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Thermal-Chemical Extraction of Bamboo-Derived Silica for Food Encapsulation Systems

Nurul Fariha Kamarul Rashid[1,a)], Saiful Azhar Mahat@Kassim[1,b)], Massitah Kipli[1,c)], Rafidah Abu Nasir[1,d)], Budiah Karmilie Che Kadir[1,e)] and Musfafikri Musa[2,f)]

[1] *Politeknik Sultan Idris Shah, Sabak Bernam, 54100 Sungai Air Tawar, Selangor, Malaysia*
[2] *Kolej Kemahiran Tinggi Mara, Lenggong, 33030, Lenggong, Perak, Malaysia*

[a)] *Corresponding author: nurul_fariha@psis.edu.my*
[b)] *saifulazhar@psis.edu.my*
[c)] *massitah@psis.edu.my*
[d)] *rafidah@psis.edu.my*
[e)] *budiahkarmilie@psis.edu.my*
[f)] *musfafikri@mara.gov.my*

Abstract. This report presents an exhaustive analysis of the thermal-chemical extraction of silica from bamboo for food encapsulation, illuminating its transformative potential as a sustainable and functional ingredient. Bamboo, a rapidly renewable resource, distinguishes itself as an exceptionally rich source of natural silica, offering a compelling alternative to conventional silica sources. The investigation delves into the scientific principles, technical methodologies, practical applications, safety considerations, and future trajectory of bamboo-derived silica within the food industry. Key findings indicate that thermal-chemical methods, particularly acid leaching combined with calcination, are highly effective in producing high-purity silica with desirable properties for encapsulation. To advance this field, strategic recommendations focus on developing greener, more cost-effective industrial-scale extraction methods. Further efforts should be directed towards advanced material engineering to tailor silica properties for specific encapsulation needs and conducting comprehensive in vivo safety studies. Expanding novel food applications while proactively engaging with regulatory bodies to establish clear guidelines for bamboo-derived food-grade silica will be crucial for widespread adoption and commercial success.

Keywords: Bamboo, Silica, Encapsulation, Halal Innovation.

1. Introduction

Silica, or silicon dioxide (SiO2), stands as the second most abundant element in the Earth's crust, surpassed only by oxygen. It is a naturally occurring mineral widely distributed in various environments, found predominantly in vegetables and diverse water sources. Beyond its geological prevalence, silicon, in the form of silica, functions as an essential trace element within biological systems. Its critical roles encompass maintaining the structural integrity of connective tissues, skin, ligaments, tendons, and bone. The recognition of silicon as an essential nutrient dates back to 1972, solidifying its importance in biological processes [1]. Within the human body, silica plays a pivotal role in numerous physiological functions. It is indispensable for collagen production, a protein fundamental for maintaining skin elasticity and firmness, thereby contributing to a youthful appearance [2]. The long-established biological importance and widespread natural occurrence of silica provide a strong foundational argument for its acceptance as a food ingredient. This inherent "naturalness" and recognized health benefits contribute significantly to its appeal for clean-label food applications, differentiating it favorably from purely synthetic alternatives.

Bamboo is globally recognized for its remarkably rapid growth rate, exceptional strength, and its rich composition of nutrients and antioxidants. Historically, bamboo has been a cornerstone in traditional medicine for centuries, particularly across Asia, where it symbolizes strength and flexibility. This deep cultural and historical integration underscores its long-standing recognition as a valuable natural resource. Significantly, bamboo stands out as one of the richest known natural sources of silica [8][14]. Its extract is reported to contain over 70% silica. Some studies specifically highlight that the silica content in bamboo leaves can exceed 70% 10, with dried bamboo leaf wastes potentially containing as much as 79.28% silica in the ash or 19.42% in the leaves themselves. This exceptionally high concentration positions bamboo as a premier raw material for silica extraction. The extraction process from bamboo is inherently sustainable. As a fast-growing plant, bamboo requires minimal water, pesticides, or fertilizers, resulting in a significantly lower environmental impact compared to many other agricultural crops [8]. The combination of high yield potential and ecological soundness makes bamboo a uniquely attractive and strategic choice for industrial-scale biosilica production, addressing both economic and ethical considerations for food manufacturers.

Food encapsulation is a sophisticated technological process that involves entrapping active ingredients within a protective matrix, thereby forming micro- or Nano capsules. The application of encapsulation technology contributes significantly to elevating food quality, ensuring safety, and extending the shelf-life of food products [8][9][10]. This synergistic relationship suggests that bamboo silica can not only protect but also potentially enhance the functionality of encapsulated food ingredients, leading to superior product performance and opening avenues for novel food applications.

