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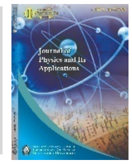

Analysis of Diffraction and Spectroscopy for bamboo Clam Shell Waste (Ensis S.P) as a Natural Source of Calcium

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ABSTRACT

Shell waste is a natural source of rich biominerals, primarily high-purity calcium carbonate ($CaCO_3$). This study utilized bamboo shell waste from three locations on the south coast of Pamekasan as a raw material for the synthesis of $CaCO_3$ compounds. The aim of this research was to characterize the composition of powdered bamboo clam shells as a source of natural calcium. The shells were prepared through several stages, including washing, drying, size reduction, and oven-drying at 105°C. They were then pulverized using a ball mill and sieved through a 200-mesh sieve. The resulting shell powder was characterized using XRF, FTIR, and XRD. The XRF results showed that the dominant chemical elements from the three locations were calcium (Ca) and its oxide compound (CaO), with average percentages of 97.95% and 98.09%, respectively. The FTIR analysis indicated the presence of $CaCO_3$ functional groups, namely CO_3^{2-}, C–O, Ca–O, and C–H, identified by absorption peaks in range 400-4000 cm^{-1}. The XRD results confirmed that bamboo clam shells powders were contained of $CaCO_3$ as a single phase with the crystalline structure of aragonite (orthorhombic). Based on these results, it can be concluded that bamboo clam shell powder is a viable source of natural calcium minerals.

1. Introduction

Pamekasan Region, as part of Madura Island, possesses significant marine and fisheries potential. One prominent commodity commonly found is bamboo clam (*Ensis* sp.). This clam is easily obtained, affordable, and has become a part of the local community's traditional cuisine. According to data from Pamekasan Fisheries Service in 2023, the production of bamboo clams in this region reached 9,234 tons per year, resulting in a corresponding amount of discarded shell waste. Activities from households, seafood restaurants, and small-scale clam processing industries in Pamekasan generate a significant tonnage of shell waste daily. To date, the utilization of bamboo clams has been focused solely on the meat, while the shells, which constitute 60-70% of total biomass, are discarded as waste that has not been optimally utilized. This shell waste is generally piled up in final disposal sites or discarded directly into the environment, which can cause pollution problems. These issues primarily include unpleasant odors due to the decomposition of residual organic compounds, as well as aesthetic degradation [1].

Behind this waste problem lies significant untapped potential. The selection of bamboo clam (*Ensis* sp.) shell waste as the research object is based not only on its abundance but also on its intrinsic uniqueness. As a highly abundant fisheries commodity, it has become part of the cultural and economic identity of Pamekasan community. From a materials science perspective, this type of clam is suspected to possess a unique biomineral structure due to its habitat and biological processes [2]. Its dense and compact laminated structure has potential to yield a calcium carbonate precursor with distinct purity, crystallinity, and morphology compared to common clams. An in-depth characterization of this local material is necessary to prove its superiority and feasibility.

Naturally, clam shells contain calcium carbonate ($CaCO_3$) compounds in various crystalline phases, positioning them as a potential source of natural calcium minerals. Clam shells, including bamboo clams, are known to consist of over 90% calcium carbonate ($CaCO_3$) within an organic matrix. The uniqueness of these clam shells lies in their hierarchical and hard biocomposite structure, formed through a biomineralization process [3]. Structurally, the shell consists of approximately 95-99% calcium carbonate in various crystalline phases, with the remainder being an organic matrix (such as protein and chitin) and small amounts of other minerals. This composition makes it an excellent precursor for the synthesis of calcium oxide (CaO) [4]. This compound serves as an excellent precursor for various applications, ranging from health supplements and food fortificants to pharmaceutical raw materials, and further to industrial applications such as a filler in polymer and paper industries. The advantage of calcium derived from natural sources like clam shells is its presence in a form that is easily absorbed by the body (bioavailable) and its accompaniment by other trace minerals, which may provide a synergistic effect [5].

