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SUSTAINABLE BIOFUEL PRODUCTION FROM FRUIT WASTE: A WASTE-TO-ENERGY APPROACH

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ABSTRACT

The prevention of food spoilage and foodborne illnesses is commonly achieved through chemical preservatives, which pose significant concerns, including potential human health hazards, chemical residues in food and feed chains, and the development of microbial resistance. These issues have increased the demand for safe, effective, and natural alternatives. Plant extracts have long been utilized for their antimicrobial properties in controlling foodborne pathogens and preserving food.

This study investigates the antimicrobial activity of five ethanolic plant extracts—Punica granatum, Syzygium aromaticum, Zingiber officinale, Thymus vulgaris, and Cuminum cyminum—against common food poisoning bacterial strains: Bacillus cereus, Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa, and Salmonella typhi, using the agar disc diffusion method. At a concentration of 10 mg/mL, extracts of P. granatum, S. aromaticum, Z. officinale, and T. vulgaris exhibited notable antimicrobial activity, while C. cyminum was effective only against S. aureus.

Among all tested extracts, P. granatum and S. aromaticum demonstrated the highest bactericidal efficacy, particularly against S. aureus and P. aeruginosa, with minimum inhibitory concentrations (MICs) ranging from 2.5 to 5.0 mg/mL. These findings suggest that selected plant extracts may serve as promising natural preservatives for controlling foodborne pathogens and minimizing the health risks associated with chemical antimicrobial agents.

INTRODUCTION

Food poisoning remains a significant public health concern, particularly in developing countries, where it is one of the most common causes of illness and mortality. The majority of food poisoning cases are linked to bacterial contamination, especially by Gram-negative bacteria such as Salmonella typhi, Escherichia coli, and Pseudomonas aeruginosa. Additionally, Gram-positive bacteria like Staphylococcus aureus and Bacillus cereus are also recognized as major contributors to foodborne diseases and spoilage.

Traditionally, food preservation and the control of these pathogens have relied heavily on the use of chemical preservatives. Although effective in reducing microbial contamination and controlling outbreaks, these chemicals have raised several concerns. Prolonged use may lead to the accumulation of harmful residues in food and feed chains, contribute to the development of antimicrobial resistance among pathogens, and pose potential health risks to consumers.

Due to these concerns, there has been a growing interest in exploring natural, safe, and effective alternatives to synthetic preservatives. Plant-based extracts have emerged as promising candidates owing to their antimicrobial properties, biodegradability, and nutritional safety. Several studies have demonstrated the antibacterial potential of plant extracts against foodborne pathogens.

For example, ethanolic extracts of Achyranthes aspera, Cynodon dactylon, Lantana camara, and Tagetes patula have shown effectiveness against S. aureus, P. aeruginosa, and Bacillus subtilis, with minimum inhibitory concentrations (MICs) ranging from 25 to 125 mg/mL. Another study found that while ginger was selectively effective against S. aureus, guava and garlic extracts exhibited broader antibacterial activity. Similarly, crude and butanolic extracts of Persea americana inhibited B. cereus, with MICs between 3.12 and 12.5 mg/mL.

Medicinal plants used in Nigerian folk medicine also displayed significant antibacterial activity against Salmonella enteritidis, E. coli, and S. aureus, albeit with varying degrees of efficacy. Among eight medicinal plants studied for activity against E. coli, B. cereus, and Listeria monocytogenes, extracts of Myrtus communis and Thymus daenensis showed the greatest potency, with MICs ranging from 0.039 to 10 mg/mL.

The antimicrobial properties of Punica granatum (pomegranate) have been well-documented. Extracts of Punica, Citrus, and Allium species were effective against S. typhi, E. coli, B. cereus, and S. aureus, with Punica granatum demonstrating the strongest activity at 500 mg/mL. Ethanolic extracts of P. granatum peel were shown to be active against Micrococcus luteus, S. aureus, Bacillus megaterium, and Gram-negative bacteria including E. coli and P. aeruginosa at concentrations ranging from 30 to 50 µg/mL. Furthermore, both crude and fractionated ethanolic extracts of P. granatum have demonstrated potent activity against Gram-positive and Gram-negative foodborne pathogens.

