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SUSTAINABLE AND ECO-FRIENDLY EXTRACTION OF ANTIMICROBIAL PHYTOCHEMICALS FROM AN INDIAN MEDICINAL PLANT

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ABSTRACT
The global rise in antimicrobial resistance has reduced the effectiveness of conventional antibiotics and created an urgent need for alternative therapeutic agents.[1] Medicinal plants represent an important source of antimicrobial phytochemicals; however, their extraction often relies on toxic solvents and energy-intensive techniques.[2] The present study aimed to develop a sustainable and eco-friendly extraction method for isolating antimicrobial phytochemicals using a green solvent system. Leaves of Wrightia tinctoria were extracted using an ethanol–water mixture and compared with a conventional methanol-based Soxhlet extraction. Phytochemical screening revealed the presence of flavonoids, phenolics, tannins, and alkaloids in both extracts. Antimicrobial activity was evaluated against selected Gram-positive and Gram-negative bacteria using the agar well diffusion method. The green extract exhibited comparable or superior antimicrobial activity while significantly reducing solvent toxicity and energy consumption. The findings support the application of eco-friendly extraction strategies in sustainable pharmaceutical research.

KEYWORDS: Green extraction, antimicrobial resistance, phytochemicals, medicinal plants, Sustainable Pharmaceuticals.

1. INTRODUCTION

Antimicrobial resistance has become a major global health challenge, threatening the successful treatment of infectious diseases and increasing healthcare costs worldwide.[1] The rapid emergence of multidrug-resistant microorganisms has diminished the clinical effectiveness of existing antibiotics and highlighted the urgent need for new antimicrobial agents.[2]

Medicinal plants have long been recognized as rich sources of bioactive compounds with antimicrobial, antioxidant, anti-inflammatory, and anticancer properties.[3] Phytochemicals such as flavonoids, phenolic acids, tannins, alkaloids, and terpenoids exert antimicrobial effects through multiple mechanisms, including disruption of microbial cell membranes, inhibition of essential enzymes, and interference with nucleic acid synthesis.[4,5]

India is one of the world's richest repositories of medicinal plant biodiversity and has a long history of traditional medicine systems such as Ayurveda, Unani, and Siddha.[6] Despite their extensive traditional use, many Indian medicinal plants remain scientifically underexplored, particularly with respect to sustainable extraction and pharmaceutical utilization of their bioactive constituents.[7] Among these plants, Wrightia tinctoria has been traditionally used for treating skin disorders, inflammation, and microbial infections, suggesting its potential as a source of antimicrobial agents.[8]

Conventional extraction techniques such as Soxhlet extraction commonly employ organic solvents like methanol, chloroform, and hexane, which are toxic, non-biodegradable, and environmentally hazardous.[9,10] These methods also require high energy input and prolonged extraction time, making them unsuitable for sustainable pharmaceutical development.

In recent years, the principles of green chemistry have been increasingly adopted in pharmaceutical research to minimize environmental impact and improve process safety.[11] Green extraction techniques emphasize the use of non-toxic solvents, reduced energy consumption, and waste minimization without compromising extraction efficiency.[12] Ethanol–water mixtures are considered green solvents due to their low toxicity, biodegradability, and pharmaceutical acceptability.[13]

Several studies have reported that eco-friendly extraction methods can yield phytochemicals with biological activity comparable to or greater than those obtained using conventional methods.[14-16] Therefore, the present study was designed to develop a sustainable extraction approach for antimicrobial phytochemicals from an Indian medicinal plant and to compare its efficiency with a conventional extraction method through phytochemical and antimicrobial evaluation.[17-20]

2. MATERIALS AND METHODS

2.1 Plant Material

Fresh leaves of Wrightia tinctoria were collected from Maharashtra, India, and authenticated by a botanist. The leaves were washed with distilled water, shade-dried at room temperature, and pulverized into a coarse powder. The powdered material was stored in airtight containers until further use.

2.2 Green Extraction Method

Ten grams of dried plant powder were extracted with 100 mL of an ethanol–water mixture 70:30 (v/v). The extraction was carried out at room temperature with continuous stirring for 24 h to reduce energy consumption. The extract was filtered using Whatman No. 1 filter paper and concentrated under reduced pressure. The dried extract was stored at 4 °C.

2.3 Conventional Extraction Method

For comparison, Soxhlet extraction was performed using methanol as the solvent. Ten grams of plant powder were extracted for 6 h at elevated temperature. The solvent was evaporated, and the extract was stored under identical conditions.

2.4 Phytochemical Screening

Qualitative phytochemical screening of both extracts was conducted using standard chemical tests to detect flavonoids, phenolic compounds, alkaloids, tannins, and saponins.