Currently, the commercial source of CaO is predominantly derived from limestone mined from mountains. Excessive limestone exploitation has negative environmental impacts, including landscape degradation and loss of biodiversity. Calcium oxide (CaO) is a functional material with broad applications in various industries. The unique structure of bamboo clam shell, which has a dense and compact lamination, is strongly suspected to influence the physicochemical properties of calcium carbonate mineral within [6].

Calcium is an essential mineral that plays a critical role in various industries, ranging from health supplements and functional foods to pharmaceuticals and biomedical applications. Currently, commercial calcium sources are largely derived from mineral rocks (such as calcite) or synthetic methods, which can involve high costs and less environmentally friendly processes [7]. Consequently, the search for sustainable, economical, and eco-friendly natural calcium sources has become a significant research focus.

Numerous previous studies have confirmed the potential of shellfish shells as a calcium source. These include the characterization of green mussel (*Perna viridis*) [8,9], blood cockle (*Anadara granosa*) [7,10,11], and oyster (*Crassostrea gigas*) [12] shells, which have demonstrated a high calcium carbonate content in the form of calcite or aragonite minerals. The synthesis and characterization of waste clam shells (*Ensis* sp.) from Kampung Laut, East Tanjung Jabung Regency, were carried out at a calcination temperature of 800-900°C. The XRD characterization results indicated that all samples exhibited sharp peaks originating from calcium oxide (CaO). However, it is important to note that the physicochemical characteristics of a biogenic material like shellfish shells are highly influenced by factors such as species, habitat, growth environment, and geographical conditions [13]. Scientific literature that specifically discusses in-depth the characterization of bamboo clam shells from Pamekasan remains very limited. This knowledge gap underlies the urgency of present research, to ensure that the potential of local bamboo clam shells is not simply generalized based on findings from other shellfish species from different regions.

The potential of bamboo clam shell waste from Pamekasan as a natural calcium source has not been comprehensively characterized, leaving its added value largely unexplored. Therefore, this research is conducted as a strategic effort to optimize the utilization of Pamekasan's local natural resources through a materials science approach. Utilizing bamboo clam shell waste as a raw material for a calcium source is a form of implementing the waste-to-wealth concept. This approach not only addresses the waste problem but also creates a circular economy where waste is processed into materials with functional and economic value, thereby supporting the principles of green and sustainable industry.

This study aims to comprehensively analyze bamboo clam shells using spectroscopic (XRF and FTIR) and diffraction (XRD) techniques to characterize their potential as a source of calcium minerals. The development of local natural resources is a crucial pillar in supporting sustainable regional economic growth. The results of this study are expected to provide valid scientific data on feasibility and advantages of Pamekasan bamboo clam shells as a source of natural calcium. Practically, these findings can serve as a foundation for developing a high-economic-value waste processing industry in Pamekasan region, while also contributing to materials science through the exploration of sustainable materials derived from renewable natural resources.

2. Methods

Samples of bamboo clam shells (*Ensis* sp.) were collected from three different locations along the southern coast of Pamekasan Regency. These locations were selected to represent the geographical distribution of this known bamboo clam harvesting area, thereby ensuring adequate sample availability and ecological relevance. The sampling locations and their nomenclature were as follows:

1. Location 1: East Pademawu Village (Sample CKB 1).
2. Location 2: Tanjung Village, Pademawu District (Sample CKB 2).
3. Location 3: West Kaduara Village, Larangan District (Sample CKB 3).

The collected clam shells underwent an initial preparation stage. This involved mechanical cleaning by brushing the shell surfaces under running water to remove macroscopic debris. Subsequently, the samples were sun-dried for 24 hours to significantly reduce their moisture content. To ensure optimal cleanliness, the dried samples were decontaminated by rinsing with a 70% alcohol solution and aquadest to dissolve and remove any remaining impurities or organic contaminants. Afterwards, the samples were sun-dried again until they reached a completely dry state.

The clean dry shells were then ground into a coarse powder using a grinder. This coarse powder was further dried in an oven at 105°C for 24 hours to remove any residual water content. To obtain a uniform particle size, the powder was sieved through a 200-mesh sieve, producing a fine, homogeneous powder (Fig. 1(b)) that is crucial for accurate characterization data [14]. The resulting powder was then ready for further characterization. (See Fig. 1).

