles in Paints

The use of nanoparticles in paints has transformed protective coatings by improving their functionality, longevity, and ability to withstand environmental influences. Nanoparticles including graphene, zinc, titanium dioxide, and silica are added to paints to enhance their mechanical strength, corrosion resistance, UV protection, and antimicrobial activity. Zinc nanoparticles (ZnNPs) function as sacrificial anodes in anti-corrosive paints, offering electrochemical protection by preferentially oxidizing and stopping the corrosion of metal substrates. In a similar vein, silica and graphene nanoparticles improve paints' barrier qualities by lowering oxygen and moisture penetration, while titanium dioxide (TiO_2) nanoparticles help paints self-clean and withstand UV rays, which stops surface deterioration over time. The maritime, automotive, aerospace, and construction industries all make extensive use of paints reinforced with nanoparticles because they provide long-term protection against adverse environmental conditions. Optimizing dispersion methods, binder compatibility, and environmentally acceptable formulations are the main areas of ongoing research to create high performance, sustainable paints infused with nanoparticles for use in commercial and industrial settings.

2. REVIEW OF LITERAURE

Gopalu Karunakara . *et al* . (2023) . The wide-ranging application of nanomedicine has been crucial to the worldwide healthcare sector in recent decades. Nanoparticles (NPs) can be obtained via biological acquisition techniques, which are inexpensive, non-toxic, and environmentally benign. This review provides up-to-date information on several ways to obtain nanoparticles as well as a thorough description of biological agents, including bacteria, fungus, yeast, algae, plants, and actinomycetes. When compared to the physical, chemical, and biological approaches for obtaining nanoparticles, the biological approach has significant advantages such as non-toxicity and environmental friendliness, which support their significant use in therapeutic applications. Researchers benefit from the bio-mediated, obtained nanoparticles, which can also be used to modify particles for safety and health. The important medicinal uses of nanoparticles, including antiviral, antifungal, antibacterial, anti-inflammatory, antidiabetic, and antioxidant properties, were also investigated. This review examines the numerous approaches put forth to characterize them and highlights the results of recent studies on the bio-mediated acquisition of new NPs. There are a number of benefits to the bio-mediated synthesis of NPs from plant extracts, such as low cost, environmental friendliness, and bioavailability. The biochemical mechanisms and enzyme reactions of bio-mediated acquisition have been analyzed by researchers, and the bioactive chemicals mediated by nanoparticle acquisition have been identified.

Shoyebmohamad F. Shaikh . ***el al*** **.(2023) .** As a great example of a technology that is currently evolving, nanotechnology enables the synthesis of designed nanomaterials, which have a great potential to produce products with significantly improved performances. At the moment, nanomaterials are employed in the manufacturing of electronics, cosmetics, surface coatings, and paints that are resistant to scratches. Furthermore, nanomaterials are being used in the study and development of applications related to drug targeting, cancer delivery, pharmacokinetics, sensors, healthcare, energy storage, biomedicine, photodetectors, photonics, and protein delivery. This editorial article's goal is to provide information about the basic concepts and emerging trends in the synthesis of nanomaterials, structural characterization, chemical and physical properties, and a variety of applications, all based on the Special Issue. In order to achieve this, relevant material will be discussed, along with synthesis techniques, properties, and opportunities related to the broad and fascinating field of nanomaterials. Although it would be impossible to cover every piece of literature on nanomaterials, this article will highlight some of the most important works from both the current literature and previous Special Issues. For the convenience of researchers, this article swiftly highlights the innovations and characteristics of a range of nanomaterials in one field, giving them crucial insights.

Muhammad Atif Irshad . et al . (2024) . Green nanotechnology holds great promise for the agricultural sector, especially because of its antifungal qualities, capacity to manage fungal diseases, and ability to lessen the need for chemical fungicides. Global agricultural damage from biotic stressors has been extensive, and green nanoparticles (NPs) have offered environmentally benign substitutes for conventional chemical treatments, which are often toxic and detrimental to the environment. If suitable studies are carried out to determine safe and sustainable applications as well as economical production techniques, green nanoparticles may prove to be a valuable instrument in contemporary agricultural operations and environmental cleanup. Research on green NPs' efficacy in agriculture sectors is still ongoing in order to comprehend their potential for sustainable agriculture and detect any hazards. In order to elucidate and comprehend the antifungal mechanisms of carbon and graphene nanotubes, green metallic nanoparticles, nanocomposites, and other types of nanomaterials, this report presents an update on research on green NPs utilizing data published on Science Direct over the previous 15 to 20 years. Compared to traditional fungicide methods, these green NPs have been shown to be more efficient against agricultural and human infections. They are highly effective against fungi that damage cereal crops, such as Candida species, Botrytis cinerea, and Fusarium oxysporum. Green synthesis techniques are used to create ecologically acceptable and economically viable green nanoparticles. Additionally, research is needed to determine the most effective ways to utilize green NPs for sustainable agriculture and crop production. Additionally, studies should be conducted to determine the most economical ways to produce and apply green nanoparticles in large-scale field settings where fungal invasion reduces agricultural productivity and impacts crop production worldwide.