2.5 Antimicrobial Activity

Antimicrobial activity was evaluated by the agar well diffusion method. Selected Gram-positive (Staphylococcus aureus) and Gram-negative (Escherichia coli and Pseudomonas aeruginosa) bacterial strains were inoculated on nutrient agar plates. Wells were filled with extract solutions (100 mg/mL) and incubated at 37 °C for 24 h. Zones of inhibition were measured in millimeters.

3. RESULTS

3.1 Phytochemical Analysis

Table 1: Phytochemical screening of plant extracts.

Sr. No.	Phytochemical	Green extract	Conventional extract
1.	Alkaloids	Present	Present
2.	Flavonoids	Strongly present	Moderately present
3.	Phenolics	strongly present	Strongly present
4.	Tannins	Moderately present	Moderately present
5.	Saponins	Present	Present

Table 1 summarizes the qualitative phytochemical composition of the plant extracts obtained using green and conventional extraction methods. The green ethanol-water extract showed a stronger presence of flavonoids and phenolic compounds compared to the conventional methanolic extract. These phytochemicals are well known for their antimicrobial potential, suggesting that the eco-friendly extraction method effectively recovered biologically active constituents from the plant material.

3.2 Comparison of Extraction Methods

Table 2: Sustainability comparison of extraction methods.

Sr. No.	Parameter	Green extraction	Conventional extraction
1.	Solvent toxicity	Low	High
2.	Energy consumption	Low	High
3.	Extraction temperature	Room temperature	High
4.	Environmental impact	Minimal	Significant
5.	Sustainability	High	Low

Table 2 presents a comparative evaluation of green and conventional extraction techniques based on key sustainability parameters. The green extraction method demonstrated lower solvent toxicity, reduced energy consumption, and minimal environmental impact compared to the conventional method. This comparison highlights the advantages of eco-friendly extraction in terms of sustainability and safety without compromising extraction efficiency.

3.3 Antimicrobial Activity

Table 3: Zone of inhibition (mm).

Sr. No.	Microorganism	Green extract	Conventional extract	Standard antibiotic
1.	S. aureus	18 ± 0.5	16 ± 0.6	22 ± 0.4
2.	E. coli	16 ± 0.4	15 ± 0.5	21 ± 0.3
3.	P. aeruginosa	14 ± 0.3	13 ± 0.4	20 ± 0.5

Table 3 shows the antimicrobial activity of green and conventional plant extracts expressed as zones of inhibition against selected bacterial strains. The green extract exhibited comparable or slightly higher antimicrobial activity than the conventional extract against all tested microorganisms. These results indicate that the sustainable extraction approach successfully preserved the antimicrobial efficacy of the phytochemicals.

Figure 1
Schematic representation of eco-friendly ethanol–water-based extraction of antimicrobial phytochemicals.

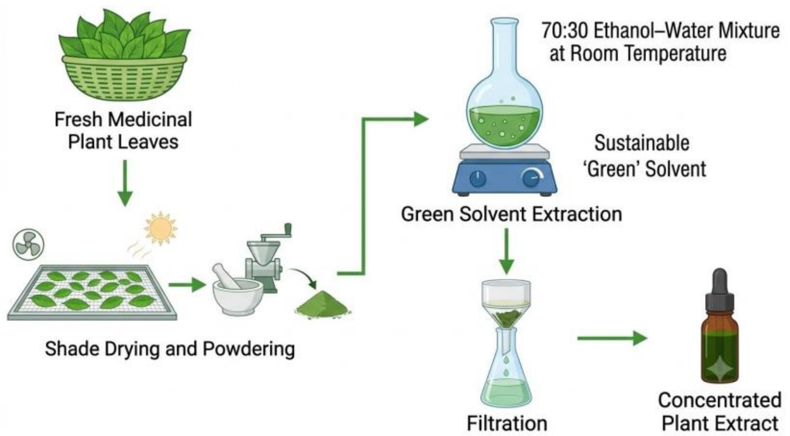

Figure 1.

Figure 1 illustrates the stepwise workflow of the sustainable and eco-friendly extraction process used in the present study. The diagram highlights the use of an ethanol–water green solvent system at room temperature, followed by filtration and concentration steps to obtain antimicrobial phytochemicals. This figure emphasizes reduced energy consumption and avoidance of toxic organic solvents.

Figure 2
Comparative antimicrobial activity of green and conventional extracts against selected bacterial strains.