Fig. 1: Bamboo clam Ensis S.P (a) Whole Shell (b) clam Shell form (c) clam shell powder.

The prepared clam shell powders were stored in labeled glass bottles corresponding to Locations I, II, and III. Elemental analysis was conducted at the Laboratory of Minerals and Advanced Materials, Faculty of Mathematics and Natural Sciences, State University of Malang.

The samples were characterized using X-ray diffraction (XRD) with a PANanalytical X'Pert PRO instrument. The analysis was performed over a 2θ range of 15–65° with a step size of 0.04° and CuKα radiation (λ = 1.5418 Å). For the Fourier Transform Infrared (FT-IR) spectroscopy analysis, performed with a Shimadzu IR Prestige 21 instrument, absorbance spectra were recorded in the wavenumber range of 400 to 4000 cm^{-1} to identify functional groups and molecular structure [15]. X-ray Fluorescence (XRF) analysis was carried out using a PANanalytical MiniPal 4 instrument with a rhodium anode target; approximately 5 grams of powder from each sample was used for this elemental composition analysis.

3. Result and discussion

The bamboo clam shells obtained from the three locations were of nearly identical size, with an average body length of 3.2 cm and a width of 0.9 cm. The shell surface was greenish brown, as shown in Fig. 1(a) and 1(b). After grinding and sieving, a fine powder was obtained (Fig. 1(c)). The greenish-brown color of the powder is attributed to impurity minerals on the shell's outermost surface, which obscure its original white color. This color change was evident during the grinding and sieving stages.

The result of bamboo clam shell powder (Fig. 1(c)) was characterized using XRF, FTIR, and XRD. The XRF data on the chemical and oxide composition for each sample location are presented in Fig. 2.

Based on data in Table 1, the composition of bamboo clam shell is dominated by the element calcium (Ca) and compound calcium oxide (CaO), with average percentages reaching 98.06% and 98.18%, respectively. Other metallic elements and oxides, such as S, Fe, Cu, Sr, and Lu, were detected in trace amounts (less than 2%) [16].

and Er, beyond those previously identified (S, Fe, Cu, Sr, Lu). The appearance of these new elements is strongly suspected to be caused by different geographical and environmental conditions of bamboo clams shells. [17].

Table 2: Result Of CKB 2 XRF Analysis

Element	Composition (%)	Oxide	Composition (%)
Ca	97.87	CaO	98.04
S	0.21	SO_3	0.43
Fe	0.13	Fe_2O_3	0.12
Co	0.076	Co_3O_4	0.068
Cu	0.04	CuO	0.03
Sr	1.3	SrO	1.0
Zr	0.1	ZrO_2	0.10
Er	0.09	Er_2O_3	0.06
Lu	0.184	Lu_2O_3	0.11

Based on the elemental composition data presented in Table 3, it can be concluded that the elements were calcium (Ca) and compound calcium oxide (CaO) remain significantly dominant in the CKB 3 powder sample, with percentage values reaching 97.93% and 98.06%, respectively. The calcium content values obtained in this study are classified as very high, considering all samples showed values exceeding 90% (Ca ≥ 95%) [18], which is consistent with the biomineral characteristics of mollusk shells.

Table 3: Result Of CKB 3 XRF Analysis

Element	Composition (%)	Oxide	Composition (%)
Ca	97.93	CaO	98.06
S	0.22	SO_3	0.45
Fe	0.16	Fe_2O_3	0.15
Co	0.095	Co_3O_4	0.085
Cu	0.043	CuO	0.035
Sr	1.4	SrO	1.1
Zr	0.2	ZrO_2	0.2