Qiang Zhu . ***et al*** **.(2022).** Coating materials are used to protect, improve, and/or give the bulk materials or surface of the underlying object new functions and qualities. Since the manipulation of materials at the nanoscale can impart certain unique chemical, mechanical, thermal, surface, and photophysical properties that can be exploited to enhance functions required in urban built environments, nanotechnologies have been widely incorporated into functional coatings in recent years. Recent developments in a number of functional coating categories were compiled in this review paper, with a focus on how they may be used in smart and green buildings. Phase change materials (PCM) coatings, hydrophobic coatings, hydrophilic coatings, hydrocatalytic coatings, and coatings for lowering surface solar radiation were among them. From the manufacturing of the material to its use in various architectural components, this review attempts to give a broad overview of the research development on these chosen functional coating technologies.

Shaik Rubeena Yasmin . *el al* . (2021) . As the world's population grows rapidly, natural resources are being consumed more and more, producing greater byproducts that are wasted in enormous quantities. These biowastes will be used for human purposes using a variety of techniques. Utilizing these biowastes to create nanoparticles is one such option. Green synthesis is the term for this process. Applications for green produced nanoparticles are numerous in the physiochemical and biological domains. The transition between bulk materials and atomic or molecular structures is accomplished by these NPs (nanoparticles). This paper focuses on the production of green synthesized nanoparticles from a variety of agricultural wastes, including animal waste.

Sevakumaran Vigneswari . *et al* . (2021) . Significant advances in the medical sciences have surely been impacted by nanobiotechnology. The utilization of nanomaterials has enabled researchers to explore a wide range of illness treatments using less invasive techniques. Since they are nanoparticles and have antibacterial qualities, silver nanoparticles (AgNPs) have been studied for a variety of uses in the food, textile, water treatment, agriculture, and medical industries. The exceptional physical, chemical, and biological features of AgNPs are generally well-known. AgNPs have different properties depending on how they are made, and the biological approach has been used up to this point since it is quick, safe, and can create well-defined size and shape under ideal circumstances. However, the sustainability of biological or biobased production is a common problem. To remedy this problem, researchers have used a variety of tactics. One such strategy is the recent testing of agricultural biowastes, like fruit peels, for the synthesis of AgNPs. Utilizing biowastes is unquestionably economical and environmentally beneficial; additionally, it has been noted that the reduction process is quick, easy, and produces a respectably high yield. The purpose of this review is to discuss the advancements in the use of biowastes derived from fruits and vegetables to biologically produce AgNPs for use as antimicrobial coatings in biomedical applications**.**

Abdelghany S. Shaban . *et al* .(2024) . Fruit peel extract mediated by green synthesis of zinc oxide nanoparticles (ZnO-NPs) is becoming more and more popular because it is environmentally friendly and reasonably priced. Here, pomegranate peel extract was used as a stabilizing and reducing agent in the synthesis of ZnO-NPs. SEM, TEM-SAID, FT-IR, XRD, and particle size analysis were used to characterize the produced ZnO-NPs. The results showed that crystallinity developed and that the ZnO-NPs aggregated into spherical and hexagonal forms with an average diameter of 20 to 40 nm. In numerous applications, ZnO-NPs shown considerable antibacterial action against pathogenic germs, with MIC values of 125 and 250 µg/ml for Aspergillus niger and Aspergillus flavus, respectively, and 62.5 and 31.25 µg/ml for both Gram-positive and Gram-negative bacteria. Furthermore, ZnO nanoparticles demonstrated antioxidant activity with IC50 values of 240 and 250 µg/ml by DPPH and ABTS, respective. All ZnO-NP concentrations markedly increased barley seed germination and shoot height; the optimal concentrations were 2 and 12 ppm for 90% seed germination and 6.5 shoot height, respectively, while 2 ppm of ZnO-NPs produced the largest root extension (6 cm). As the nanoparticle dose and exposure length grew, the mitotic index decreased significantly, but it still increased at lower concentrations and exposure times. After 12 hours, most concentrations approached 100% suppression with a variety of chromosomal abnormalities. The researchers used a green synthesis approach to produce simple, eco-friendly, and effective multifunctional ZnO-NPs and gained a deeper knowledge of the cytotoxicity and genotoxicity of ZnO-NPs in plant cells.

Sandeep Yadav. *et al* .(2024). The role that green nanoparticles play in stopping the corrosion of several alloys, including copper, zinc, steel, and aluminum alloys, is covered in the article. Green nanoparticles are distinguished by their sustainable and eco-friendly manufacturing processes, which prioritize the use of natural ingredients. Traditional corrosion inhibitors have long been associated with environmental problems, which has prompted a move toward greener substitutes. The application of green nanoparticles, which are made from biodegradable and renewable resources, is one possible solution to these problems. Green nanoparticles have potent corrosion-inhibiting qualities and help achieve sustainability goals. Together, their roles make them vital contributors to a future where material safety and environmental consciousness coexist. In crucial industrial contexts, the review envisions a paradigm shift that necessitates a strong and environmentally responsible approach to corrosion prevention. As corrosion inhibitors, green nanoparticles have the potential to completely change the field of materials protection, opening up new avenues for research and development. According to the review's conclusion, these nanoparticles are essential to building a sustainable future where innovative solutions will boost both environmental health and industrial production. Lastly, research has also been done on the potential and challenges of using green nanoparticles for corrosion prevention in a sustainable.