1.1 Problem Statement

Despite the abundant availability of bamboo leaves as an agricultural waste product globally, and their remarkable composition as a rich source of biosilica (often exceeding 70% silicon dioxide, SiO2), these valuable biomass resources are frequently discarded by communities [10]. This widespread underutilization represents a significant missed opportunity for valorization of agricultural waste, contributing to environmental burdens and inefficiencies in resource management. While the broader bamboo powder market is experiencing growth, particularly within the food and beverage sectors, the full potential of extracting high-purity silica from this waste stream for specialized, high-value food applications like encapsulation remains largely untapped [4]. Such applications demand stringent purity standards and tailored material properties that go beyond general bamboo powder uses. The current underutilization of bamboo waste for high-value silica extraction highlights an economic inefficiency and an environmental burden. Developing robust thermal-chemical extraction methods directly addresses this by converting a low-value waste product into a high-value, functional food ingredient, thereby contributing to circular economy principles and sustainable resource management. This transformation offers a dual benefit: waste reduction and the creation of a novel, marketable product.

The extraction of silica from bamboo, particularly through thermal-chemical methods, presents inherent complexities that pose challenges for industrial scalability and environmental sustainability. While various methodologies, including thermal, biological, and chemical approaches, have been explored for silica extraction from diverse bio-ash sources, optimizing these for efficiency, purity, and environmental impact is crucial. A primary challenge lies in achieving consistent high purity and yield [10]. Studies have shown varying silica yields depending on the type and concentration of acid used in leaching. For instance, hydrochloric acid (HCl) has yielded up to 65.17% silica from bamboo leaves ash (BLA), while nitric acid (HNO3) has resulted in yields around 38.88% [10]. The concentration of the acid significantly influences both the yield and purity, indicating a delicate balance in process parameters [15]. Achieving high purity, such as 98% or 99% amorphous silica, often requires specific acid concentrations (e.g., at least 1.5 M HNO3) to eliminate impurities like magnesium, potassium, and calcium, which can affect the crystalline phase of the extracted silica [10].

Furthermore, conventional acid leaching treatments, while effective, often involve the use of strong acids like sulfuric acid (H2SO4), hydrochloric acid (HCl), and nitric acid (HNO3) [13]. These reagents are classified as hazardous chemicals, posing significant environmental and human safety risks. The use of strong acids also incurs economic challenges due to the necessity of expensive corrosion-resistant materials for equipment, extensive water rinsing of the processed material, and specialized waste disposal. This highlights a critical need for developing more environmentally benign processes, potentially exploring organic acids as safer alternatives [13]. However, identifying the precise conditions that maximize yield and purity while minimizing energy consumption and hazardous waste generation remains an active area of research. The application of bamboo-derived silica in food encapsulation necessitates rigorous attention to purity and safety, particularly when considering its use as a food additive or ingredient. While amorphous silicon dioxide is generally recognized as safe (GRAS) and approved as a food additive (E551) with an "not specified" Acceptable Daily Intake (ADI) by regulatory bodies like the FDA and JECFA 3, specific concerns arise with plant-derived extracts and nano silica. [8][9][10][11][14].

1.2 Research Objective

i) To develop and optimize a thermal-chemical extraction method for synthesizing high-purity silicon dioxide (SiO_2) from agricultural waste, specifically bamboo leaves, using sustainable and cost-effective techniques.

ii) To characterize the physicochemical properties of the extracted amorphous silica and evaluate its suitability for applications in food additives, pharmaceuticals, cosmetics, and encapsulation.

iii) To assess the viability of bamboo-derived silica as an eco-friendly, inorganic, and halal-compliant alternative to commercially available silica, promoting circular economy practices through agricultural waste valorization.

2. LITERATURE REVIEW

2.1. Extraction and Characteristics of Bamboo-Derived Silica

A contemporary study by [11] explored the sol–gel extraction of silica from Gigantochloa albociliata bamboo leaves ash. Their FTIR analysis revealed pronounced –Si–OH (hydroxyl) groups at 3381.25 cm^{-1}, indicative of abundant surface hydroxyl functionality. These groups may play a pivotal role in the adsorption and binding of encapsulant compounds such as biomolecules and flavors

Next, another research has been investigated the ultrasonication-based synthesis of nanosilica from betung bamboo (Dendrocalamus asper) sticks and leaves. They reported silica yields of 45.7% (sticks) and 79.9% (leaves) on an ash dry-weight basis. Ultrasonication for two hours transformed the ash-derived silica into nanosilica, although particle sizes remained relatively large (~≥6000 nm) [12].