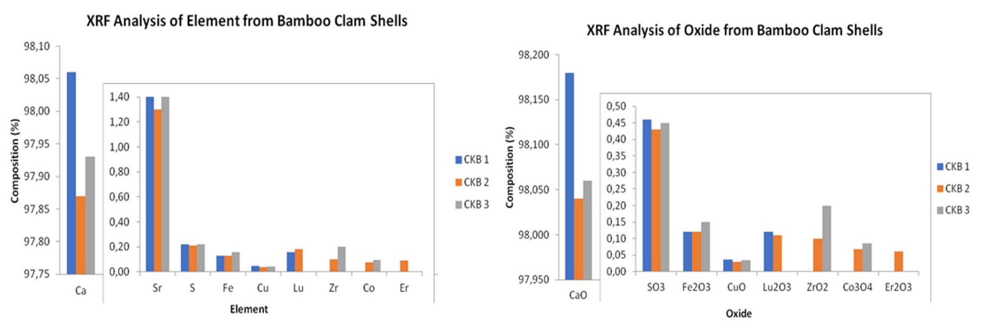

Fig. 2: Percentage of XRF analysis from CKB 1, CKB 2 and CKB 3

Table 1: Result Of CKB 1 XRF Analysis

Element	Composition (%)	Oxide	Composition (%)
Ca	98.06	CaO	98.18
S	0.22	SO_3	0.46
Fe	0.13	Fe_2O_3	0.12
Cu	0.046	CuO	0.037
Sr	1.4	SrO	1.1
Lu	0.16	Lu_2O_3	0.12

According to Table 2, the dominance of elements are calcium (Ca) and compound calcium oxide (CaO) remains significant with percentage 97.87 % and 98.04%. However, a difference in composition was observed in sample CKB 2, marked by the emergence of new metallic elements and oxides, such as Co, Zr,

Based on data in Fig. 2, the composition of CKB 1 is significantly dominated by element calcium (Ca) and compound calcium oxide (CaO), with percentages reaching 98.06% and 98.18%, respectively. Meanwhile, other metallic elements and oxides, such as S, Fe, Cu, Sr, and Lu, were detected in lower quantities (less than 2%). For CKB 2, the dominance of element calcium (Ca) and compound calcium oxide (CaO) remains significant with 97.87 % and 98.04%. However, a difference in composition was observed in sample CKB2, marked by the emergence of new metallic elements and oxides, such as Co, Zr, and Er, beyond those previously identified (S, Fe, Cu, Sr, Lu). For samples of CKB 3 powder show that the element calcium (Ca) and compound calcium oxide (CaO) remain significantly dominant, with percentage values reaching 97.93% and 98.06%, respectively.

From Fig 2, it can be determined that the main component in bamboo clam shell powder samples CKB 1, CKB 2, and CKB 3 is calcium oxide (CaO), with a very high concentration of 98.18%, 98.04%, and 98.06%, respectively. The impurity element profiles of CKB 1, CKB 2, and CKB 3 samples show similar compositions, with very low percentages of impurity elements, all of purity percentage below 2%. The minor differences in calcium oxide percentages (ranging from 98.04% to 98.18%) are caused by several factors, including the presence of heavy metals such as S, Fe, Cu, Sr, and Lu, which were detected as "impurities." The sample for CKB 2, with the lowest CaO composition, is likely situated in other areas more exposed to heavy metal pollution. This is further indicated by the emergence of new metal and oxide elements such as Cobalt (Co), Zirconium (Zr), and Erbium (Er), which were not previously identified

factor. The water temperature on CKB 1 is higher than the other at CKB 2 and CKB 3. Temperature effect of metabolic rate and biomineralization process in clams; a higher temperature can increase the growth rate and shell deposition. Sample of CKB 1, with its higher primary productivity (abundant plankton), supports more optimal clam growth. In contrast, sample CKB 2 and CKB 3, where food quality is lower due to mangrove forests being situated quite far from bamboo clam habitat, impair the clams' metabolism. This ultimately affects the efficiency and purity of the shell formation process. The calcium content values obtained in this study are classified as very high, given that all samples show values exceeding 95% (Ca ≥ 95%), which is consistent with the biomineral characteristics of shells from different clam species. The element of Ca has a very high content in hairy clam shells (*Anadara antiquata*), ale-ale clam shells (Meretrix -meretrix). This research agrees with the

