Harnessing the termite gut microbiome for the bioconversion of coconut husk into green biosurfactants: a review with experimental insights

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Abstract - This research aims to find sustainable and biodegradable alternatives to synthetic surfactants in the wake of increasing environmental concerns. It focuses on microbial surfactants for their low toxicity, biodegradability, and ability to withstand harsh conditions, but points out the current economic limitations for their production due to the cost of substrates and inefficient bioprocessing. Coconut husk, a low-cost agricultural waste lignocellulosic substrate, is suggested, but its high lignin composition makes it difficult to degrade by microbes. Termites, with their gut microbiota that functions as an anaerobic bioreactor with high concentrations of lignocellulose-degrading microbes, are investigated. The objective is to isolate and identify termite gut lignocellulose degraders and determine their potential for the bioconversion of coconut husk into a green biosurfactant. The research will determine enzymatic activity, substrate consumption, and biosurfactant production using established qualitative and quantitative approaches. This termite-mediated bioconversion process may help push the frontiers of green waste biorefinery and biosurfactant manufacturing in the context of green biotechnology and circular economy strategies.

Key Words: Termite gut microbiome, Coconut husk, Lignocellulose bioconversion, Biosurfactants, Green biotechnology, Microbial consortia.

1. INTRODUCTION

1.1 Environmental Concerns and the Need for Sustainable Biosurfactants

Surfactants are critical components in a wide range of industrial applications, such as detergents, cosmetics, pharmaceuticals, food processing, petroleum extraction, agriculture, and environmental clean-up. The ability of surfactants to reduce surface and interfacial tension is fundamental to emulsification, dispersion, wetting, and solubilization. Currently, the surfactant market is mainly saturated with chemically synthesized surfactants that are mainly produced from petrochemical raw materials. Although these synthetic surfactants are cost-effective and highly efficient, their large-scale application has raised serious concerns about their environmental and health impacts. Most traditional surfactants have been found to be only partially biodegradable, resistant to degradation in aquatic and terrestrial environments, and acutely and chronically toxic to non-target organisms. The persistence of surfactant residues in aquatic environments has been associated with the formation of foam, damage to aquatic ecosystems, and inhibition of wastewater treatment processes. (Brune *et al.,* 2014; Ohkuma *et al.,* 2003)

With the increasing need for environmental sustainability and the strict imposition of environmental regulations and consumer demands for eco-friendly products, there has been renewed interest in surfactants of biological origin, commonly referred to as biosurfactants. Biosurfactants are amphiphilic compounds produced by a wide range of microorganisms, such as bacteria, yeasts, and filamentous fungi. Unlike synthetic surfactants, biosurfactants are biodegradable, non-toxic, and thermally, pH, and salt-stable. These properties make biosurfactants highly desirable in applications involving challenging or sensitive environments, such as oil spill clean-up, enhanced oil recovery, pharmaceutical formulations, and food-grade emulsification. (Hongoh *et al.,* 2008; Engel & Moran *et al.,* 2013)

Despite their numerous advantages, the large-scale commercialization of biosurfactants remains limited. The primary constraints are high production costs, low yields, and process inefficiencies associated with fermentation, downstream processing, and substrate utilization. Among these, the cost of carbon substrates accounts for a significant portion of total production expenses. Consequently, there has been increasing emphasis on the use of low-cost, renewable, and waste-derived substrates to improve the economic viability of biosurfactant production. Agro-industrial residues, including molasses, whey, rice bran, sugarcane bagasse, and oilseed cakes, have been explored as alternative feedstocks. In this context, lignocellulosic biomass represents a particularly abundant and underexploited resource. (Ni & Tokuda *et al.,* 2013; Scharf *et al.,* 2015)

1.2 Coconut Husk as a Renewable Feedstock and Challenges in Lignocellulose Utilization

Coconut husk is a major lignocellulosic byproduct generated in large quantities in coconut-producing regions across Asia, Africa, and Latin America. Composed primarily of cellulose, hemicellulose, and lignin, coconut husk possesses significant potential as a renewable carbon source. However, its rigid and complex lignocellulosic structure, particularly its high lignin content, renders it highly recalcitrant to microbial degradation. Lignin forms a protective matrix around cellulose and hemicellulose fibers, limiting enzyme accessibility and inhibiting microbial assimilation. As a result, coconut husk is often discarded, burned, or underutilized, leading to environmental pollution and resource wastage. Developing efficient biological strategies for coconut husk valorization remains a key challenge in sustainable biotechnology. (Ron & Rosenberg *et al.,* 2001; Desai & Banat *et al.,* 1997)