H. Abd El-Wahab.*et al* . (2024). The green production of copper oxide and zinc nanoparticles using plant extracts is the main focus of this work. Based on characteristics such hydrogen ion concentration, oil absorption, moisture content, fineness of grinding, bleeding, and loss on igniting, the resultant metal oxides were examined using FT-IR spectroscopy, TGA, TEM, and zeta potential. They were also evaluated for their effectiveness as pigments. The outcomes verified that the produced ZnO and CuO nanoparticles showed the ability to generate nanoparticles with pigment-like potential in the 10–40 nm range. Tests were conducted on the physico-mechanical properties, corrosion resistance, heat resistance, and chemical resistance of two paint formulations that included these nanoparticles and silicon resins as binders. After being exposed to temperatures as high as 500 °C, the films containing the produced oxides showed no signs of degradation or color change, according to the study. After a 500-hour salt spray test, the paint films with ZnO nanoparticles outperformed those with CuO nanoparticles in terms of efficiency. According to these results, the produced mixed oxide nanoparticles show promise as heat-resistant pigment possibilities.

Lili He . *et al* . (2011). The present work examined the antifungal properties of zinc oxide nanoparticles (ZnO NPs) and their mechanism of action against two postharvest pathogenic fungi, namely Botrytis cinerea and Penicillium expansum. The amounts of ZnO NPs utilized were 0, 3, 6, and 12 mmol l^{-1}, and their diameters were 70 ± 15 nm. ZnO NPs' antifungal properties were investigated using Raman spectroscopy, scanning electron microscopy (SEM), and traditional microbiological plating. The morphological and cellular compositional changes of fungal hyphae treated with ZnO NPs were also characterized. The findings indicate that ZnO NPs can considerably suppress the growth of B. cinerea and P. expansum at concentrations higher than 3 mmol l^{-1}. When treated with ZnO NPs, P. expansum showed greater sensitivity than B. cinerea. Two distinct antifungal activity of ZnO NPs against B. cinerea and P. expansum are shown by SEM pictures and Raman spectra. Fungal hyphae were deformed as a result of ZnO NPs' impact on cellular processes, which in turn prevented B. cinerea from growing. Alternatively, ZnO NPs inhibited P. expansum's conidiophore and conidia development, which ultimately resulted in fungal hyphae mortality. According to these findings, ZnO NPs may be employed as a successful fungicide in applications pertaining to food safety and agriculture.

Rita Carvalho Veloso. *et al* . (2024) . This study investigates the incorporation of TiO2, SiO2, and ZnO nanoparticles into coatings for thermally improved façade systems in an effort to promote energy-efficient building and less environmental impact. A significant amount of energy is used in buildings, and façades are crucial to this. The impact of nanoparticle type, size, and material combination on thermo-optical performance was investigated through systematic analysis. Our findings reveal significant improvements in near-infrared (NIR) reflectance, a crucial factor in minimising heat absorption. With a color difference (ΔE) of 3.4, TiO2 nanoparticles exhibit a notable 50% increase in NIR reflectance. ZnO (28 percent, ΔE 3.2) and SiO2 (22 percent, ΔE 4.61) follow. Variations by application demonstrate how TiO2 in coatings for ETICS (Exterior Thermal Insulation Composite Systems), SiO2 in acrylic paints, and ZnO in dye compositions behave better. As a result, architects and builders can use dark colors in façade design while yet ensuring thermo-optical durability and efficiency. Our research helps shape the future of energy-efficient building materials and design techniques as the need for sustainable building practices increases. One crucial area for further research is examining the long-term stability of these coatings boosted by nanoparticles.

3. MATERIALS AND METHODS

3.1 Preparation Of Aqueous Extract

Pomegranate and orange peels were collected from local juice shops as part of a sustainable approach to utilizing bio-waste. The collected peels were thoroughly washed, shade-dried, and ground into a fine powder. For the preparation of the aqueous extract, 5 grams of the peel powder were mixed with 100 mL of distilled water. This mixture was then heated at 60°C for 30 minutes to facilitate the extraction of bioactive compounds. The resulting extract was filtered and used for further experimental procedures.

Fig 3.1 Aqueous Extract From Orange And Pomegranate Peels

3.2 Preparation Of Zno Nanoparticles

The synthesis of ZnO nanoparticles was initiated by adding 0.4069 grams of zinc oxide (ZnO) powder to 45 mL of distilled water. While continuously stirring the mixture, 5 mL of the prepared aqueous peel extract was gradually added. Stirring was continued for 3 hours to ensure thorough mixing and effective interaction between the extract and ZnO. This green synthesis approach facilitated the formation of ZnO nanoparticles, with the extract serving as a natural reducing and stabilizing agent.

Fig 3.2 Preparation Of Zno Nanoparticles

3.2 Antifungal Activity Of Zno-Pomo Nanoparticles

For antifungal activity, we have chosen two fungi: Aspergillus niger and Aspergillus flavus, as they are commonly found on the walls of houses, rooms, and over the paints

Fig 3.3 Aspergillus niger and Aspergillus flavus Fungus present on walls

3.2.1. Preparation Of Potato Dextrose Agar Plates

To prepare the growth medium, 30 g of potato was boiled in 150 mL of distilled water and sterilized in a pressure vessel for two whistles. Following sterilization, 3 g of agar and 3 g of dextrose were added to the resulting potato extract. The mixture was subsequently re-sterilized in the pressure vessel for eight whistles. After cooling, the medium was poured into two pre-sterilized Petri dishes one designated for *Aspergillus niger* and the other for *Aspergillus flavus* and allowed to solidify at room temperature for 20 minutes. Once solidified, the fungal cultures were aseptically inoculated onto the surface of the PDA plates. The plates were then transferred into an incubator, where the test samples were aseptically loaded at concentrations of 25, 50, 75, and 100 µL, with a 20 µL control applied at the center. The plates were incubated at room temperature for 48 hours. Antifungal activity was determined by observing and measuring the zone of inhibition around the sample application sites.