Furthermore, another research has been also demonstrated that bamboo leaf biomass can yield up to 50.2% silica with exceptional purity (~99%) and high surface area. Importantly, these bamboo-derived silica nanoparticles exhibited minimal cytotoxicity at concentrations up to 100 µg/mL in osteoblast-derived MG-63 cells, suggesting strong biocompatibility [18].

2.2 Encapsulation-Relevant Properties

The structural attributes of bamboo-derived silica—including high surface area, surface hydroxyl groups, and biocompatibility—position it as a promising matrix for food encapsulation systems. The abundant surface –Si–OH groups detected by [11] indicate high hydrophilicity and potentially enhanced adhesion to hydrophilic bioactive compounds, such as vitamins, antioxidants, or flavors. The nanoscale or microporous structure achieved through ultrasonication [12] increases potential loading capacity and may regulate release profiles. Exceptional biocompatibility, as shown by non-toxic reactions in cell studies, supports safe interaction with food ingredients or human consumption.

While encapsulation applications have been demonstrated in pharmaceuticals and cosmetics, there is a lack of direct studies applying bamboo-derived silica explicitly to food encapsulation systems—such as flavor delivery, nutrient stability, or controlled-release packaging. Yet, the properties identified in the literature strongly support its suitability for such innovations.

3. RESEARCH METHODOLOGY

The extraction of silica from bamboo leaves was conducted through a systematic multi-step process. Initially, fresh bamboo leaves were carefully washed to remove dirt and impurities, then sliced into smaller pieces and dried in an oven at 90°C for 24 hours to eliminate moisture content. The dried leaves were subsequently calcined in a muffle furnace at a temperature of 700°C for 5 hours, with a controlled heating rate of 2°C per minute, to produce bamboo ash rich in silica content. Silica extraction was carried out by treating the bamboo ash with a 2M sodium hydroxide (NaOH) solution at a solid-to-liquid ratio of 1:25. This mixture was maintained at 85°C for 2 hours under constant stirring to facilitate the dissolution of silica. Following extraction, the mixture underwent filtration using Whatman filter paper (medium fast) to separate the insoluble residues from the silica-rich solution. The sol-gel method was then employed for silica recovery by carefully adding 1M hydrochloric acid (HCl) dropwise under continuous stirring until the solution reached a neutral pH of 7, promoting gelation. The resultant silica gel was collected through vacuum filtration and dried in a universal oven at 90°C for 24 hours to obtain purified silica powder. The yield of silica was quantified by calculating the percentage ratio of the dried silica mass to the initial dried bamboo leaves mass. Finally, the chemical composition and structural characteristics of the extracted silica were analyzed using Fourier Transform Infrared Spectroscopy (FTIR) to verify the success of the extraction and purity of the silica. [8][9][10][11][14]

4. Results

The current study highlights the significant variation in silica content among different anatomical parts of the bamboo plant, with a specific focus on leaves, shoots (including blanched shoots), and culm. Among all tested parts, only the leaves yielded extractable silica, with a measured extraction yield of 4.77%. In contrast, the shoot, blanched shoot, and culm yielded no measurable silica under the same extraction conditions.

Table 1. Comparative Silica Extraction Efficiency from Various Anatomical Parts of Bamboo