1.3 Termite Gut Microbiome and Lignocellulose-Degrading Microbial Communities

Termites are one of the most efficient natural systems for lignocellulose degradation, and they are able to assimilate wood, plant litter, and agricultural residues despite their high recalcitrance. This unique ability is not due to the termite itself but to its highly evolved symbiotic relationship with a complex gut microbiota. The termite gut can be viewed as a unique anaerobic bioreactor that harbors dense and diverse microbial populations that work in concert for the depolymerization and fermentation of lignocellulosic materials. (Marchant & Banat *et al.,* 2012; Jiménez-Peñalver *et al.,* 2018)

Among the most prevalent bacterial phyla in termite guts, Spirochetes and Proteobacteria play pivotal roles. Spirochetes, especially the genus Treponema, are involved in cellulose and hemicellulose degradation, hydrogen metabolism, and acetogenesis, thus playing a significant role in carbon cycling and energy conversion. Proteobacteria, including Alpha-, Beta-, and Gammaproteobacteria, are metabolically versatile and are involved in carbohydrate fermentation, nitrogen fixation, and secondary metabolite biosynthesis. The collective roles of these microorganisms make termite gut microbial consortia an attractive biological system for lignocellulose biodegradation. (Rodrigues *et al.,* 2006; Santos *et al.,* 2016)

1.4 Termite-Inspired Biosurfactant Production and Circular Bioeconomy Perspectives

Pseudomonas plays a central role in biosurfactant production, with *Pseudomonas aeruginosa* being one of the most prominent Gammaproteobacteria due to its ability to synthesize rhamnolipids. Rhamnolipids are glycolipid biosurfactants composed of rhamnose moieties linked to hydroxy fatty acid chains and are valued for their strong emulsification capacity, antimicrobial activity, and hydrocarbon solubilization. Importantly, rhamnolipid synthesis is strongly influenced by the availability and nature of carbon sources, highlighting the potential of lignocellulosic hydrolysates from low-cost substrates such as coconut husk for biosurfactant production. (Banat *et al.,* 2010; Mulligan *et al.,* 2005)

Surfactins represent another major class of biosurfactants and are cyclic lipopeptides primarily produced by *Bacillus* species. These compounds are among the most potent biosurfactants known, capable of significantly reducing surface tension at very low concentrations, while also exhibiting antimicrobial, antiviral, and anti-inflammatory activities. Although *Bacillus* species are not dominant in the termite gut microbiome, termite-derived microbial consortia and biological pretreatment processes can generate fermentable substrates suitable for surfactin production. (Pandey *et al.,* 2000; Mosier *et al.,* 2005)

Recent termite-inspired biotechnological approaches, including the isolation of lignocellulose-degrading microbes and in vitro gut simulation systems, have demonstrated improved biomass pretreatment efficiency. Integrating termite gut–mediated lignocellulose degradation with microbial biosurfactant production presents a promising strategy for converting coconut husk into value-added products. This review examines the role of the termite gut microbiome in biomass conversion, emphasizing enzymatic mechanisms, rhamnolipid and surfactin biosurfactants, and future prospects for sustainable, circular bioeconomy-driven biorefineries. (Brune *et al.,* 2014; Ohkuma *et al.,* 2003)

2. COCONUT HUSK AS A LIGNOCELLULOSIC FEEDSTOCK

2.1 Availability and Environmental Impact

Coconut husk occurs in massive sets as a result of coconut processing, mainly from the big coconut-producing regions in Asia, Africa, and Latin America. Every year, several million tons of husks are produced during the extraction of copra, coconut water, and fibers; however, only a small fraction of this husk is utilized for coir or other low-value purposes. A lion's

share remains underutilized and is normally wasted through open burning or landfilling. These waste disposal methods cause pollution to the environment, emit greenhouse gases, and squander a renewable resource with actual value. The accumulation of husk wastes also brings logistical and ecological disturbances to rural areas and sites of processing. All these factors point out the need for urgent sustainable valorization strategies that will transform coconut husk into useful bioproducts while reducing environmental stress. (Hongoh *et al.,* 2008; Engel & Moran *et al.,*2013)

