AGRO-WASTE VALORIZATION THROUGH NANOGEL FORMULATION: ENHANCING THE ANTIMICROBIAL EFFICACY OF COCONUT SHELL OIL

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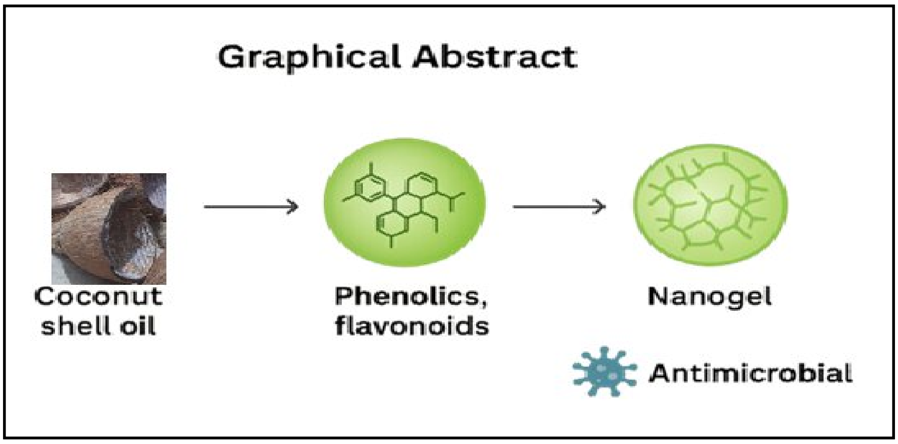
Abstract:
Coconut shell oil, obtained from agro-industrial waste, is a rich source of diverse bioactive compounds including phenolics, long-chain hydrocarbons, and antioxidants. These constituents contribute to its wide range of applications, extending from natural preservatives and biofuels to antimicrobial formulations. In the medicinal and pharmaceutical domains, the biological activities of these compounds further highlight the value of coconut shell oil in agro-waste valorization. Plant-derived extracts such as this are often recognized for their phenolic and flavonoid content, which are directly linked to antimicrobial efficacy. Nevertheless, the therapeutic potential of natural extracts is frequently constrained by factors such as low stability, poor solubility, and limited bioavailability, which can reduce their overall effectiveness. To understanding these challenges, formulation strategies such as incorporation into gel matrices have been explored. Embedding bioactive oils within a nanogel system provides several advantages: improved stability of active components, controlled and sustained release, and enhanced delivery to target sites. Such modifications can significantly influence antimicrobial performance by maintaining effective concentrations over extended periods. This study investigates the comparative antimicrobial activity of coconut shell oil in its native form and as a nanogel-based formulation. The outcomes are expected to provide insights into the efficiency of gel-based delivery systems in preserving and amplifying the bioactivity of natural compounds. By emphasizing the dual advantages of waste valorization and biomedical utility, this work underscores the potential of coconut shell-derived nanogels as a sustainable platform for developing natural antimicrobial agents.

Keywords: Nanogel, Antimicrobial Activity, Bioactive, Coconut Shells, Antioxidant.



1.0. Introduction

Coconut shell oil is a lesser-known yet valuable byproduct derived from the hard shell of mature coconuts (*Cocos nucifera*). Unlike coconut oil obtained from the kernel, coconut shell oil is extracted from the pyrolyzed or thermally treated shell, which is rich in lignin, phenolic compounds, and carbon-based constituents. This oil possesses a unique chemical composition, including polyphenols, long-chain hydrocarbons, and bioactive molecules that contribute to its biological and pharmacological properties [1-2]. Coconut shell oil has gained attention for its antimicrobial, antioxidant, and anti-inflammatory properties. The phenolic-rich content makes it effective against certain bacteria and fungi, potentially useful in treating skin infections or as a component in natural wound-healing formulations. Studies have also suggested its potential in cancer research due to cytotoxic effects on certain cell lines. Moreover, its natural origin and bioactivity make it a promising candidate for green pharmaceutical formulations, especially in antimicrobial coatings, ointments, and as an ingredient in herbal therapies [3].

