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REVIEW ARTICLE **OPEN ACCESS**

Coconut Shell Liquid Smoke: Production, Composition, Yield and Multifaceted Applications

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ABSTRACT
The coconut, scientifically known as Cocos nucifera, belongs to the Arecaceae family and is categorized as an erect palm. Its fruit, notable for oil extraction, develops from a swollen base, resulting in an erect stem. This fruit is a drupe, characterized by its ovoid shape with three distinct ridges. The husk comprises both exocarp and mesocarp layers. While the coconut plant thrives in regions with consistent rainfall, it's essential to avoid water stagnation. Interestingly, the plant requires chloride for optimal growth and can tolerate up to 1% salt content in the soil. Various coconut varieties exist, largely influenced by their geographic origins. Ideally, these palms flourish in sandy terrains and are sensitive to freezing temperatures. Propagation primarily occurs through germination, spanning 3-6 months. Early harvesting might compromise the quality of the yield. One noteworthy byproduct of the coconut shell is liquid smoke, derived through pyrolysis. Detailed evaluations have shed light on the shell's compositional percentages and the intricacies of liquid smoke production. Furthermore, the plant's chemical constituents exhibit a range of therapeutic properties, including anthelmintic, anti-inflammatory, antinociceptive, antioxidant, antifungal, antimicrobial, and antitumor activities.
Keywords: *Cocos nucifera (Coconut); Pyrolysis; Liquid smoke; Therapeutic properties; Arecaceae family.*

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INTRODUCTION

This comprehensive review delves into the intricate processes involved in the production of liquid smoke from coconut shells, with a focus on the identification of its composition, determination of percentage yield, and exploration of its diverse applications. Notably, the lack of a distinct identification method poses a challenge, leading to the consideration that the products obtained through destructive distillation could be either liquid smoke or wood vinegar. This ambiguity highlights the need for a thorough investigation of coconut shell liquid smoke, a valuable resource derived from a potential source of hardwood.

The manufacturing of coconut shell liquid smoke is explored, encompassing both batch and continuous production methods, necessitating the use of reactors such as rotary calciners, heated screws, and batch charcoal calciners to expedite the pyrolysis process. Unlike other condensation processes, this mode of processing introduces numerous variables, including factors like feed rate, vapor residence time, particle size, oxygen penetration, and temperature, all of which significantly influence the yield and composition of the condensation products (1).

Extensive literature is reviewed to unveil the chemical compositions and their resulting applications. Manufacturers identify specific process control parameters to achieve standardized products with specified characteristics. Water emerges as a cost-effective resource, added strategically before and after condensation to facilitate three-layer separation, yielding an aqueous base fraction rich in various components. A highly polar fraction is characterized by carboxylic acids, aldehydes, and phenols, which contribute to the flavor, browning, antioxidant, and antimicrobial properties of liquid smoke. In contrast, the less dense upper layer condensation fraction contains a mixture of phytosterols, along with other oily and waxy substances, while the denser bottom layer, commonly referred to as tar, comprises phenolic polymers, secondary and tertiary reaction products, and a majority of polycyclic aromatic hydrocarbons.

Historically, wood tar, a constituent of liquid smoke, has been employed as a preservative and water repellent. This process elucidates the current manufacturing procedures adopted in commercial production. It's important to note that liquid smoke, also known as pyroligneous acid, remains unregulated in terms of both its manufacturing and utilization, emphasizing the need for a comprehensive review to elucidate its generation, composition, yield, and wide-ranging applications.

Coconut Development Board in India:

In support of the enduring traditional significance of coconut, the Ministry of Agriculture and Farmers' Welfare, Government of India, has established the Coconut Development Board. This governmental body focuses on the enhancement and development of various coconut-based products, including Kernel-based coconut products, Coconut water-based products, Coconut convenience food products, and Coconut shell-based products. The board plays a pivotal role in setting comprehensive specifications for all coconut-related products, ensuring quality and standards across the industry.

Among the range of coconut products, one of the areas under scrutiny is Coconut Charcoal. The board has established specific criteria and limits for Coconut Charcoal, which are detailed in the table below:

Specifications	Limits
Moisture	Less than 10%
Ash	Not more than 2%
Volatile matter	Not more than 15%
Fixed carbon	Not more than 75%
Foreign matter	Not more than 0.5%
Color	Black
Size	Not more than 5%, shall pass 0.63 cm mesh sieve.