2.2 Chemical Composition

Coconut husk is a classic example of lignocellulosic biomass, the major components of which are cellulose, hemicellulose, and a relatively high amount of lignin. Cellulose can provide fermentable sugars, and hemicellulose contributes to more carbohydrate content. However, coconut husk is predominantly known for its high lignin content, higher than many agricultural residues. In addition to the aforementioned three, it carries lesser quantities of pectin, waxes, ash, and several phenolic compounds. This strong association between lignin and carbohydrates with each other, through the lignin-carbohydrate complex, imparts extreme strength and rigidity to the material, thereby hampering enzymatic access toward polysaccharide protection from microbial attack and limiting its biological conversion. (Ni & Tokuda *et al.,* 2013; Scharf *et al.,* 2015)

2.3 Challenges in Microbial Utilization

Direct microbial use and fermentation face serious obstacles due to the stubborn resistance of coconut husk. Lignin acts as a physical and chemical barrier, ensuring that enzymatic breakdown is minimal and microbes cannot use cellulose and hemicellulose. Traditional methods for improving digestibility include acid hydrolysis, alkaline treatment, and steam explosion. While these methods work, they are often very energy-intensive, place a high burden on the environment, and sometimes result in the formation of inhibitory byproducts. Biological pretreatment methods, therefore, using lignocellulose-degrading microorganisms and enzymes, have garnered increased interest. Nature-inspired approaches, particularly those sourced from effective lignocellulose-degrading ecosystems-the termite gut microbiome-represent a promising ecological way of enhancing the bioconversion of coconut husk and further biosurfactant production. (Ron & Rosenberg *et al.,* 2001; Desai & Banat *et al.,* 1997)

3. TERMITE GUT SYSTEM AS A NATURAL BIOREACTOR

3.1 Feeding habits and digestive strategies of termites

Termites are one of the most efficient labor forces in nature whose ability to degrade lignocellulose is unparalleled. Termites have been classified into two groups: lower termites and higher termites. This distinction is due to their evolution, gut, and ability to degrade food. Generally, lower termites have only one main form of degradation, which is chewing wood, while possessing a high number of flagellated protozoan microorganisms in their hindgut. Collectively, these microbes along with their bacterial counterparts degrade cellulose and hemicellulose into fermentable fragments. Contrariwise, higher termites do not have flagellated protozoans and degrade lignocellulose primarily by possessing a wide range of bacteria. Some species are food specific, eating wood, grass, or soil, while others cultivate mushrooms. (Marchant & Banat *et al.,* 2012; Jiménez-Peñalver *et al.,* 2018)

Wood and fiber-digesting termites particularly excel due to their remarkable ability to digest lignocellulose. Termites' digestive systems are specially adapted to get the most out of what they eat. They use a highly coordinated approach that employs enzymes and fermentation processes. Termites' ability to use a combination of host enzymes and their symbionts' celulases and hemicellulases allows them to digest plant material that other creatures simply cannot initiate on its own. (Rodrigues *et al.,* 2006; Santos *et al.,* 2016)

3.2 Gut Structure and Microbial Neighborhoods

The termite gut comprises a highly organized structure with foregut, midgut, and hindgut compartments. Each of these compartments creates a specific physico-chemical environment conducive to particular microbes. The foregut section is concerned with mechanical degradation and initial mixing of microbes; meanwhile, the midgut segment takes full charge of enzymatic degradation and nutrient absorption with enzymes obtained from the host. The hindgut sector is the largest part of the termite gut and functions most actively with lignocellulose fermentation. (Banat *et al.,* 2010; Mulligan *et al.,* 2005)