Shell oil is a valuable derivative obtained from coconut shells, which are typically considered agro-industrial waste in coconut-producing regions. With millions of tons of coconut shells discarded annually by the food, coir, and oil industries, the efficient utilization of this biomass offers both environmental and economic benefits. Rather than being burned or left to decompose, coconut shells can be transformed into high-value products, with coconut shell oil emerging as a sustainable byproduct through pyrolysis or other extraction methods [5]. The conversion of coconut shells into oil exemplifies waste-to-wealth technology. The oil derived from these shells contains a complex mixture of phenolics, long-chain hydrocarbons, and antioxidants. These bioactive compounds lend the oil multiple industrial applications including antimicrobial formulations, biofuels, and natural preservatives. In the medicinal and pharmaceutical sectors, its biological activities further reinforce the potential of agro-waste valorization.

Figure 1, Coconut shells collected as agro-industrial waste for oil extraction and subsequent nanogel formulation.

Using coconut shell oil not only adds value to agricultural residues but also contributes to circular economy models by minimizing waste and maximizing resource efficiency. This aligns with global sustainability goals and promotes innovation in waste management and green chemistry. ***(Figure 1)***, shown Coconut shells, a widely available agricultural by-product, serve as a sustainable raw material for the extraction of bioactive oil. The oil contains phenolics, flavonoids, and antioxidants, which are utilized in developing nanogel formulations with potential antimicrobial and biomedical applications.

For people living in coastal and beach regions, where coconut trees grow abundantly, coconut shell oil offers a sustainable and locally accessible solution to health and livelihood challenges. Often discarded as waste, coconut shells can be converted into medicinally valuable oil through simple pyrolysis techniques, turning a common byproduct into a community asset. Using coconut shell oil supports traditional knowledge, reduces dependence on imported synthetic medicines, and promotes eco-friendly healthcare practices. With proven antibacterial, antifungal, and anti-inflammatory properties, the oil can be used in natural remedies for skin infections, minor wounds, or insect bites conditions commonly encountered in tropical, coastal environments. Promoting its use helps create local employment opportunities, reduces environmental waste, and encourages self-reliance in health and wellness practices [6-7].

2.Methodology

Coconut shells were cleaned, sun-dried, and crushed into small pieces. The material was then subjected to pyrolysis at 400–600°C in a closed furnace under oxygen-limited conditions. The resulting vapours were condensed using a water-cooled condenser, producing a liquid mixture of bio-oil, tar, and water. The bio-oil layer (coconut shell oil) was separated using a separating funnel and purified by filtration. The final oil was stored in dark glass bottles at room temperature or under refrigeration to maintain its stability [14].

Coconut shell oil–based nanogels were synthesized using polyvinyl alcohol (PVA) as a stabilizing polymer. PVA solution was prepared by dissolving PVA in distilled water at 85 ± 5°C with constant stirring, followed by cooling to room temperature. Coconut shell oil was premixed with Tween 80 to form a stable emulsion, which was added dropwise into the PVA solution under continuous stirring for 2 hrs. to obtain a uniform dispersion [13].

The resulting formulation was probe-sonicated for 10 min to reduce particle size and generate nanogel particles. The product was purified by centrifugation to remove unbound oil and impurities. The purified nanogel was collected and stored in sterile dark glass vials at 4°C. Characterization was carried out using scanning electron microscopy (SEM) for morphology, and EDS for elemental analysis.

The (***Figure 2***), shown Nanogels were prepared by dissolving the polymer (gelling agent) in water to form an aqueous solution, followed by the incorporation of coconut shell oil extract. The mixture was subjected to sonication to achieve uniform dispersion and nanoscale gel formation, resulting in a stable nanogel suitable for biomedical applications.