Part	Silica extraction
Leaves	4.77%
Shoot	-
Shoot (Blanching)	-
Culm	-

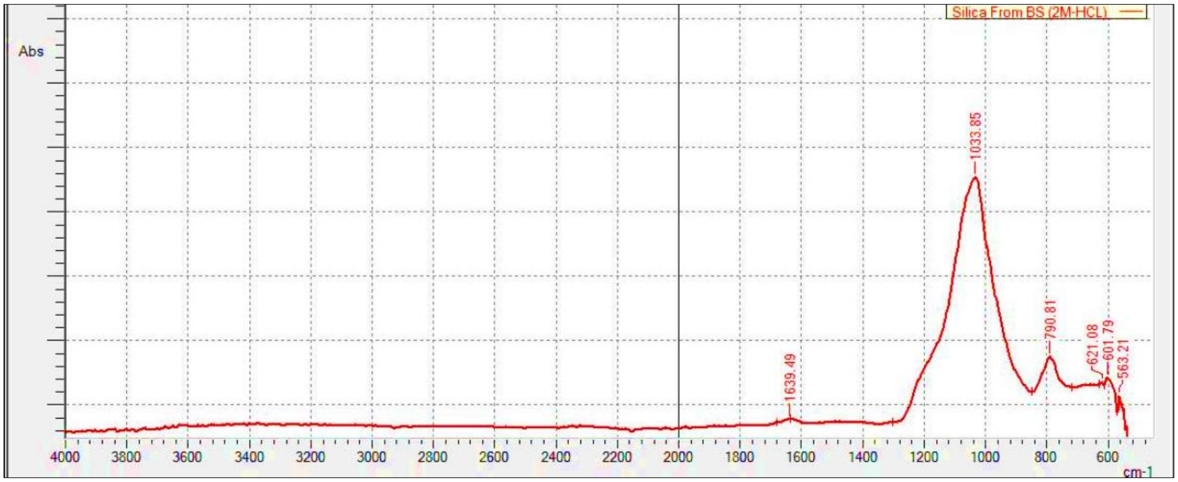

Figure 1. Fourier Transform Infrared (FTIR) Spectrum of Silica Extracted from Bamboo Shoot Using Hydrochloric Acid

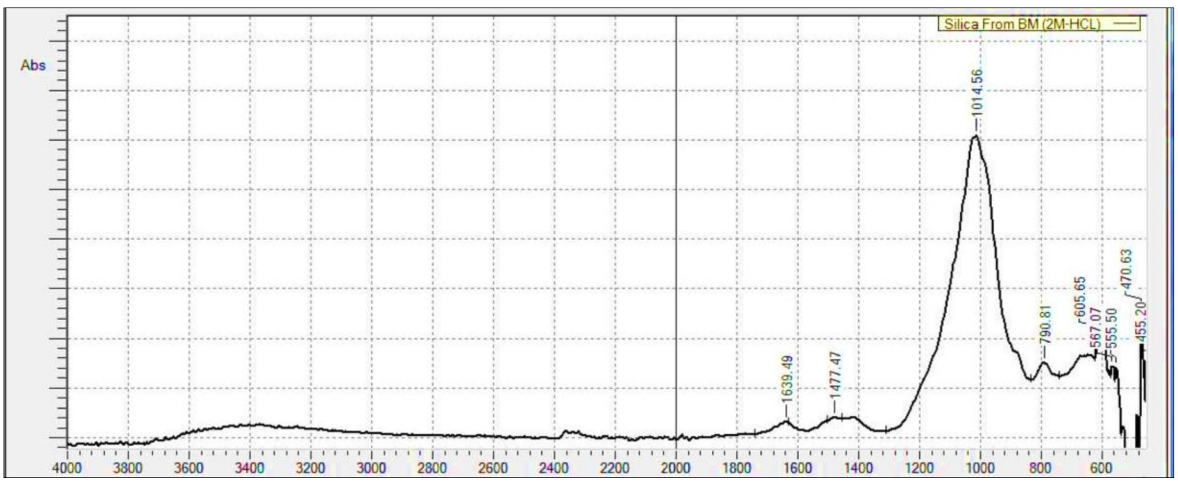

Figure 2. Fourier Transform Infrared (FTIR) Spectrum of Silica Extracted from Bamboo Leaves using Hydrochloric Acid

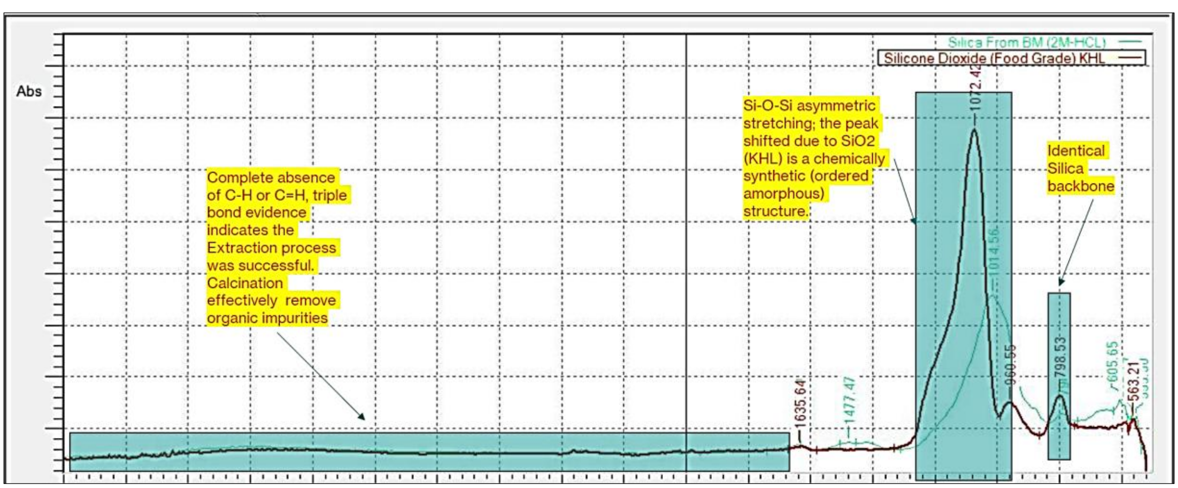

Figure 3. Comparative FTIR Spectrum of Bamboo Midrib-Derived Silica (2M HCl) and Commercial Food-Grade Silica (SiO_2 KHL)