These precise standards serve as a foundation for maintaining the quality and integrity of Coconut Charcoal products, ensuring they meet the required specifications, and contribute to the promotion of the coconut industry in India.

Composition of Coconut and Coconut Shell:

A comprehensive analysis reveals that the coconut fruit comprises three distinct layers, each with varying compositions. The coir layer, constituting approximately 55% of the coconut, forms the outermost layer. The second layer, the coconut shell, accounts for about 15% of the coconut's composition. The innermost layer contains the edible flesh, making up 22% of the coconut, and the drinkable liquid, representing 8%.

The coconut shell, being the second layer, is characterized by its robust and protective nature, safeguarding the coconut from external damage. What makes the coconut shell particularly interesting is its high carbon content and solid fuel properties, making it an excellent source for obtaining liquid smoke. Within coconut shells, you can find lignin, albeit in lesser quantities compared to cellulose. The hemicellulose content is similar to that found in other types of wood, while the water content varies depending on environmental conditions and the maturity of the coconut.

In specific environmental conditions, such as a dry air environment with a water content of approximately 6-9% (as observed in research conducted in Indonesia), the composition of the coconut shell is as follows:

Composition of Coconut Shell	Percentage (%)
Lignin	23.84%
Cellulose	30.44%
Hemicellulose	25.64%
Water content	14.00%

These precise composition details highlight the potential of coconut shells as a valuable resource, particularly for their lignin and cellulose content, which can be harnessed for various applications, including the production of liquid smoke.

Principle Involved in the Preparation of Liquid Smoke:

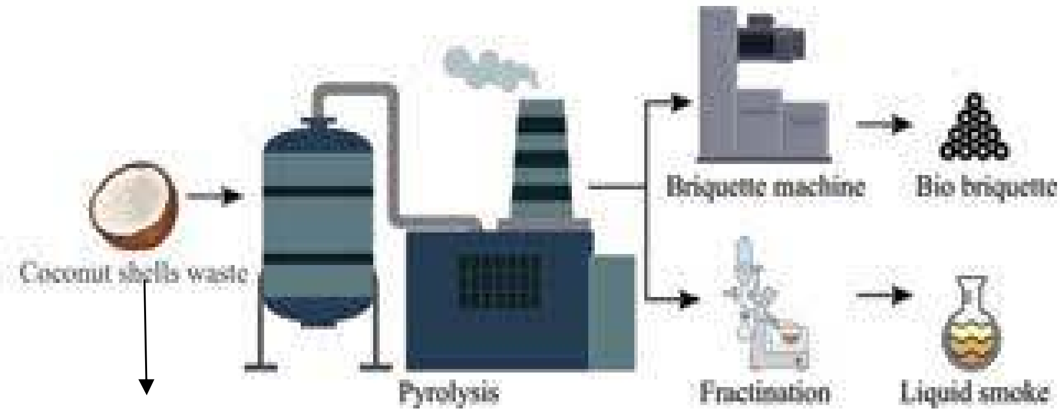
The production of liquid smoke is primarily achieved through the process of pyrolysis (4), which involves the controlled decomposition of raw materials through heating in an environment devoid of oxygen or with carefully controlled oxygen levels. During this intricate process, several products are generated, including gases, pyrolysis oil, and charcoal. The specific outcomes are influenced by factors such as the chosen pyrolysis method, the characteristics of the biomass used, and the precise parameters governing the manufacturing process.

While direct heat treatment of biomass yields some results, its efficiency remains relatively low, typically reaching only around 10%. An alternative approach to harnessing biomass involves the conversion of its liquid phase. The liquid generated through biomass processing is typically in the form of crude oil(5).

In the context of coconut shell pyrolysis, three distinct fractions are obtained: solid charcoal, tar, and gas. This process reveals the presence of over 400 different chemical components within the resulting smoke, all of which can be identified(6). However, the composition of these components varies significantly depending on factors such as the type of wood or biomass used, the age of the plant, prevailing climate conditions, and soil quality. Among these components, certain noteworthy compounds include acids, carbonyls, and phenols. Of particular interest, phenol exhibits antioxidant activity, contributing to the overall characteristics and utility of liquid smoke.