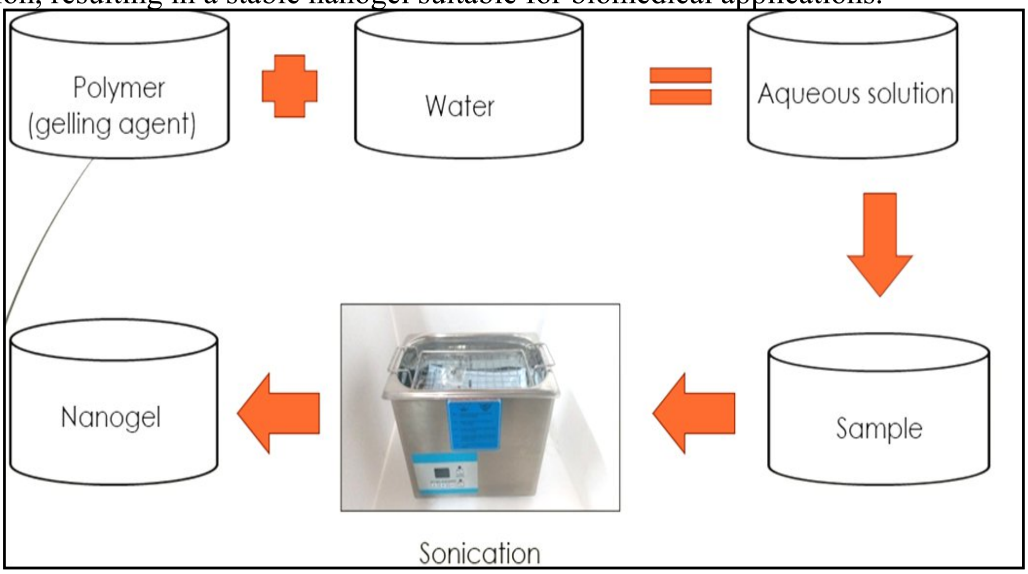


Figure 2, Schematic representation of nanogel formulation process using polymer and coconut shell oil extract.

3. Characterization & Identification

3.1 Scanning Electron Microscopy

Scanning Electron Microscopy (SEM) was conducted to evaluate the surface morphology and microstructural features of the polyvinyl alcohol (PVA)-based nanogel formulated with coconut shell extract shown in ***(Figure 3)***. The main objective of SEM analysis was to observe the topographical architecture, particle distribution, and surface texture of the prepared nanogel, which directly influences its biomedical efficacy, bio adhesion, and drug delivery potential.

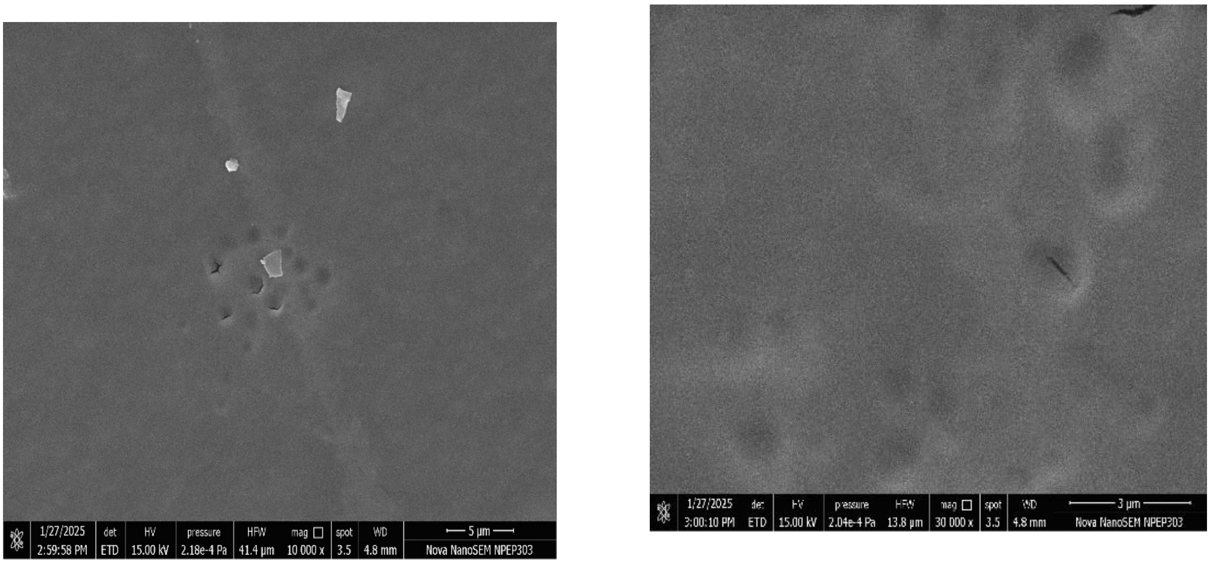
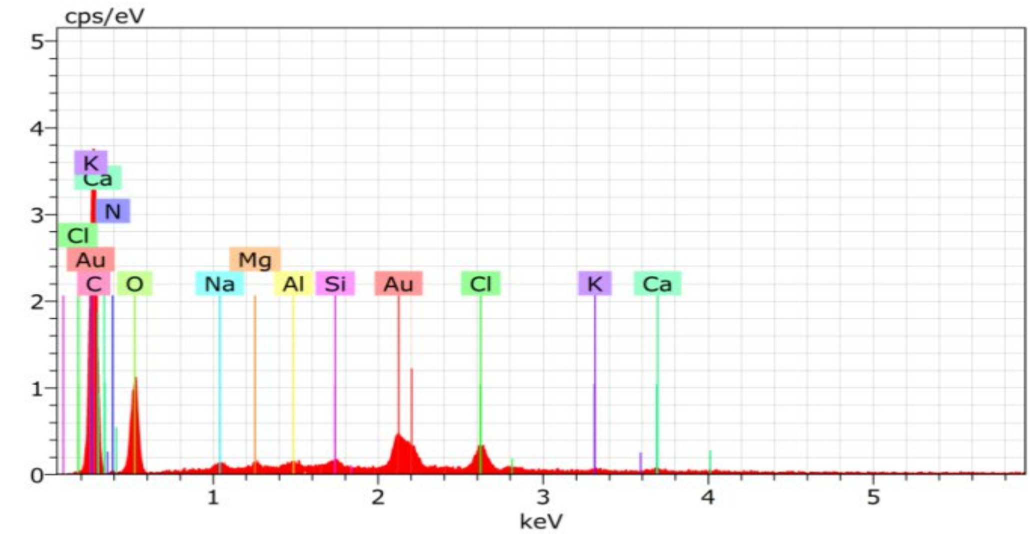