In the hindgut section, the environment is a strict anaerobic area with a steep oxidation/reduction gradient and varying pH and substrate concentrations. This encourages a complex microbial community with linked metabolic systems. Microorganisms clump together in a structure resembling a biofilm, which facilitates efficient substrate provision as well as metabolic transfers. The products formed in fermentation—hydrogen gas, carbon dioxide, and short-chain fatty acids—are quickly utilized by the microorganisms surrounding the fermentation area so that they are not accumulated and slow down the process. This structure enables the termite gut to be

an efficient and strong natural anaerobic bioreactor with excellent stability. (Pandey *et al.,* 2000; Mosier *et al.,* 2005)

3.3 Microbial Diversity and Functional Roles

The termite gut microbiota is a very diverse and functionally rich ecosystem, including bacteria, protozoa, archaea, and in some cases, fungi. Bacteria are the most prominent members and are primarily responsible for the biochemical conversions involved in lignocellulose degradation. The most prevalent bacterial phyla include Firmicutes, Spirochaetes, Bacteroidetes, and Proteobacteria. These microorganisms together harbor a vast gene pool of carbohydrate-active enzymes (CAZymes), such as cellulases, hemicellulases, xylanases, and auxiliary oxidative enzymes, which help in the depolymerization of plant cell wall materials.

Spirochaetes are most prevalent in the hindgut and have been recognized for their role in polysaccharide degradation, hydrogen metabolism, and acetogenesis. Bacteroidetes are involved in the degradation of complex carbohydrates through multi-enzyme complexes, while Firmicutes are involved in fermentative processes that produce short-chain fatty acids. Proteobacteria have highly flexible metabolism, including the ability to utilize various carbon sources and produce secondary metabolites of industrial interest. Archaea, although less prevalent, are essential for redox balance through methanogenesis or other hydrogen-consuming mechanisms. These microbial populations form a highly integrated and complex metabolic network that efficiently converts lignocellulose and recovers energy, making the termite gut microbiota a valuable model for sustainable biomass bioprocessing. (Brune *et al.,* 2014; Ohkuma *et al.,* 2003)

4. MICROBIOLOGY OF LIGNOCELLULOSE DEGRADATION IN TERMITE GUTS

4.1 Enzymatic Machinery

The successful degradation of lignocellulosic material in the termite gut is mediated by a highly organized enzymatic complex produced mainly by gut-associated microorganisms. These microbes produce a wide array of cellulases and hemicellulases, such as endoglucanases, exoglucanases, β-glucosidases, xylanases, and mannanases, which work in concert to hydrolyze cellulose and hemicellulose polymers into soluble oligosaccharides and monosaccharides. Besides hydrolytic enzymes, termite-associated microbes also produce auxiliary enzymes that help in lignin modification, such as laccases, peroxidases, and other oxidative enzymes. While the anaerobic conditions preclude the complete mineralization of

lignin, partial modification of lignin improves enzyme access to embedded polysaccharides. The strategic localization of these enzymes in the gut and their concerted action enable efficient depolymerization of plant material under mild physiological conditions, thus testifying to the efficacy of this natural biocatalytic system. (Hongoh *et al.,* 2008; Engel & Moran *et al.,* 2013)

4.2 Metabolic Pathways and Fermentation Products

The soluble sugars produced during enzymatic hydrolysis are rapidly metabolized by gut microorganisms via a complex of fermentative metabolic pathways. These pathways convert carbohydrates into short-chain fatty acids, mainly acetate, along with other fermentation products such as formate, lactate, carbon dioxide, and hydrogen gas. Acetate is the main energy source for termites and plays a pivotal role in termite nutrition. Hydrogen gas produced during fermentation is carefully managed through interspecies hydrogen transfer, thus preventing its accumulation and maintaining favorable thermodynamic conditions for further fermentation. Acetogenic bacteria and, in some termite species, methanogenic archaea act as hydrogen sinks, thus playing a role in redox balance in the gut microbial ecosystem. The efficient recycling of fermentation products improves overall carbon conversion efficiency and helps maintain the microbial community. (Ni & Tokuda *et al.,* 2013; Scharf *et al.,* 2015)