3.3 Preparation of Zinc Oxide Nanoparticle Based Anticorrosivity Spray.

The formulation of the anticorrosivity spray involved the following components: 40 mL of ZnO nanoparticle solution was used as the main active ingredient. Citric acid (5 g) served as the rust-dissolving agent, while 10 mL of ethanol was added to improve drying and penetration of the spray. Sodium benzoate (0.5 g) was included as a corrosion inhibitor to prevent future rust formation. Deionized water was used as the solvent to make up the total volume to 100 mL.

Initially, 5 g of citric acid was dissolved in 50 mL of deionized water. To this solution, 40 mL of ZnO nanoparticle solution was added and mixed thoroughly. Ethanol (10 mL) was then added slowly to the mixture while stirring continuously to ensure uniform blending. Next, 0.5 g of sodium benzoate was incorporated into the solution to inhibit further corrosion. The final volume was adjusted to 100 mL by adding additional deionized water. The mixture was stirred for 30 minutes to achieve complete homogenization and then transferred into a spray bottle for application.

Fig 3.4 Anti Corrosivity Spray

3.4 Incorporation Of Zno Nanoparticles With Paints

For the preparation of zinc nanoparticle-incorporated paint, 2 mL of a pre-dispersed aqueous zinc oxide (ZnO) nanoparticle solution was mixed with 8 mL of water-borne acrylic paint to obtain a total volume of 10 mL. The ZnO nanoparticle suspension was added slowly into the paint under continuous stirring for approximately 10-15 minutes to ensure homogeneous distribution of the nanoparticles within the paint matrix. The resulting mixture was then allowed to rest at room temperature for one hour to ensure stability and remove any entrapped air bubbles. The final formulation appeared visually uniform, with no observable sedimentation or phase separation, indicating good compatibility between the ZnO nanoparticle suspension and the water-borne paint.

3.4.1 Comparative Corrosion Testing Of Normal And Nanoparticle-Incorporated Paints On Metal Surfaces

To evaluate the effectiveness of zinc nanoparticles in enhancing corrosion resistance, two identical metal substrates were selected for coating. One metal surface was coated with normal water-borne paint, while the other was coated with zinc nanoparticle-incorporated water-borne paint. Prior to coating, both metal surfaces were cleaned thoroughly to remove any dust, oil, or oxide layers. The paints were applied uniformly using a brush and allowed to dry under ambient conditions for 24 hours. These coated samples were then used for further analysis to compare the anti-corrosive performance of the nanoparticle modified paint with that of the conventional paint.

Fig 3.5 Comparative Corrosion Testing Of Normal And Nanoparticle Incorporated Paints On Metal Surfaces

To simulate and accelerate the corrosion process, both coated metal samples were subjected to a salt spray test. A salt solution was prepared by dissolving 5 grams of sodium chloride (NaCl) in 15 mL of distilled water. This concentrated saline solution was sprayed evenly onto the surfaces of both samples once daily for a period of 10 days. The metals were kept in an open environment to allow natural air drying between each spray cycle. This procedure was intended to replicate aggressive corrosive conditions and evaluate the protective performance of the normal water-borne paint versus the zinc nanoparticle-incorporated paint. After the testing period, the extent of rust formation on each surface was visually assessed to determine the relative corrosion resistance.

4. RESULTS AND DISCUSSION

4.1 Characterization Of Nanoparticles

To confirm the successful synthesis and understand the properties of the ZnO nanoparticles, various characterization techniques were employed. UV-Visible spectroscopy was used to monitor the optical properties and confirm nanoparticle formation. Scanning Electron Microscopy (SEM) provided insights into the surface morphology and size of the particles. Dynamic Light Scattering (DLS) was utilized to determine the hydrodynamic size distribution and assess the stability of the nanoparticles in suspension. Fourier Transform Infrared Spectroscopy (FTIR) was used to identify the functional groups and bonding present in the nanoparticles. X-ray Diffraction (XRD) analysis was conducted to determine the crystalline structure and phase purity of the synthesized nanoparticles.