Figure 3, SEM Images of Nanogel

The micrographs revealed predominantly spherical to near-spherical particles with a smooth surface texture, indicating successful encapsulation of the extract within the PVA polymer matrix. Particle sizes appeared in the nanometer to submicron range. The finally, SEM observations confirm that the fabrication method yielded well-formed nanogel particles with morphological characteristics favorable for biomedical applications.

3.2 Energy Dispersive X-ray Spectroscopy (EDX)

Energy Dispersive X-ray Spectroscopy (EDX) was used in conjunction with SEM to determine the elemental composition of the PVA-based nanogel containing coconut shell extract. The purpose of EDX shown in ***(Figure 4),*** analysis was to confirm the presence and relative abundance of essential elements associated with the bioactive constituents and the polymeric carrier matrix, providing a compositional validation of the nanogel formulation.



Spectrum: 1

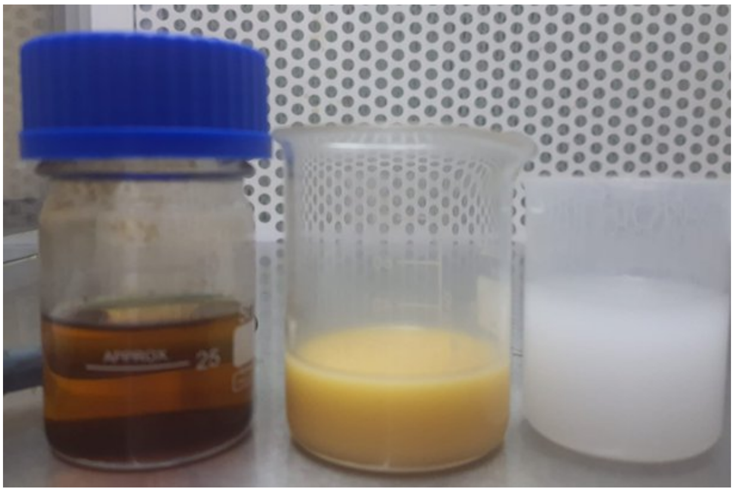
El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
C	6	K-series	60.27	60.27	68.31	8.37
O	8	K-series	33.72	33.72	28.70	5.54
Cl	17	K-series	2.61	2.61	1.00	0.14
Na	11	K-series	0.72	0.72	0.42	0.10
N	7	K-series	0.69	0.69	0.67	0.63
Si	14	K-series	0.48	0.48	0.23	0.06
Ca	20	K-series	0.43	0.43	0.15	0.06
Al	13	K-series	0.42	0.42	0.21	0.06
Mg	12	K-series	0.36	0.36	0.20	0.06
K	19	K-series	0.30	0.30	0.11	0.05
Au	79	M-series	0.00	0.00	0.00	0.00
		Total:	100.00	100.00	100.00	