Table 4: Percentage of element and oxide of bamboo clam shell (*Ensis, S.P*), *anadara antiquate* and *meretrix-meretrix*

Element	Composition (%)			Oxide	Composition (%)		
	Ensis S.p	***Anadara Antiquata***	***Meretrix-meretrix***		***Ensis S.p***	***Anadara Antiquata***	***Meretrix-meretrix***
Ca	98,06	96,49	89,887	CaO	98,18	96,51	87,476
S	0,22	-		SO_3	0,46	-	-
Fe	0,13	1,33	2,003	Fe_2O_3	0,12	1,22	1,816
Cu	0,046	0,093	-	CuO	0,037	0,071	-
Sr	1.4	0,615	-	SrO	1,1	0,462	-
Lu	0,16	-	-	Lu_2O_3	0,12	-	-
Al	-	1	1,33	Al_2O_3	-	1	2,111
K	-	0,17		K2O	-	0,15	-
Ti	-	0,09	0,275	TiO_2	-	0,09	0,175
Mn	-	0,049	0,025	MnO	-	0,04	0,016
Br	-	0,02	-	Br_2O_3	-	0,09	-
Mo	-	0,02	-	MoO_3	-	0,02	-
Ba	-	0,08	-	BaO	-	0,05	-
Mg	-	-	1,295	MgO	-	-	1,818
Si	-	-	2,354	SiO_2	-	-	4,197
P	-	-	0,307	P_2O_5	-	-	0,579
Cl	-	-	0,053	Cl	-	-	0,042
V	-	-	0,008	V	-	-	0,005

identified in the CKB 1 and CKB 2 samples. During the biomineralization process, these impurity metal ions can inadvertently replace calcium ions (Ca^{2+}) within the crystal structure of calcite or aragonite (the shell-forming minerals), thereby reducing the weight percentage of pure calcium. The presence of Copper (Cu), even in trace amounts, is often associated with anthropogenic pollution. The availability of bicarbonate ions (HCO_3^-) in the surrounding environment also influences the calcium percentage. Sample CKB 1, the proximity of bamboo clams to a river estuary, which carries minerals from the land, likely allows the clams to deposit more pure calcium in their shells. Water temperature at the shell location is another influence

study, although using a different sample (a different organism), reported consistent findings, as can be seen in Table 4.

The percentage of calcium can be further contextualized by comparing of Ca content in bamboo clam shells with that of hairy clam shells (*Anadara antiquata*) and ale-ale clam shells (*Meretrix meretrix*). As shown in Table 1, while all three shell types are dominated by Ca and CaO, the specific compositions differ due to distinct biomineralization processes and habitats. The comparison reveals that $CaCO_3$ content in bamboo clam shells is higher than the other two species. The presence of impurity elements also influences the overall composition and can lead to variations between different samples.

Based on these results, it can be concluded that the main component of bamboo clam shells powdered is calcium oxide (CaO), with a very high average concentration of 98%. This high purity indicates that bamboo clam shells from Pamekasan are a highly potential source of calcium and are suitable for use in synthesis of calcium carbonatein another application [19].

Fourier Transform Infrared (FT-IR) spectroscopy was performed in fig 3. on the homogenized shell powder in the range of 400-4000 cm^{-1} to identify the characteristic functional groups of the compounds, primarily to confirm $CaCO_3$ formation by detecting its specific absorption bands. Figure 3 shows the FTIR spectra for samples CKB 1, CKB 2, and CKB 3, indicating no significant spectral differences between three locations [20].

The FTIR spectrum for sample CKB 1 shows absorption peaks at 712 cm^{-1}, 864 cm^{-1}, 1082 cm^{-1}, 1417 cm^{-1}, 1614 cm^{-1}, 1786 cm^{-1}, 2152 cm^{-1}, 2520 cm^{-1}, and 2980 cm^{-1}. The spectrum for CKB 2 exhibits peaks at 712 cm^{-1}, 862 cm^{-1}, 1082 cm^{-1}, 1417 cm^{-1}, 1614 cm^{-1}, 1788 cm^{-1}, 2152 cm^{-1}, 2520 cm^{-1}, and 2980 cm^{-1}. Similarly, the spectrum for CKB 3 shows peaks at 712 cm^{-1}, 864 cm^{-1}, 1082 cm^{-1}, 1417 cm^{-1}, 1614 cm^{-1}, 1786 cm^{-1}, 2152 cm^{-1}, 2520 cm^{-1}, and 2980 cm^{-1}. Minor but significant shifts in wavenumber are observed, particularly between samples CKB 1 and CKB 2.