4.1.1 UV-Visible Spectroscopy Analysis

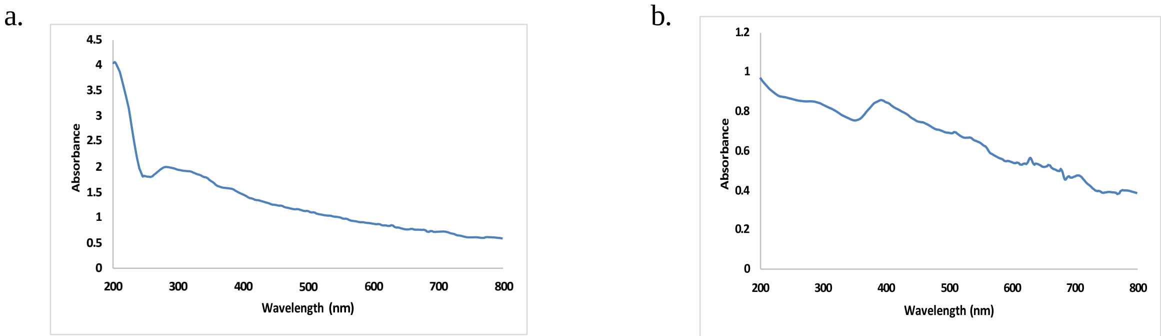


Fig 4.1 (a,b) UV-Visible Spectroscopy Analysis

The UV-Visible spectroscopy analysis revealed distinct absorption peaks for the ZnO nanoparticles synthesized using different fruit extracts. The ZnO nanoparticles prepared using pomegranate extract exhibited a strong and well-defined absorption peak at 390 nm, indicating the formation of nanoparticles with suitable optical properties. In contrast, the nanoparticles synthesized using orange extract showed a peak at 285 nm, which is less characteristic of typical ZnO nanoparticle absorption behavior. The absorbance intensity for the pomegranate sample was also more consistent and prominent, suggesting better particle formation and stability. Based on this comparison, the ZnO nanoparticles synthesized with pomegranate extract were selected for further characterization and application studies.

The observed UV-Vis absorption peak at 390 nm for the ZnO-pomegranate nanoparticles aligns well with the known surface plasmon resonance (SPR) behavior of ZnO nanoparticles, indicating successful synthesis and good optical quality. The relatively high wavelength peak may also suggest a narrower band gap and better interaction with visible light, which can be advantageous in applications like photocatalysis and UV-blocking coatings. On the other hand, the peak at 285 nm observed for the ZnO-orange nanoparticles is significantly lower and does not correspond well with typical ZnO nanoparticle spectra, suggesting incomplete or inefficient nanoparticle formation. This could be due to the lower concentration of reducing or stabilizing agents in the orange extract compared to pomegranate. Therefore, pomegranate extract was considered more suitable for green synthesis and selected for further processing and classification steps.

4.1.2 FTIR Analysis

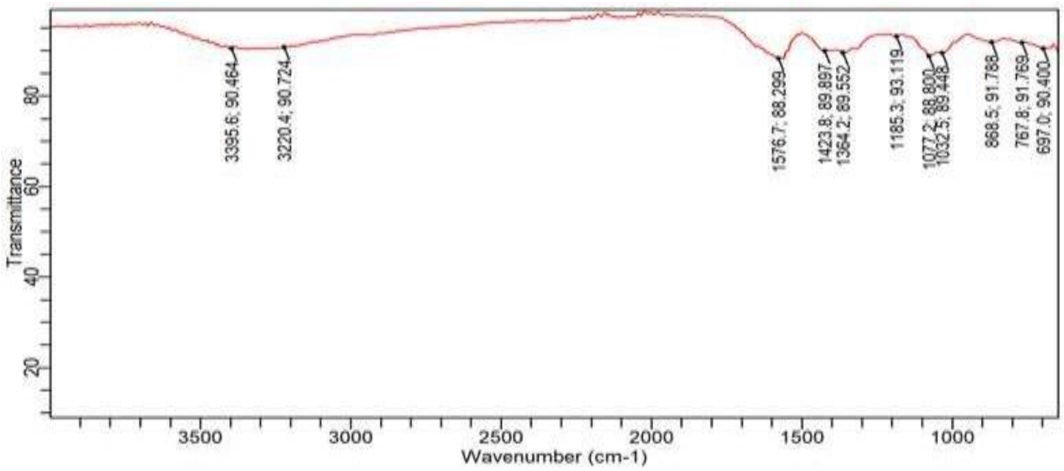


Fig 4.2 FTIR Analysis

The FTIR spectrum of the synthesized ZnO nanoparticles exhibited characteristic peaks that confirm the successful formation of ZnO and provide insights into the surface chemistry of the particles. Notably, distinct absorption bands observed at approximately 697 cm^{-1} and 767 cm^{-1} are attributed to ZnO stretching vibrations, confirming the presence of ZnO in the sample. The broad peaks in the region of 3220 cm^{-1} and 3395 cm^{-1} correspond to O–H stretching vibrations, which may indicate the presence of surface hydroxyl groups or adsorbed moisture a common feature in green-synthesized nanoparticles. Furthermore, peaks in the range of 1364–1576 cm^{-1} suggest the presence of C–H bending and C=O stretching, implying the existence of organic compounds or phytochemicals from the pomegranate extract that may act as natural capping or stabilizing agents. The broad spectral range from 4000–650 cm^{-1} ensures comprehensive detection of various functional groups, confirming the dual role of the plant extract in both reducing and stabilizing the ZnO nanoparticles.

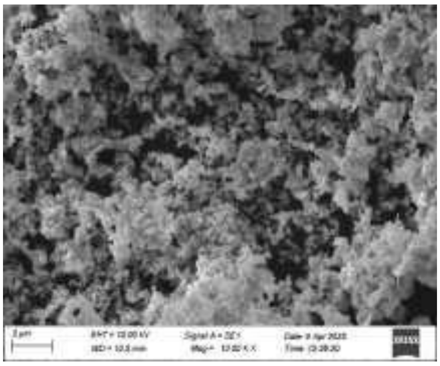
Table 4.1 FTIR Analysis

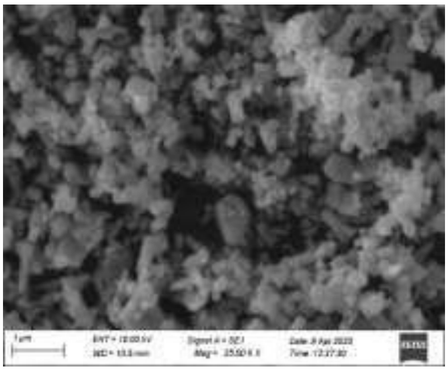
Peak Number	**Wavenumber (cm^{-1})**	**Intensity (%)**
1	697.01218	90.39998
2	767.83159	91.76912
3	868.46972	91.78846
4	1032.47258	89.44794
5	1077.20063	88.80027

6	1185.29343	93.11944
7	1364.20565	89.55195
8	1423.84305	89.89730
9	1576.66391	88.29922
10	3220.41989	90.72440
11	3395.60477	90.46380

4.1.3 Scanning Electron Microscopy Analysis

a.