The FTIR spectra of silica extracted from bamboo midrib using 2M HCl exhibit characteristic absorption bands closely matching those of commercial food-grade silica (SiO_2 KHL). Notably, the absence of peaks related to C–H or C=H bonds confirms effective removal of organic impurities through the thermal-chemical extraction and calcination processes, resulting in a high-purity silica product. Key peaks at approximately 1014–1033 cm^{-1} correspond to the Si–O–Si asymmetric stretching vibrations, with the slight peak shift in the commercial silica attributed to its chemically synthesized, more ordered amorphous structure. Additional absorption bands near 798 cm^{-1} and 605 cm^{-1}, associated with Si–O–Si symmetric stretching and bending modes, respectively, are observed in both samples. These findings indicate that the bamboo-derived silica possesses a comparable molecular structure to commercially available food-grade silica. The structural integrity and purity demonstrated by FTIR analysis support the suitability of bamboo-derived silica for advanced food encapsulation applications. Its biomaterial origin, combined with effective organic matter removal, ensures a safe, halal-compliant, and sustainable alternative to synthetic silica, with promising implications for enhancing food additive stability and bioavailability. In conclusion, the FTIR analysis validates that the extraction methodology employed yields high-quality silica from bamboo midrib, comparable to commercially available food-grade silica. This biomass-derived silica offers a sustainable and halal-compliant alternative for food encapsulation and other industrial applications.

5. Discussion

The present study demonstrates an effective thermal-chemical extraction protocol to obtain high-purity silica from bamboo leaves, validating the integration of calcination and sol-gel acid leaching methods. Calcination at 700°C for five hours was critical in decomposing organic components, which was evidenced by the absence of C-H and C=C stretching peaks in the FTIR spectra, indicating successful removal of organic impurities. The alkaline extraction step, employing 2M NaOH at 85°C, facilitated the conversion of silica present in bamboo leaves into soluble sodium silicate. Subsequent acidification with 1M HCl induced gelation and precipitation of silica at a controlled pH of 7, maximizing recovery while maintaining an amorphous silica structure favorable for encapsulation applications. The FTIR results showed characteristic Si–O–Si asymmetric stretching bands, closely matching those of commercial food-grade silica, confirming the chemical purity and structural integrity of the bamboo-derived silica. The use of bamboo leaves, an abundant and renewable agricultural waste, as a silica source promotes sustainable material sourcing, aligning with principles of green chemistry and circular economy. Moreover, the inorganic and halal-compliant nature of the extracted silica presents valuable opportunities for its application in food additives, pharmaceuticals, and encapsulation systems designed for halal markets. Overall, this study provides a scalable, environmentally benign, and cost-effective methodology for producing high-quality bamboo-derived silica, highlighting its promising potential in advanced food encapsulation technologies and other industrial applications.

6. Conclusion

Based on the high silica content derived from bamboo leaves and its demonstrated potential for diverse applications in food additives, pharmaceuticals, cosmetics, and encapsulation, it is strongly recommended to further explore bamboo leaves as a sustainable and cost-effective source of silica. Future research should focus on scaling up the extraction process while ensuring the purity and functional quality of the silica meet industry standards. Additionally, investigating the integration of bamboo-derived silica into commercial formulations can open new avenues for eco-friendly and halal-compliant materials in various sectors. Emphasis should also be placed on optimizing extraction techniques to enhance yield and reduce environmental impact, thereby promoting the valorization of agricultural waste into high-value biomaterials. Future research should prioritize optimizing extraction methods to improve yield and purity while reducing environmental impact. Scaling up production and validating the performance of bamboo-derived silica in real-world applications will be critical steps. Additionally, ensuring strict halal certification will be essential for market acceptance and expanding the use of this biomaterial in halal industries worldwide. This work underscores the potential of agricultural waste valorization to produce valuable, eco-friendly materials that meet both industrial and ethical standards.

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