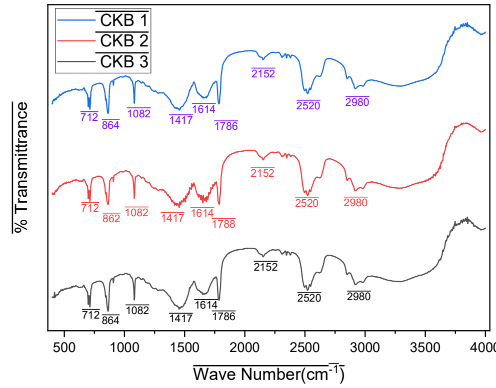

Fig. 3: FTIR spectra of bamboo clam shell powder for CKB 1: CKB 2: CKB 3

The FTIR analysis was conducted to identify the characteristic functional groups of $CaCO_3$ carbonate ion, specifically CO_3^{2-}, OH^-, Ca-O, and C-O [21]. Based on Fig. 3, the spectra show strong absorption peaks for the CO_3^{2-} functional group at wavenumbers 712 cm^{-1} and 864 cm^{-1}. These sharp bands correspond to carbonate ion vibrations and confirm that the primary compound in the bamboo clam shells is calcium carbonate. Furthermore, the absorption peak at 1082 cm^{-1} indicates symmetric stretching of CO_3^{2-}, while the antisymmetric stretching vibration of C-O at 1417 cm^{-1} is characteristic of aragonite

Table 5: type of bonds of CaCO3 absorption peaks [24]

Functional group	Wave Number (cm^{-1}) CKB 1	Wave Number (cm^{-1}) CKB 2	Wave Number (cm^{-1}) CKB 3	Reference
Ca-O	712	712	712	712;710
CO_3^{2-}	864	862	864	874;876
CO_3^{2-} symmetric stretching	1082	1082	1082	1081;1082
C-O antisymmetric stretching Ca-O Asymmetric stretching	1417 1614	1417 1614	1417 1614	1451;1466 1611
Ca-O stretching	1786	1788	1786	1798
HCO_3	2520	2520	2520	2517
CH_2 symmetric stretching	2980	2980	2980	2925

In FTIR spectroscopy, peak shifts indicate changes in bond strength or the local chemical environment of the vibrating atoms. The XRF data indicate that the sample from location 2 (CKB 2) was exposed to a higher concentration of heavy metal impurity elements compared to the other two samples. Metal ions such as Sr^{2+} and Cu^{2+} have ionic radii different from that of Ca^{2+}. When these foreign ions substitute for calcium in the aragonite crystal lattice, a process known as isomorphic substitution, it induces lattice strain and alters the length and strength of the bonds within the CO_3^{2-} groups. This lattice strain manifests as the small, yet measurable, wavenumber shifts observed in the FTIR spectrum of CKB 2. The presence of these impurities disrupts the crystal formation, which is consistent with the XRF analysis showing that the CKB 2 sample has the lowest CaO percentage among the three samples.

crystalline phase [22].

At a wavelength of 1614 cm^{-1}, the spectrum indicates Ca-O asymmetric stretching. The peak at 1786 cm^{-1}, characterized by a broad absorption band, is identified as Ca-O stretching and carbonate ion vibration from calcium carbonate polymorphs. The sharp bands at 712 cm^{-1}, 864 cm^{-1}, 1082 cm^{-1}, and 1786 cm^{-1} are characteristic of aragonite phase. HCO_3 group appears at an absorption peak around 2520 cm^{-1} [23], and peak at 2980 cm^{-1} indicates CH_2 symmetric stretching. The results in Figure 3 show the specific absorption peak values of $CaCO_3$ produced from bamboo clam shell powders.