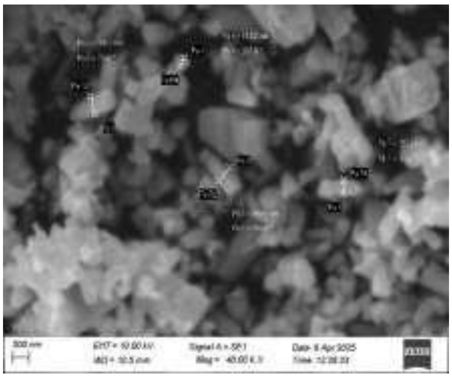


b.

Fig 4.3(a,b)ZnO-NPs-Low Magnification

The surface morphology and particle structure of the synthesized zinc nanoparticles were examined using Scanning Electron Microscopy (SEM). A series of high-resolution SEM images (Figures X.1 to X.6) revealed that the nanoparticles exhibited a generally spherical to slightly oval shape with smooth and compact surfaces. The overall distribution appeared moderately uniform, indicating successful particle formation during the synthesis process. No significant structural deformities or irregular morphologies were observed, suggesting good control over nucleation and growth phases.

a.



b.

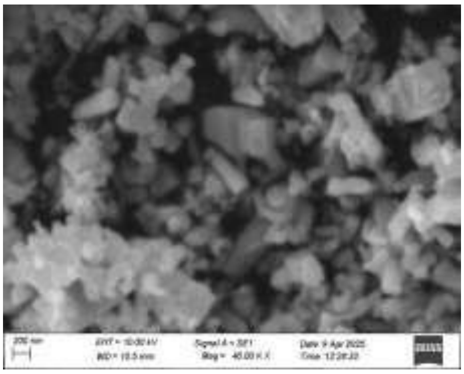


Fig 4.4 (a,b) ZnO-NPs-High Magnification

At higher magnifications, some degree of agglomeration was evident in the micrographs, which is commonly attributed to the intrinsic high surface energy of nanoparticles. Despite the clustering effect, individual particles were still distinguishable, and their morphology remained consistent throughout the samples. The absence of porous, flaky, or dendritic formations indicates a clean surface profile, further supporting the structural stability and phase purity of the zinc nanoparticles.

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a. b.

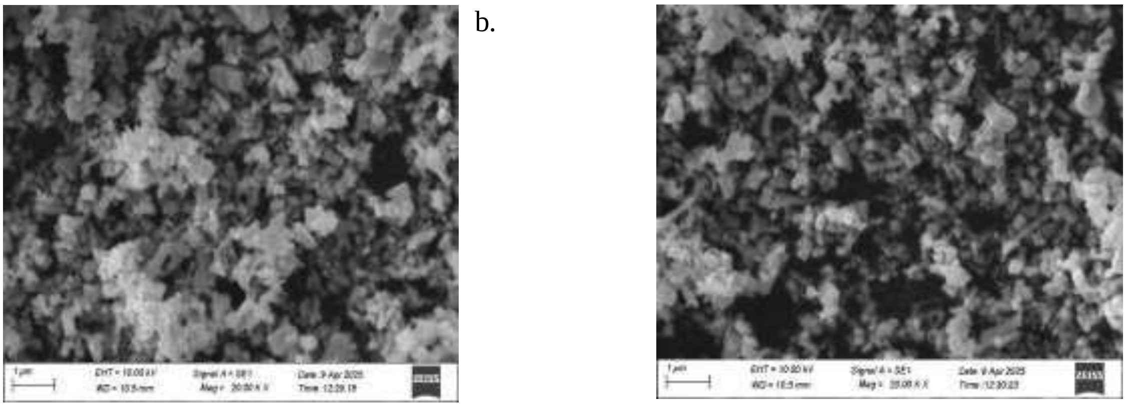

Fig 4.5 (a,b) ZnO-NPs Agglomeration

Visual estimation from the SEM images suggests that the particle sizes predominantly range between 100-250 nm. The fairly narrow distribution and uniform appearance indicate that the synthesis method employed was effective in producing nanoparticles with desirable physical characteristics. These features are particularly beneficial for surface-related applications, such as in protective coatings, where uniform morphology and nanoscale size can enhance barrier performance and functional behavior.

4.1.4 X-Ray Diffraction Analysis

X-ray diffraction (XRD) is a key technique for identifying the crystalline structure and phase purity of nanoparticles. It helps in confirming the formation of ZnO with a wurtzite structure and evaluates the crystallinity of the sample. The sharpness and position of the diffraction peaks reveal important structural information, validating the success of the synthesis process.