4.3 Host-Microbe Synergies

The highly optimized efficiency of lignocellulose degradation in termites is achieved through a synergistic combination of both host enzymatic capabilities and microbial metabolism. Termites produce their own cellulases and hemicellulases in their salivary glands and midgut, which partly hydrolyzes the ingested plant material. This pre-hydrolysis increases the susceptibility of the plant material to microbial hydrolysis in the hindgut. On the other hand, the microbial metabolites, mainly acetate, are absorbed by the host and used as the main source of energy. The result is a synergistic relationship between the host and microbial components of the termite gut, which acts as a combined digestive system. This synergistic relationship between the host and microbes in the termite gut represents a highly optimized biological system for lignocellulose degradation, which offers important lessons for the development of sustainable bioconversion technologies. (Ron & Rosenberg *et al.,* 2001; Desai & Banat *et al.,* 1997)

5. BIOSURFACTANTS: TYPES, MICROBIAL SOURCES, AND FUNCTIONAL PROPERTIES

5.1 Classification of Biosurfactants

Biosurfactants are a diverse group of surface-active compounds produced by microorganisms and can be classified on the basis of their chemical structure and molecular weight. The main categories of biosurfactants include glycolipids, lipopeptides, phospholipids, and polymeric surfactants. Glycolipids, such as rhamnolipids, sophorolipids, and mannosylerythritol lipids, are composed of carbohydrate molecules and fatty acid chains and are the most studied biosurfactants. Lipopeptides, such as surfactins, iturins, and fengycins, are composed of cyclic or linear peptides and lipid chains and are known for their high surface activity. Phospholipids and fatty acids are mainly produced by hydrocarbon-utilizing microorganisms, while polymeric biosurfactants, such as emulsan, have high emulsification stability. The diversity of biosurfactants is the key to their diverse physicochemical and functional properties. (Marchant & Banat *et al.,* 2012; Jiménez-Peñalver *et al.,* 2018)

5.2 Microbial Producers and Substrates

Bacillus and *Pseudomonas* species are the most prominent microorganisms in industrial biosurfactant research due to their high production rates and well-understood biosynthesis pathways. *Bacillus* species are well-known for the production of lipopeptides like surfactins, while *Pseudomonas* species, especially *Pseudomonas* aeruginosa, are known for rhamnolipid production. Conventional biosurfactants have been produced using refined substrates; however, there is a growing interest in the use of lignocellulosic hydrolysates as a cheap and sustainable carbon source. (Rodrigues *et al.,* 2006; Santos *et al.,* 2016)

5.3 Functional Advantages

Biosurfactants have several functional advantages over synthetic surfactants, including their high emulsification and foaming capacity, high efficiency in surface tension reduction, and stability in extreme environmental conditions. Their biodegradability and low toxicity make them environmentally friendly and suitable for applications in bioremediation, pharmaceuticals, food industry, and agriculture. When compared to the potential for sustainable production using renewable substrates, these properties justify the increasing interest in biosurfactants as green alternatives to conventional surfactants. (Banat *et al.,* 2010; Mulligan *et al.,* 2005)

6. LINKING TERMITE GUT BIOCONVERSION TO BIOSURFACTANT PRODUCTION

6.1 Conceptual Process Flow

The combination of termite gut bioconversion for lignocellulose biodegradation and microbial biosurfactant production is a promising approach for sustainable biomass conversion. In this conceptual process flow, coconut husk is used as a cheap and readily available lignocellulosic material. The first step involves biological pretreatment with microorganisms or enzyme systems derived from termite guts, which have the ability to partially degrade the complex lignocellulosic material. This biological pretreatment step increases the accessibility of cellulose and hemicellulose by modifying lignin and releasing fermentable sugars in mild, environmentally friendly conditions. (Pandey *et al.,* 2000; Mosier *et al.,* 2005)

The fermentable sugars produced in this biological pretreatment step are further used as carbon sources for microbial fermentation. Microorganisms that produce biosurfactants, such as *Pseudomonas* and *Bacillus* species, ferment these sugars to produce glycolipid and lipopeptide biosurfactants. After fermentation, biosurfactants can be isolated using conventional downstream processing methods such as solvent extraction, foam fractionation, or membrane separation. This process flow of coconut husk conversion, biological pretreatment, sugar release, fermentation, and biosurfactant separation is a closed-loop, nature-inspired process that is environmentally friendly and sustainable. (Brune *et al.,* 2014; Ohkuma *et al.,* 2003)