Production process of liquid smoke:

Liquid smoke (7) is derived from raw materials such as coconut shells, which are abundant in lignin, cellulose, hemicellulose, and various carbon compounds. When these materials undergo pyrolysis, the evaporating compounds condense into liquid smoke through a cooling process(8). This process initially produces a coarse smoke, which then separates into three distinct phases. One phase is water-soluble and can be used directly. The primary fraction, known as the tar phase, is instrumental in forming the liquid smoke. Below is a schematic diagram outlining the development process of liquid smoke.



Steps that are followed in production of coconut shell Liquid smoke:

1. **Preparation:** Coconut shells are initially cleaned to remove any dirt. They are then size-reduced to expose more surface area, facilitating better efficiency during the burning process.
2. **Drying:** The shells are dried to minimize water content.
3. **Pyrolysis:** The dried shells undergo pyrolysis, which is a dry combustion process that takes place in the presence of oxygen. This happens at temperatures ranging from 300°C to a maximum of 650°C over a period of 3 to 5 hours.
4. **Condensation:** The combustion smoke is then channeled through a circular coil, leading to the formation of three grades of liquid smoke, as well as tar and charcoal.

I.A Tabulation of the yield of the liquid smoke in various pyrolysis duration are researched which are as follows:

Raw Material	Raw Material	Duration of Pyrolysis	Total	Total liquid	Tar
Coconut shell	2500	180	6987	6422	8.09
	2500	240	8175	7516	8.06
	2500	300	8439	7758	8.07

II. A Tabulation of the yield of the liquid smoke in various temperature are researched which are as follows:

Raw Material used	Raw Material weight (kg)	Temperature (°C)	Charcoal weights (kg)	Volume of Liquid smoke (ml)
Coconut shell	1.2	400	0.3	245
		500	0.35	250
		600	0.33	260

Key Insights:
From the research, it is evident that the total yield of liquid smoke is significantly influenced by the type of raw material, the duration of the pyrolysis process, and the temperature (9).
Several micro-scale liquid smoke pyrolysis machines are available that significantly reduce the smoke emitted during charcoal burning. An added benefit of these machines is the by-product: liquid smoke. When coconut shells undergo the condensation process during pyrolysis at around 400°C, liquid smoke is produced. This smoke comprises various chemical components, including phenols, aldehydes, ketones, organic acids, alcohols, and esters. These components act as antioxidants and antimicrobials, and they impart a distinct smoky color and flavor to food products.
Co-pyrolysis:
Both coconut shells and empty fruit bunches have intricate chemical structures, resulting in varying thermal decomposition patterns. Combining these two (co-pyrolysis) harnesses a synergistic effect, enhancing both the quantity and quality of the output. Numerous studies have been conducted to determine the benefits of co-pyrolysis. Overall, co-pyrolysis technology produces high-quality products and is cost-effective.

Quantitative Analysis of Chemical Components in Coconut Shell:
Coconut shells primarily contain holocellulose, lignin, and extractives. These components were quantified through specialized extraction processes.
Determination of Extractives:
Methodology: A Soxhlet extraction system, utilizing a flask (250 ml) and an extraction tube (30-40 mm inner diameter), was employed. The flask was charged with a 50 ml ethanol and 100 ml benzene mixture. This mixture was heated to 90°C for approximately 6 hours using a steam bath. An air-dried sample (2.0-10 grams) was placed in a tared extraction thimble, which was then positioned inside the extraction tube. After 6 hours of heating, the solvent extract was concentrated to a volume of 20-25 ml. This concentrate was washed with fresh solvent and transferred to a drying dish. The dish was dried using a chemical fume hood, cooled in a desiccator, and then weighed. A control (blank) was established by drying 150 ml of solvent to calculate the residue.
Calculation: Extract %=$(W_e-W_0)/W_b$ X 100.
Where;
We = Dry weight of the extract
$W0$ = Dry weight of blank residue
Wb = Oven-dry weight of biomass (10)
Determination of Holocellulose:
Methodology: An Erlenmeyer flask received 2.5 g of the previously obtained extract. To this, 150 ml of deionized water, 1 g of $NaClO_2$, and 0.2 ml acetic acid were added. The mixture was heated at 80°C on a steam bath. After an hour, 1 ml sodium chlorate and 0.2 ml acetic acid were introduced. This process was repeated thrice. The resulting solution was filtered to collect the holocellulose, which was then dried overnight, cooled, and weighed.
Calculation: Holocellulose, %=$(He-H0)/Hb$ X 100.
Where;
He = Dry weight of holocellulose
$H0$ = Filter weight
Hb = Oven-dry weight of biomass (11)
Determination of Lignin:
Methodology: The H_2SO_4 method was utilized for lignin determination. An air-dried, extract-free sample (1.00 g) was combined with 15 ml of 72% H_2SO_4 in a 50 ml flask. After reacting at approximately 25°C, the biomass was further treated with 72% H_2SO_4 and allowed to stand at room temperature for around 4 hours. The mixture was then diluted with 560 ml of water in a 1000 ml flask and heated to 100°C for another 4 hours. The solution was cooled, filtered, and the obtained lignin was dried and weighed.
Calculation: Lignin%=$(Le-L0)/Lb$ X 100.
Where;
Le = Dry weight of holocellulose
$L0$ = Filter weight
Lb= Oven-dry weight of biomass (12)
The decomposition of key components, namely hemicelluloses and cellulose, is primarily due to heating at elevated temperatures.