Spice extracts, commonly used as flavoring agents, have also shown notable antimicrobial effects. Among these, cinnamon extract exhibited the most substantial antibacterial activity, while cumin, ginger, and clove demonstrated weaker activity in some studies. Syzygium aromaticum (clove) ethanolic extract was active against S. aureus, Vibrio parahaemolyticus, and P. aeruginosa, though it showed limited activity against E. coli and S. enteritidis. Other studies have reported the efficacy of clove oil against all tested pathogens, while aqueous clove extracts were less effective against species like Vibrio cholerae, S. typhi, and Klebsiella pneumoniae. Methanolic clove extract was found to be effective against S. aureus, P. aeruginosa, and E. coli, with MICs ranging from 0.1 to 2.31 mg/mL.

The antimicrobial potential of Cuminum cyminum (cumin) extract has also been documented, with MICs against E. coli, P. aeruginosa, S. aureus, and Bacillus pumilus ranging from 6.25 to 25 mg/mL, though some studies report effective concentrations as high as 60 mg/mL. In addition, ethanolic extracts of Zingiber officinale (ginger), Thymus kotschyana, and Punica granatum were found to be effective against clinically relevant bacteria such as S. aureus, E. coli, P. aeruginosa, and K. pneumoniae, with MICs as low as 0.2 mg/mL in some cases.

Given that food poisoning is often caused by Gram-negative pathogens like E. coli, S. typhi, and P. aeruginosa, as well as Gram-positive bacteria such as S. aureus and B. cereus, there is a critical need for effective natural antimicrobial agents. However, limited research has been conducted in the Arabian region on the antibacterial efficacy of Syzygium aromaticum, Thymus vulgaris, Punica granatum, Zingiber officinale, and Cuminum cyminum against these foodborne pathogens.

Therefore, the present study aims to evaluate the in vitro antibacterial activity of selected plant extracts against key foodborne pathogens, including S. aureus, B. cereus, E. coli, S. typhi, and P. aeruginosa.

2. LITERATURE REVIEW

M. S. Abdulrahman et al[1] evaluated the antimicrobial and biochemical properties of spice extracts against food spoilage pathogens. Their findings showed that certain spices possess significant antimicrobial activity, making them viable natural preservatives. The study demonstrated that spice extracts such as clove and cinnamon exhibited broad-spectrum antibacterial effects against both Gram-positive and Gram-negative bacteria. This supports the application of spices as bioactive agents in food preservation. Ahmad and Beg [2]. In a comprehensive study, I. Ahmad and A. Z. Beg screened 45 Indian medicinal plants for antimicrobial activity against multi-drug resistant pathogens. The results revealed strong antibacterial potential in several extracts, especially against Gram-positive bacteria. The study emphasized the relevance of ethnomedicinal knowledge and phytochemical components as a source of novel antimicrobial agents to combat drug resistance. Ahmad et al[3]. This study assessed the antimicrobial efficacy of selected Indian medicinal plant extracts. Using standard disc diffusion methods, the authors observed that many of the extracts had strong inhibitory effects on pathogenic bacteria. The results highlight the therapeutic potential of plant-derived compounds and their role in traditional medicine systems as effective antimicrobial agents. D. A. Akinpelu et al[4]. focused on the antibacterial properties of *Persea americana* (avocado) stem bark extracts against *Bacillus cereus*, a known food poisoning bacterium. The study revealed that both the crude extract and its fractions showed significant bactericidal activity. These findings suggest the potential of avocado-derived phytochemicals for application in food safety and pharmaceutical formulations.