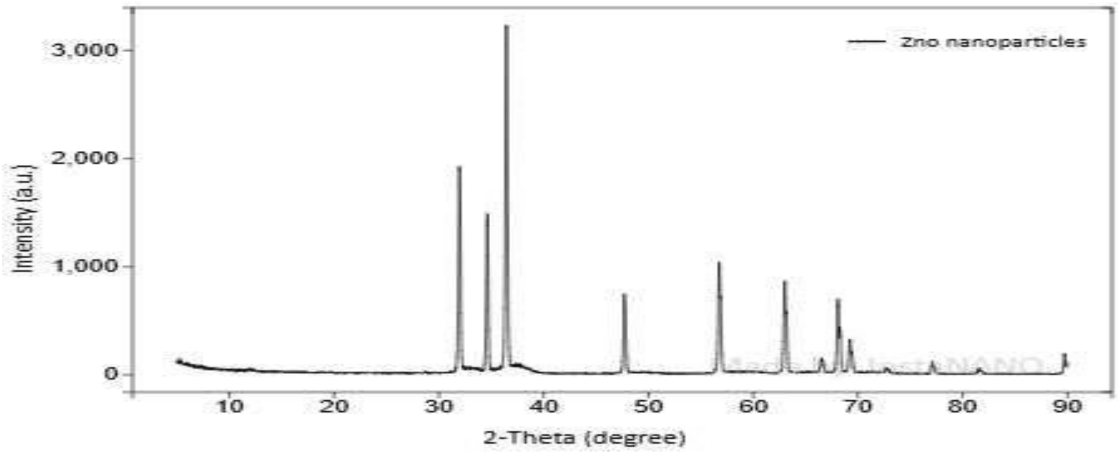

Fig 4.6 X-Ray Diffraction Analysis

The X-ray diffraction (XRD) pattern of the synthesized ZnO nanoparticles revealed distinct and sharp diffraction peaks, indicating the high crystallinity of the nanoparticles. The most intense peak was observed at $2\theta \approx 37°$, which corresponds to the (101) crystal plane a well-known characteristic peak of hexagonal wurtzite ZnO. Additionally, multiple peaks appearing at 2θ values of 31°, 34°, 47°, 56°, 63°, and 68° were indexed to the (100), (002), (102), (110), (103), and (112) planes, respectively. These match well with the standard JCPDS card for ZnO, confirming the formation of a wurtzite hexagonal structure. Importantly, the absence of any additional or unexpected peaks suggests that the synthesized ZnO

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nanoparticles are phase-pure, with no detectable impurities or secondary phases present in the sample. These findings validate the efficiency of the green synthesis method using pomegranate extract in producing crystalline and pure ZnO nanoparticles.

4.1.5 Dynamic Light Scattering Analysis

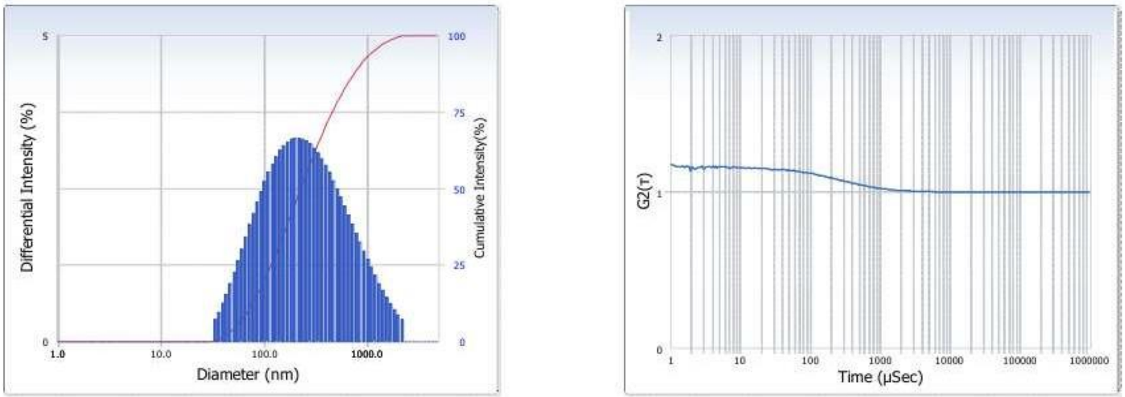

Fig 4.7 Dynamic Light Scattering Analysis

The average hydrodynamic diameter and size distribution of the synthesized zinc oxide (ZnO) nanoparticles were analyzed using Dynamic Light Scattering (DLS). The measurement was performed in aqueous medium at 25°C using a NanoPlus instrument. The results indicated an average particle size of 238.7 nm, with a polydispersity index (PDI) of 0.296, suggesting a moderately narrow size distribution. The intensity distribution showed a dominant peak centered around 372.4 nm, which may be due to minor agglomeration in the dispersion. The particle size percentiles were recorded as follows: D10 (10% of particles are below this size) = 69.1 nm, D50 (median particle size) = 225.5 nm, and D90 (90% of particles are below this size) = 833.7 nm. These values indicate that the majority of the particles are within the nanometer range, confirming the successful synthesis and dispersion of ZnO nanoparticles suitable for incorporation into water-borne paint formulations.

4.2 Anti-Fungal Activity Of The Nanoparticles

Fig 4.8 Anti Fungal Activity On A.flavus And A.niger Fungus

The antifungal activity of the prepared formulation was tested against two fungal species, *Aspergillus flavus* and *Aspergillus niger*, using the agar well diffusion method. The results clearly showed a concentration dependent response. In the case of *A. flavus*, the control had a zone of inhibition measuring 20 mm. When 100 µL of the formulation was applied, the zone reduced to 12 mm, and further decreased to 9 mm with 75 µL. A similar pattern was observed for *A. niger*, where the control also showed a 20 mm inhibition zone. The treated samples produced zones of 15 mm and 8 mm for 100 µL and 75 µL, respectively. These results indicate that the formulation was more effective at higher concentrations, showing a stronger ability to suppress fungal growth.