phase identification of bamboo clam shell powders was conducted by analyzing the X-Ray Diffraction (XRD) patterns. The diffractograms correspond well with the standard aragonite reference (ICDD card 00-005-0453). Figure 4 reveals that the crystalline phase of bamboo clam shell is predominantly aragonite (100%) with an orthorhombic crystal structure. The analysis shows the highest intensity peak at a diffraction angle (2θ) of 33.11° with Miller indices (002). Other diffraction angles can be observed on Fig. 4. This result is consistent with previous research, which states that the shell's crystalline phase is aragonite [25].

The formation of a single aragonite phase demonstrates the effectiveness of biomineralization process, where the organic matrix and environmental conditions (such as the presence of Mg^{2+}) work together to kinetically stabilize the metastable aragonite phase, overcoming the thermodynamic tendency to form calcite. The aragonite crystal structure is more tolerant of Mg^{2+}, making its formation kinetically favored in Mg^{2+}-rich environments like seawater. The slight differences in peak intensities are likely caused by variations in crystal orientation or particle size, rather than differences in phase composition [26].

The XRD reflections for aragonite phase of bamboo clam shells were observed at 2θ positions symbolic for the respective planes: 26.2° (111); 27.2° (021); 31.1° (002); 33.1° (012); 36.1° (200); 37.8° (112); 38.6° (130); 41.2° (211); 42.8° (220); 45.8° (221); 48.3° (041); 50.1° (132); 52.4° (113) and 52.8° (231). These recorded reflections are indistinguishable from the standard ICDD database for aragonite. The sharp, strong peaks confirm that the product is well-crystallized. However, much of the aragonite phase remains largely amorphous due to the absence of heat treatment.

Although aragonite is metastable and can undergo diagenesis into the more stable calcite, it can persist for long periods due to a high kinetic barrier to transformation. In biological systems, the organic matrix acts as a kinetic inhibitor, preventing this change [27]. This aligns with the XRF results, which show nearly identification of calcium (Ca) percentages in each sample.

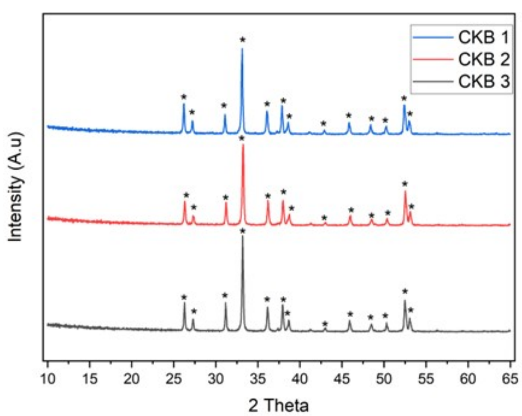

Fig. 4: X ray Diffraction pattern of bamboo clam shell powder (a) CKB 1: location 1; (b) CKB 2: location 2; (c) CKB 3: location 3

Aragonite's stability is kinetic, not thermodynamic. It can persist for long periods as long as there is no significant energy disturbance (such as high-temperature heating >400°C) that can trigger a phase transformation into calcite. Due to its dense structure and higher hardness, the aragonite in clam shells provides excellent mechanical strength and wear resistance. This makes it an inspiration for bio-mimetic composite materials. Its higher solubility compared to calcite makes aragonite potentially more easily absorbed by the body (higher bioavailability). Calcium sources from shells and corals are often in the form of aragonite [24].

4. Conclusion

Based on the results of XRF, XRD, and FTIR analyses, the characterization of bamboo clam shells confirms an optimal calcium content of approximately 98%. The formation of a 100% single-phase aragonite crystal structure (XRD) indicates the production of calcium carbonate in its metastable polymorph. The FTIR spectra further support this, showing sharp carbonate (CO_3^{2-}) peaks with high absorbance intensity, confirming the dominance of the aragonite phase of $CaCO_3$. These collective results demonstrate that bamboo clam shells possess significant potential as an environmentally friendly and highly valuable source of natural calcium.

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