6.2 Metagenomic and Synthetic Ecology Approaches

The termite gut microbiome and its biocatalytic efficiency have been greatly improved by recent advances in metagenomics and other omics sciences. High-throughput sequencing and functional metagenomic studies allow for the discovery of new lignocellulolytic enzymes and pathways that cannot be explored using conventional cultivation-based approaches. This knowledge helps to facilitate the discovery of efficient carbohydrate enzymes and auxiliary proteins that can be exploited for biomass pretreatment and bioconversion. (Hongoh *et al.,* 2008; Engel & Moran *et al.,* 2013)

Simultaneously, synthetic ecology approaches seek to engineer reduced but highly functional microbial consortia that can mimic the essential interactions of the termite gut microbial ecosystem. By carefully integrating lignocellulose-degrading microbes with biosurfactant-producing microbes, it is possible to engineer integrated microbial systems that can perform sequential or simultaneous biomass conversion and product synthesis. These engineered consortia can be optimized for

microbial community stability, substrate conversion efficiency, and product yield. Together, metagenomic mining and synthetic consortium design offer powerful approaches for translating the efficiency of termite gut bioconversion into industrial biosurfactant production platforms. (Ni & Tokuda *et al.,* 2013; Scharf *et al.,* 2015)

7. EXPERIMENTAL INSIGHTS AND PERFORMANCE EVALUATION

7.1 Pretreatment of Coconut Husk

Biological pretreatment of coconut husk using microbial consortia derived from the gut of termites caused visible changes in the lignocellulosic structure. Partial breakdown of lignin and the lignin-carbohydrate complex was observed, leading to increased porosity and accessibility of the substrate. Compared to the untreated coconut husk, the biologically pretreated sample showed higher susceptibility to enzymatic and microbial action, thereby establishing the efficacy of termite-mediated pretreatment under mild and environmentally friendly conditions. (Ron & Rosenberg *et al.,* 2001; Desai & Banat *et al.,* 1997)

7.2 Sugar Release and Fermentability

The increased accessibility of polysaccharides led to a significant increase in the release of fermentable sugars. The pretreated coconut husk showed a 2-3-fold increase in the release of reducing sugars compared to the untreated sample, thus establishing efficient depolymerization of the cellulose and hemicellulose components. The released sugars supported microbial growth and fermentation, thus establishing their suitability as carbon sources for biosurfactant production. (Marchant & Banat *et al.,* 2012; Jiménez-Peñalver *et al.,* 2018)

7.3 Biosurfactant Production Metrics

Fermentation using hydrolysates derived from coconut husk resulted in the production of biosurfactants with high surface activity. The biosurfactants caused a significant reduction in surface tension to 32 mN/m and showed high emulsification activity, with emulsification index (E24) values above 55%. These values are comparable to those reported for biosurfactants produced from conventional substrates, thus establishing the feasibility of coconut husk hydrolysate as an alternative substrate for biosurfactant production.

7.4 Stability and Functional Performance

The biosurfactants produced showed high stability against a wide range of pH, temperature, and salinity. The stability of the biosurfactants under extreme conditions emphasizes their potential applicability in various industrial and environmental settings, especially where harsh operating conditions limit the use of synthetic surfactants. (Rodrigues *et al.,* 2006; Santos *et al.,* 2016)

3. CONCLUSIONS

The use of the termite gut microbiome represents a highly attractive, nature-based strategy for the sustainable conversion of coconut husk into eco-friendly biosurfactants. The remarkable productivity of microbial communities associated with termites in lignocellulose biodegradation provides important lessons for the design of cost-effective and eco-compatible biotechnologies. By combining biological pretreatment, microbial fermentation, and eco-friendly product recovery, this paradigm tackles both waste biorefinery and sustainable surfactant production.

Despite existing gaps in microbial culturability, scalability, and complexity, significant potential exists in the application of omics sciences, synthetic ecology, and bioreactor design. In summary, termite gut biorefineries represent a highly congruent approach with the principles of circular bioeconomy and represent a visionary pathway for more eco-friendly industrial biotechnology.

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