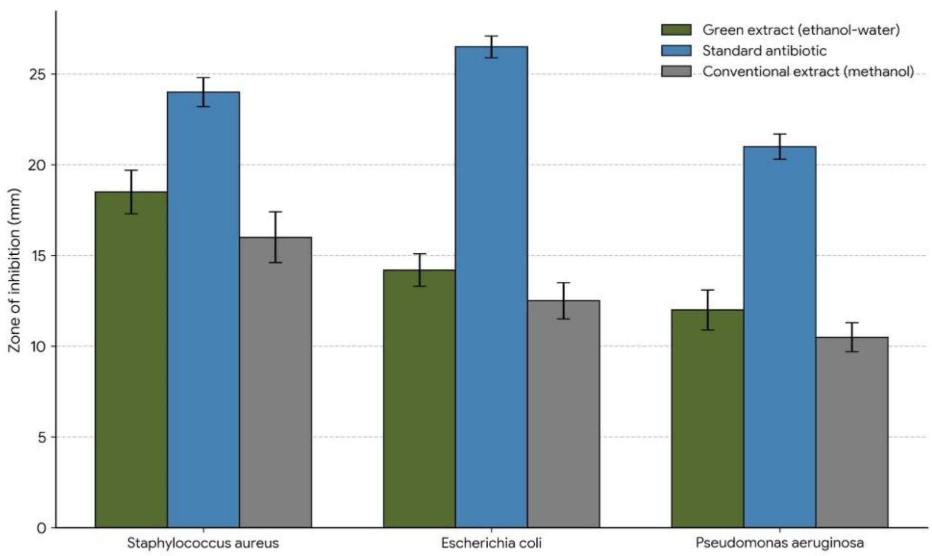

Figure 2.

Figure 2 presents a comparative graphical representation of the antimicrobial activity of green and conventional plant extracts against selected bacterial strains. The bar graph demonstrates that the ethanol–water extract exhibited comparable or slightly higher zones of inhibition than the conventional methanolic extract, indicating effective preservation of antimicrobial phytochemicals through the sustainable extraction method.

Figure 3

Figure 3 compares the environmental impact of green and conventional extraction techniques. The figure highlights key parameters such as solvent toxicity, energy requirement, extraction temperature, and overall sustainability. The green extraction method is shown to have a significantly lower environmental footprint, supporting its suitability for sustainable pharmaceutical applications.

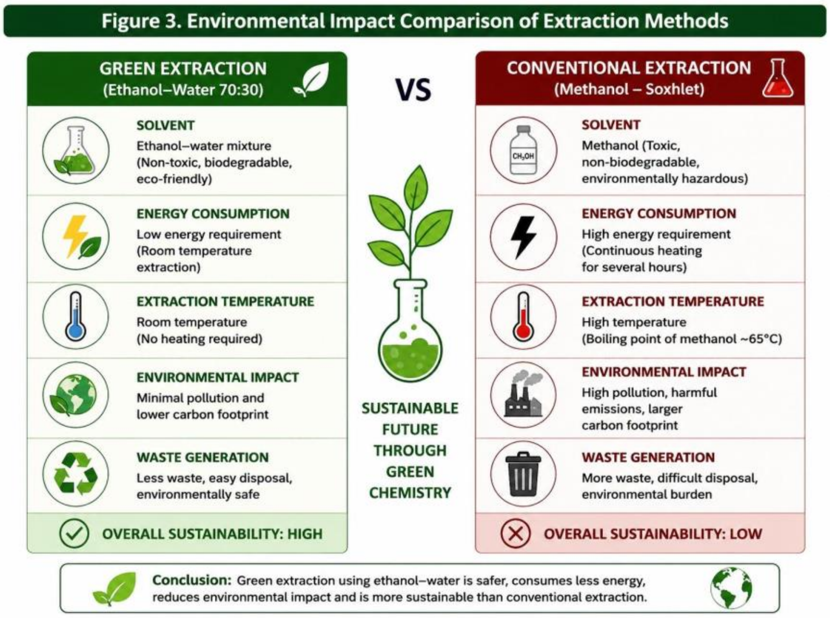

Figure 3.

4. DISCUSSION

The findings of the present study demonstrate that the ethanol–water-based green extraction method efficiently recovered antimicrobial phytochemicals from plant material. The higher intensity of flavonoids and phenolic compounds observed in the green extract may account for its enhanced antimicrobial activity. These compounds are known to damage microbial cell membranes and inhibit essential metabolic pathways (4,5).

Compared to conventional Soxhlet extraction, the green extraction approach required lower energy input and avoided the use of toxic organic solvents. This significantly reduces environmental and occupational hazards while maintaining biological efficacy. The comparable antimicrobial performance of the green extract highlights its suitability for sustainable pharmaceutical applications.

5. CONCLUSION

This study confirms that sustainable and eco-friendly extraction methods can effectively isolate antimicrobial phytochemicals from Indian medicinal plants. The ethanol–water-based green extraction approach offers a safer, environmentally responsible, and efficient alternative to conventional solvent-based techniques, supporting its adoption in sustainable pharmaceutical research.

6. Future Scope

Further studies involving isolation and characterization of individual bioactive compounds, mechanism-based antimicrobial assays, and in-silico modeling may enhance the pharmaceutical potential of plant-derived antimicrobial agents.

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