Figure 4, EDS Spectrum

The EDS spectrum revealed that carbon (C) and oxygen (O) were the predominant elements, accounting for 60.27 wt% and 33.72 wt%, respectively. This high proportion of C and O is characteristic of an organic polymer matrix, in this case polyvinyl alcohol (PVA), combined with bioactive coconut shell oil constituents rich in carbon–oxygen functional groups such as phenols, esters, and alcohols.

4. Antimicrobial Activity

For Antimicrobial activity nutrient agar plates were seeded with 100 µl of bacterial inoculum and evenly spread using a sterile glass spreader. Wells of 8 mm diameter were punched into the agar using a sterile cork borer. Each well was filled with 100 µl of *Cocos nucifera* extract. The plates were incubated at 37 ± 1°C for 24 hours. Following incubation, the zone of inhibition surrounding each well was measured to determine the antibacterial potential of the extract [7]. ***(Figure 5)***, shows the preparation of nanogel formulations intended for antimicrobial evaluation



Figure, 5 Coconut shell oil and its derived formulations prepared for antimicrobial study

4.1. Observations & Result

The antibacterial activities of the coconut shell extract, its gel formulation, and the standard control were compared in order to assess the therapeutic potential of the generated formulations. Extracts from natural plants are frequently abundant in bioactive substances including flavonoids and phenolics, which support their antibacterial activity. However, the way they are delivered can affect how successful they are. The extract's stability, bioavailability, and prolonged release of active ingredients may all be improved by incorporating it into a gel matrix, which could impact antibacterial activity.