Analytical Method for Liquid Smoke Identification:
Gas Chromatography (GC) is pivotal for the identification of liquid smoke. Retention time is instrumental in chromatographic identification. Liquid smoke derived at 400°C comprised components that separated within a retention time of 1.86 to 19.27 minutes, resulting in approximately 20 isolated compounds. Similarly, smokes obtained at 500°C and 600°C yielded separations within the same retention range, with each temperature producing 14 unique compounds (13).
Applications of Liquid Smoke Derived from Coconut Shell in Food and Other Industries:
Liquid smoke, primarily derived as a byproduct from coconut shell charcoal production, has seen increased utilization as a substitute for direct wood-based food smoking. Its multifaceted application spectrum spans across both food and non-food industries.
Applications in Food:
Preservation and Flavouring: Liquid smoke acts as a potent preservative while imparting a unique flavour and colour to food items. Its antibacterial properties combined with its textural and colouring effects are particularly prominent when applied topically and subsequently heat-treated.
Meat Processing: The meat industry extensively applies liquid smoke through shower or dip systems installed on continuous production lines. Approximately 35 meat processing facilities in North America deploy this methodology. Another approach involves encasing meat products in plastic followed by heat treatment.
Natural Flavour Source: Liquid smoke serves as a natural flavouring agent. This is achieved either by blending it directly with meats and other foods or by infusing it into whole muscle groups.
Condiments and Seasonings: This aromatic liquid finds its way into barbecue sauces and dry seasonings, often being blended with other flavor profiles for a richer taste.
Food Grade Processing: Prominent applications also include its extraction into oils, spray drying on maltodextrin carriers, or integration into food ingredients such as malt flour, yeast, or salt.
Applications Beyond Food:
Agriculture: Liquid smoke plays a pivotal role in seed germination, pest control, microbial control, and enhancing plant structure, owing to its pyroligneous acid content. Its ability to enhance soil quality, promote seed germination, and bolster leaf health has been reported in several agricultural studies.
Livestock Feed: It's recognized for its antimicrobial preservation of feed and for increasing the digestibility of nutrients.
Medicinal Claims: Anecdotal evidence suggests potential therapeutic effects of liquid smoke in managing various human ailments, ranging from gastrointestinal to dermatological conditions. However, current scientific literature lacks conclusive evidence to corroborate these claims.
Safety and Regulatory Oversight:
U.S. Food and Drug Administration (FDA) Evaluation: The role of the U.S. FDA in the evaluation of food additives is crucial in safeguarding public health. In its early recognition of the potential widespread use of liquid smoke, the FDA took pioneering steps to ensure its safety for consumption.
In 1981, in response to emerging concerns about the health implications of liquid smoke, the FDA commissioned a specialized panel to examine its safety profile (14). After rigorous assessments, the panel concluded that there was no substantial evidence to suggest that consumption of liquid smoke posed any significant risk to public health. This landmark decision led to liquid smoke being classified as Generally Recognized as Safe (GRAS) within the U.S. It means that the substance is accepted as safe based on substantial evidence of its safety under its intended conditions of use (15).
Furthermore, to ensure that manufacturing standards are consistently upheld, the FDA routinely conducts inspections of facilities producing liquid smoke. These inspections are not only focused on the final product but also the processes, ensuring adherence to stringent quality and safety guidelines (16).
European Union (EU) & European Food Safety Authority (EFSA) Evaluation: Parallel to the U.S., the European Union recognized the importance of having a consistent safety evaluation framework for smoke flavors, which are integral components of various European cuisines.
In 2003, the European Union laid down protocols to evaluate the safety of smoke flavors used in or on food (17). The task of these evaluations was entrusted to the European Food Safety Authority (EFSA), an independent European agency dedicated to ensuring the safety of Europe's food.
One of EFSA's significant evaluations centered on assessing the primary condensate smoke flavors. From a total of 12 products presented by 10 distinct applicants for assessment, each product was subjected to in-depth analysis using both in vitro and in vivo methods (18). While all products were found to be genotoxic-positive when evaluated using in vitro methods, a noteworthy distinction emerged when assessed through in vivo methods. Ten of these products were deemed devoid of any concerning attributes, marking them as safe for consumption.