The visual appearance of the petri dishes supported these measurements. The plate with *A. flavus* showed the typical yellow-green growth of the fungus, with clear inhibition zones around the wells especially where the higher volume of the sample was placed. In the case of *A. niger*, known for its dark, powdery spores, distinct halos formed around the wells, again more prominent at the higher concentration. These visible zones confirm that the formulation was able to diffuse through the medium and effectively inhibit fungal growth in its vicinity.

Overall, both the measured data and the visible results suggest that the formulation has good antifungal properties. Its effectiveness increases with concentration, making it a promising candidate for further exploration in controlling fungal contamination.

4.3 Anti-Corrosivity Of Zno Nanoparticles

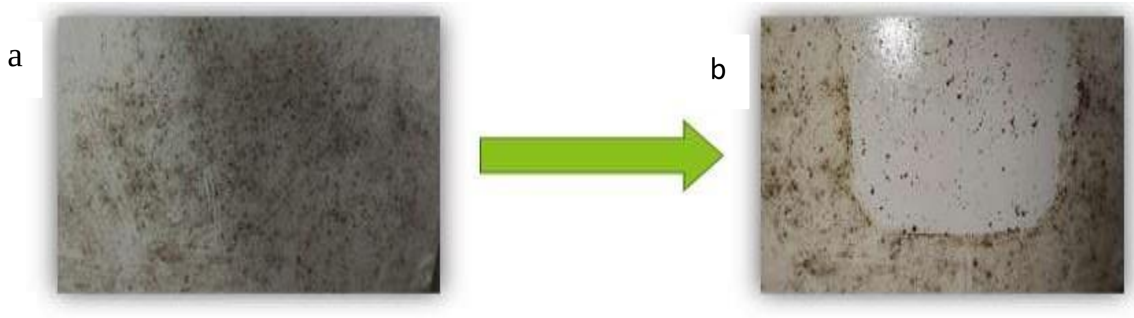

Fig 4.9 (a,b) Anti-Corrosivity Of Zno Nanoparticles

The anticorrosive property of the synthesized ZnO nanoparticles was evaluated through a simple surface application test on a visibly corroded metal substrate. The procedure involved spraying the nanoparticle formulation directly onto the corroded surface, allowing it to remain undisturbed for approximately 5 minutes, and then gently wiping the area with a tissue paper. As shown in the visual representation (Figure a), the surface initially appeared heavily corroded with visible rust deposits. After treatment, a significant improvement in surface appearance was observed, with a clean and restored metallic region clearly visible at the center of the treated area. This change demonstrates the formulation's effectiveness in breaking down corrosion deposits and restoring surface integrity. The result highlights the practical potential of ZnO nanoparticles in anticorrosive applications, particularly for cleaning or protective coating purposes in environments prone to metal degradation.

4.5 Effect Of Zinc Oxide Nanoparticles On Rust Prevention In Painted Metal Surfaces

Fig 4.10 (a,b) Anti-Corrosivity Test of Nanoparticles

After 10 days of salt spray exposure using a 5 g/15 mL NaCl solution, a clear difference in corrosion resistance was observed between the two coated metal samples. Sample A, coated with normal water-borne paint, exhibited significant rust formation across the surface, particularly along the edges. This indicates that the plain paint was insufficient in preventing moisture and salt penetration. In contrast, Sample B, coated with zinc nanoparticle-incorporated paint, showed minimal to no visible rusting, and the coating remained largely intact. The enhanced corrosion resistance in Sample B highlights the effectiveness of zinc nanoparticles in improving the protective properties of the coating by acting as a barrier and possibly contributing to corrosion inhibition.

5. CONCLUSION

This study successfully demonstrated the green synthesis of zinc oxide (ZnO) nanoparticles using pomegranate and orange peel extracts, with pomegranate proving more effective. The synthesized ZnO nanoparticles showed good crystallinity, uniform morphology, and stability, as confirmed by UV-Vis, FTIR, SEM, DLS, and XRD analyses.

These nanoparticles exhibited strong antifungal activity against *Aspergillus niger* and *A. flavus*, and also showed effective anti-corrosive properties, both as a spray and when incorporated into paint. The nanoparticle-infused paint provided significantly better corrosion resistance than conventional paint.

This work highlights a sustainable approach to converting fruit waste into valuable nanomaterials for protective coatings and environmental applications.

6. SCOPE FOR FUTURE WORK

Future studies can focus on optimizing synthesis parameters such as pH, temperature, and extract concentration to improve nanoparticle quality. Broader antifungal testing against various strains and mechanistic studies like ROS generation and membrane damage analysis could enhance understanding of their antimicrobial action. Evaluating the environmental safety and cytotoxicity of ZnO nanoparticles is also important for real-world applications. Long-term stability and shelf-life of the formulations should be assessed, along with potential scale-up using other agricultural wastes like banana or mango peels. Additionally, combining ZnO with other nanoparticles such as TiO_2 or AgNPs may enhance coating functionalities like UV protection and self-cleaning. Finally, commercialization and patent opportunities can be explored to promote sustainable, eco-friendly products.

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