K. O. Akinyemi et al[5]. Evaluated crude extracts from three Nigerian medicinal plants for antibacterial activity against foodborne pathogens. The extracts demonstrated variable but noteworthy efficacy, indicating their potential as natural preservatives or therapeutic agents. The study reinforces the importance of indigenous plant knowledge in the search for alternative antimicrobial agents. N. S. Alzoreky et al[6]. investigated the antimicrobial properties of *Punica granatum* (pomegranate) fruit peel. The ethanolic extracts were found to be highly effective against a range of foodborne bacteria. The study contributes valuable evidence supporting the use of pomegranate by-products in food preservation and as functional food ingredients. Alzoreky and Nakahara [7] This study explored the antibacterial activity of various edible plants commonly consumed in Asia. The authors discovered that several extracts had potent activity against common foodborne pathogens. The research emphasized the dual nutritional and antimicrobial roles of these plants, advocating their broader use in food systems. D. S. Arora and J. Kaur[8] investigated the antimicrobial effects of common spices. They demonstrated that spices such as clove, cinnamon, and mustard exhibited strong inhibitory activity against multiple bacterial strains. Their study highlighted the long-standing antimicrobial roles of spices in traditional diets and their potential industrial applications. Ateb and Erdogrul [9]. This study assessed the antimicrobial activities of various medicinal and commercial plant extracts. The authors reported significant antibacterial activity, particularly from essential oil-containing plants. The study reinforces the potential of plant-derived compounds in the formulation of natural antimicrobial agents for food and pharmaceutical industries. A. Berahou et al[10]. Studied the antibacterial properties of *Quercus ilex* bark extract. Their results showed strong activity against several bacterial strains, including foodborne pathogens. The findings support the continued investigation of tree bark and woody plant materials as sources of effective natural antimicrobials.

D. Jose et al[11]. This study evaluates the pretreatment of pineapple peel using Deep Eutectic Solvents (DES) to enhance cellulose conversion for sustainable biofuel production. The DES method improved the breakdown of lignocellulosic bonds, increasing fermentable sugar availability. This research supports eco-friendly pretreatment alternatives and their application in low-cost bioethanol production from fruit waste. Nemati and M. S. Vojdani [12]. The feasibility study focuses on utilizing palm oil waste as biomass for a 10 MW power plant in Iran. Through a technical and economic lens, it confirms that palm waste offers a reliable energy source for decentralized electrification, especially in regions with high agricultural waste availability. This work demonstrates biomass-to-energy scalability from agricultural residues. C. R. Rumple et al [13]. This paper explores the densification of mango residues as a biofuel for low-resource agricultural processing. The study found that compacted fruit waste residues (briquettes) present a viable fuel alternative with significant energy density. This innovation is especially relevant for rural areas with limited access to conventional energy. R. A. Pribadi and Syafii [14]. The research proposes a hybrid biogas/diesel/solar PV system to power palm oil factories and nearby settlements. It emphasizes cost-effectiveness and sustainability through energy diversification. The inclusion of waste-to-biogas pathways aligns with circular economy models in agro-industrial zones.

S. V. Akram and A. Joshi [15]. Though primarily centered on IoT applications in cattle shed management, this paper indirectly supports biomass generation from animal waste. While not focused on fruit waste directly, it provides a systems-level perspective on agricultural resource optimization that complements sustainable fuel initiatives. M. Petrollese et al [16]. A techno-economic comparison between biomass combustion and anaerobic digestion was presented, particularly in CSP hybrid systems. The study confirmed that integrating biomass with solar thermal energy improves efficiency and reduces emissions. This has implications for fruit-waste-derived biomass use in hybrid renewable energy systems. M. M.

Khandaker et al[17]. The authors explore bioethanol production from fruit and vegetable waste using *Saccharomyces cerevisiae*. The study validates the yeast's effectiveness in converting high-sugar waste into ethanol, promoting circular waste management practices. It demonstrates the potential of domestic-scale fermenters for urban biofuel production. Vinotha et al [18]. This experimental study used a bacterial consortium to ferment mango, orange peel, and tapioca shells into biofuel. The consortium demonstrated high conversion efficiency, indicating that mixed microbial systems are promising for enhancing yield and reducing process time in waste valorization. Y.-L. Lin and N.-Y. Zheng [19]. The paper examines the torrefaction of fruit waste seeds and shells as a pre-processing method to reduce CO_2 emissions. Torrefaction improved energy density and combustion properties. This research supports the thermal upgrading of fruit waste into a high-performance solid biofuel suitable for co-firing.