This detailed evaluation by the EFSA underscores the importance of multifaceted testing methodologies in drawing comprehensive safety conclusions. The variance in results between in vitro and in vivo methods emphasizes the need for a holistic evaluation approach to ensure that products reaching consumers are genuinely safe.

Liquid smoke, while a valuable flavoring agent, has been at the forefront of safety and regulatory evaluations. Bodies like the FDA and EFSA have played pivotal roles in ensuring that its consumption remains safe. Such rigorous evaluations underscore the importance of consistent safety checks, especially when it concerns widely used food additives.

Expert Opinion:

The utilization of coconut shell charcoal to produce liquid smoke showcases a promising pathway to sustainable and multifunctional bio-derived products. By turning an often-discarded byproduct into a valuable commodity, this approach epitomizes the principles of circular economy and sustainable resource management. Given the myriad of potential applications for this form of liquid smoke, ranging from food preservation to potential therapeutic applications, its importance cannot be overstated.

However, a holistic evaluation is crucial. While the current literature sheds light on its potential benefits, it is equally essential to ensure that the liquid smoke is produced, used, and disposed of in a manner that is environmentally sustainable, socially responsible, and economically viable. Moreover, the biochemical complexities of liquid smoke, given its rich matrix of compounds, warrant deeper exploration to fully harness its benefits and address any potential challenges.

Future Research Directions:

Comprehensive Chemical Profiling: While we have some understanding of the chemical constituents of coconut-derived liquid smoke, a more in-depth and comprehensive profiling using advanced chromatographic and spectroscopic techniques can reveal minor but crucial components that may influence its functionality.

Health Impact Studies: More extensive in vivo and clinical studies are needed to determine the potential health benefits and risks associated with consuming products treated with or containing this form of liquid smoke. Such studies should look at both acute and chronic effects.

Technological Innovations: Modern innovations in pyrolysis and related technologies can potentially enhance the yield, quality, and diversity of compounds within liquid smoke. Investigating these avenues can result in better and more consistent products.

Application Diversification: Beyond its established uses, research could explore novel applications of liquid smoke. Possible avenues include its potential role in organic agriculture, as a natural herbicide or insect repellent, or in green chemistry as a natural solvent or reactant.

Environmental and Economic Lifecycle Analysis: A lifecycle analysis, examining the environmental and economic impacts from sourcing coconut shells to producing and using liquid smoke, can shed light on its true sustainability credentials. Such analyses can help identify areas for improvement and ensure its long-term viability.

Sensory and Consumer Research: Given its application in food, understanding consumer perceptions, sensory experiences, and potential cultural influences related to liquid smoke-treated products is crucial. This can guide its optimized usage in food products.

Ethical and Societal Considerations: As the demand for such products grows, ensuring ethical sourcing practices, fair compensation for farmers, and understanding societal implications become pivotal.

On a whole, the future of liquid smoke from coconut shell charcoal appears bright with vast untapped potential. By approaching it with a multidisciplinary lens, the scientific and industrial community can ensure its benefits are maximized for both society and the environment.

CONCLUSION

Liquid smoke, derived from the pyrolysis of coconut shell charcoal, exemplifies the ingenious repurposing of byproducts traditionally viewed as waste. This substance has carved out a versatile niche for itself, not only as a robust preservative in the food industry but also as a promising candidate for various medicinal applications. As the demand for such versatile compounds increases, it is imperative to intensify research efforts aimed at optimizing its production. Harnessing the potential of this traditional resource, while ensuring sustainable and cost-effective methodologies, will pave the way for not only meeting industrial needs but also mitigating environmental challenges. By capitalizing on innovative processes and embracing the full spectrum of its benefits, we can unlock new avenues for both sustainable development and holistic utilization of resources.

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