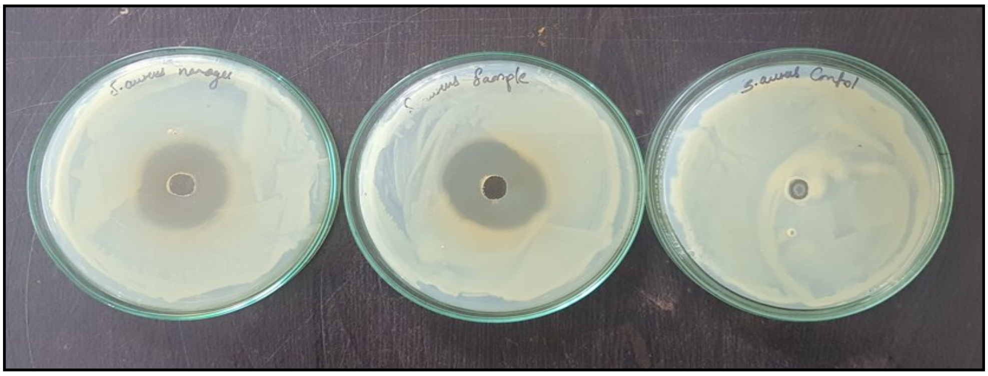


Figure 6: Antimicrobial Activity with *S.aureus*

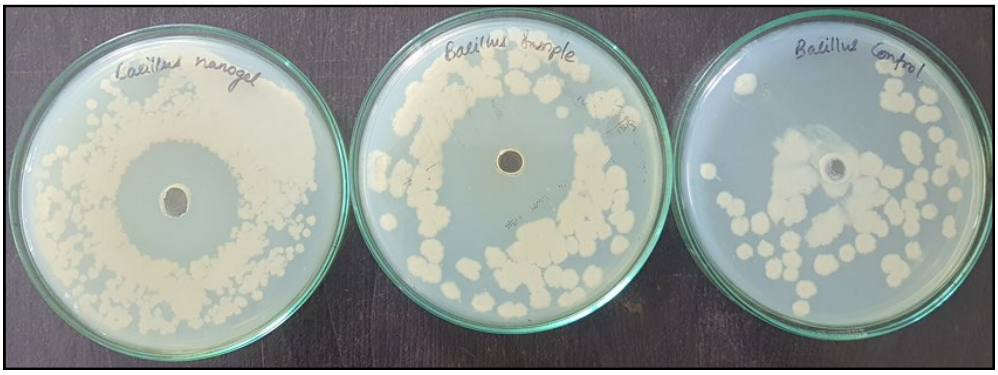


Figure 7: Antibacterial Activity with Bacillus

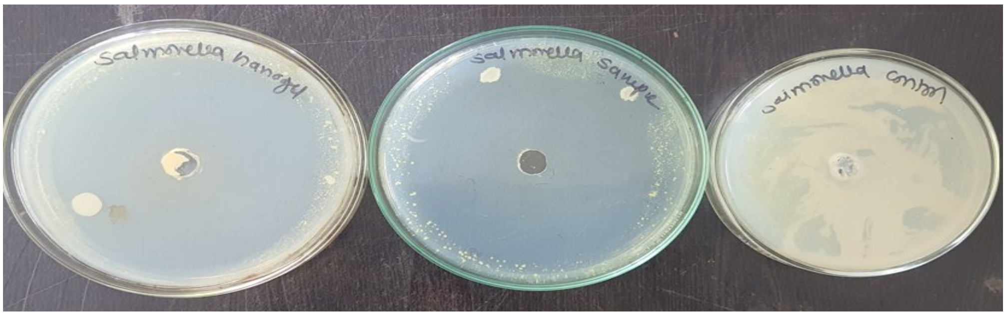


Figure 8: Antimicobial Activity with M. lutus

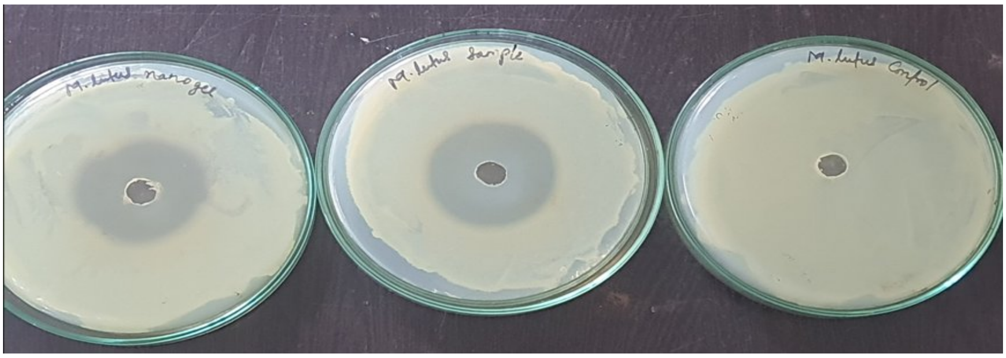


Figure 9: Antimicrobial Activity with Salmonella

The well diffusion assay of Nanogel exhibited significant inhibitory activity against all tested bacterial species, with inhibition zones ranging from 16 mm to 27 mm. The largest inhibition zones were observed against *Staphylococcus aureus ATCC 25293* and *Pseudomonas aeruginosa* (27 mm each), suggesting that the extract possesses potent activity against both Gram-positive and Gram-negative bacteria. This finding indicates the presence of bioactive components capable of disrupting bacterial growth, possibly through membrane damage or interference with essential cellular processes.

5. Conclusion

Coconut shell, a lignocellulosic byproduct of *Cocos nucifera*, is increasingly recognized for its bioactive phytochemical content, particularly phenolics and flavonoids, which contribute to its antimicrobial efficacy. The concentration-dependent response indicates that active phytoconstituents from coconut shell extract are retained within the nanogel matrix, enabling gradual release and sustained antimicrobial action. By converting agro-industrial waste like coconut shells into high-value medicinal products, countries can reduce dependency on imported pharmaceuticals and promote local, natural healthcare solutions.

6. References

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