S. Choi et al [20]. This study presents a low-energy method for converting citrus peel waste into bioethanol, using cost-effective acid hydrolysis and enzymatic treatments. The approach minimizes processing energy and chemical input, making it viable for deployment in energy-poor regions with abundant citrus waste. M. Patsalou et al [21]. The authors propose a sustainable strategy for converting citrus industrial waste into bioethanol. Using multi-step fermentation and saccharification, the study showcases industrial scalability. The process also emphasizes closed-loop water and energy usage, enhancing its environmental footprint. L. K. Sarao et al[22]. In this comprehensive review, the authors summarize recent advancements in bioethanol production from fruit waste. Topics include pretreatment techniques, enzymatic hydrolysis, microbial fermentation, and process integration. The chapter concludes that fruit waste remains a largely untapped, high-potential resource for next-generation biofuels.

3. MATERIALS AND METHODS

3.1. PLANT MATERIAL COLLECTION AND EXTRACTION

Five plant species were procured from local markets in Riyadh, Saudi Arabia. The plant materials were washed, disinfected, and dried in the shade. Dried samples were powdered and sieved (100 mm mesh). 50 g of each sample was soaked in 200 mL of ethanol for 48 hours with continuous stirring. Extracts were filtered, centrifuged, and further purified using Whatman No. 41 filter paper. The ethanol was evaporated under reduced pressure at 40°C using a rotary vacuum evaporator. Extract yields were calculated as follows:

Extract yield (%) = (Weight of extract / Weight of raw sample) × 100

Table 1 . The ethnobotanical data of employed plant species and their extract yield percentage.

Plant species	Family	Local name	Common name	Plant part used	Extract pH	Extract yield (%)
Cuminum cyminum	Apiaceae	Kammun	Cumin	Seeds	6.2	3.12
Punica granatum	Lythraceae	Romman	Pomegranate	Peels	4.7	9.74
Syzygium aromaticum	Myrtaceae	Koronfil	Clove	Flowers	5.3	4.38
Thymus vulgaris	Lamiaceae	Za'ater	Thyme	Leaves	6.8	6.54
Zingiber officinale	Zingiberaceae	Zanjabil	Ginger	Rhizome	7.1	5.26

3.2. ANTIBACTERIAL ACTIVITY TESTING

The agar disc diffusion method was used. 50 mg of each extract was dissolved in 2.5 mL ethanol, sterilized (0.22 µm filter), and loaded onto sterile discs (8 mm diameter) for a concentration of 10 mg/disc. Mueller-Hinton agar was used with bacterial suspensions at 10^5 CFU/mL. Discs were placed on the inoculated medium, followed by pre-incubation at 5°C for 2 hours and incubation at 35°C for 24 hours. Gentamycin (5 µg/disc) served as the positive control. Inhibition zones were measured with a Vernier caliper.

3.3. MINIMUM INHIBITORY CONCENTRATION (MIC) DETERMINATION

MICs were determined for the most effective extracts. Serial concentrations (1.25 to 15.0 mg/mL) were prepared. The disc diffusion procedure was repeated, and the smallest concentration showing clear inhibition was recorded as the MIC.

4. RESULTS AND DISCUSSION

4.1. EXTRACT YIELD

Among the tested plants, Punica granatum yielded the highest extract percentage (9.74%), followed by Thymus vulgaris (6.54%) and Zingiber officinale (5.26%). Cuminum cyminum had the lowest yield (3.12%).

4.2. ANTIBACTERIAL EFFICACY

Extracts of P. granatum, S. aromaticum, Z. officinale, and T. vulgaris were effective against multiple pathogens at 10 mg/mL. C. cyminum showed activity only against S. aureus. MIC values for P. granatum and S. aromaticum ranged between 2.5 and 5.0 mg/mL, indicating strong antibacterial potential.

CONCLUSION

Plant extracts, particularly those of Punica granatum and Syzygium aromaticum, exhibit strong antimicrobial activity and are promising natural alternatives to synthetic preservatives in food safety applications. Their use could reduce the health risks associated with chemical preservatives while effectively controlling foodborne pathogens.

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