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A Systematic Review on the Acoustic Performance of Nanocellulose-Modified Natural Fibers for Sound Insulation and Absorption Applications

Muchlisinalahuddin[1], Meifal Rusli[1,2,a)], Hendery Dahlan[1,2], Melbi Mahardika[3,b)]

[1]*Mechanical Engineering Department, Faculty of Engineering, Universitas Andalas, Kampus Limau Manis, Padang, 25163, Indonesia*
[2]*Research Collaboration Center for Nanocellulose, BRIN-Universitas Andalas, Kampus Limau Manis, Padang, 25163, Indonesia*
[3]*Research Center for Biomass and Bioproducts, National Research and Innovation Agency (BRIN), Cibinong, 16912, Indonesia*

E-mail: [a)] meifal@eng.unand.ac.id
[b)] melbi.mahardika@brin.go.id

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Abstract: Noise pollution has become an increasingly concerning environmental issue, driving the development of sustainable acoustic materials as alternatives to conventional synthetic materials. This research conducts a systematic literature review on the acoustic effectiveness of natural fiber-based nanocellulose in sound isolation and absorption applications. The research method employs a qualitative approach with a comprehensive analysis of scientific publications from Scopus, Web of Science, ScienceDirect, and Google Scholar databases over the past ten years. The review results indicate that modification of natural fibers such as coconut coir, hemp fiber, banana pseudostem, and rice straw with nanocellulose at a concentration of 1-1.5% w/v is capable of improve sound absorption coefficients up to 0.7-0.9 in the 500-2000 Hz frequency range, comparable to synthetic materials such as fiberglass and mineral wool. This material demonstrates advantages in terms of dimensional stability improvement of 35-40%, lightweight density (150-300 kg/m³), balanced acoustic characteristics across a broad frequency spectrum, and biodegradable properties providing minimal environmental impact. The potential applications of this material are extensive in construction, automotive, and acoustic industries, with noise reduction capabilities of up to 8-12 dB. Despite facing challenges in raw material variability and production scalability, natural fiber and nanocellulose-based acoustic materials have promising prospects as sustainable solutions to global noise pollution problems with competitive performance against conventional materials.

Keywords: Nanocellulose, Acoustics, Natural Fibers, Biodegradable, Soundproofing.

Abstrak: *Polusi kebisingan telah menjadi isu lingkungan yang semakin mengkhawatirkan, mendorong pengembangan material akustik berkelanjutan sebagai alternatif terhadap material sintetis konvensional. Penelitian ini melakukan tinjauan literatur sistematis mengenai efektivitas akustik serat alam berbasis nanoselulosa dalam aplikasi isolasi dan penyerapan suara. Metode penelitian menggunakan pendekatan kualitatif dengan analisis komprehensif terhadap publikasi ilmiah dari basis data Scopus, Web of Science, ScienceDirect, dan Google Scholar selama sepuluh tahun terakhir. Hasil tinjauan menunjukkan bahwa modifikasi serat alam seperti sabut kelapa, serat rami, pelepah pisang, dan jerami padi dengan nanoselulosa pada konsentrasi 1–1,5% w/v mampu meningkatkan koefisien penyerapan suara hingga 0,7–0,9 dalam rentang frekuensi 500–2000 Hz, setara dengan material sintetis seperti fiberglass dan mineral wool. Material ini menunjukkan keunggulan dalam hal peningkatan stabilitas dimensi sebesar 35–40%, densitas ringan (150–300 kg/m³), karakteristik akustik yang seimbang pada spektrum frekuensi yang luas, serta sifat biodegradable yang berdampak minimal terhadap lingkungan. Potensi aplikasi material ini sangat luas, mencakup sektor konstruksi, otomotif, dan industri akustik, dengan kemampuan reduksi kebisingan hingga 8–12 dB. Meskipun menghadapi tantangan dalam hal variabilitas bahan baku dan skalabilitas produksi, material akustik berbasis serat alam dan nanoselulosa memiliki prospek yang menjanjikan sebagai solusi berkelanjutan terhadap permasalahan polusi suara global, dengan performa yang kompetitif dibandingkan material konvensional.*

Kata kunci: *Nanocellulose, Akustik, Serat Alami, Biodegradable, Peredam Suara.*

INTRODUCTION

Noise pollution has become one of the most concerning environmental issues in the modern era, especially in urban areas densely populated with industrial and transportation activities [1]. Excessive noise levels not only disrupt public comfort however can also lead to various negative health impacts, ranging from hearing impairment to psychological issues such as stress and sleep disorders [2]. The World Health Organization has even classified noise pollution as a serious public health threat, requiring concrete efforts to address it through the development of effective sound isolation and absorption technologies. The demand for environmentally friendly acoustic materials is becoming increasingly urgent as global awareness of sustainability and the environmental impact of industrial activities rises. Conventional acoustic materials such as fiberglass, polyurethane foam, and mineral wool, while performing well in sound absorption, pose several environmental and health issues. These materials are non-biodegradable, contain harmful chemicals, and their production processes generate high carbon emissions. Moreover, prolonged exposure to fine particles from these synthetic materials can cause respiratory irritation and other health problems [3].

Natural fibers have long been recognized as promising alternatives to synthetic materials in various applications, including acoustics [4]. Natural fibers such as cotton, hemp, coconut coir, banana pseudostems, and rice straw offer advantages in terms of availability, relatively low production cost, and biodegradable properties, making them environmentally friendly. The natural porous structure of these fibers allows for the absorption of sound waves through the mechanism of converting acoustic energy into heat, which represents the fundamental principle of sound-absorbing materials. However, natural fibers in their raw form often have limitations in terms of consistent acoustic performance and durability under harsh environmental conditions. The advancement of nanomaterial technology has provided new opportunities to enhance the performance of natural fiber-based acoustic materials [5]. Nanocellulose, a form of cellulose at the nanometer scale, has garnered widespread attention due to its unique properties, such as high mechanical strength, large surface area, and the ability to form controllable structures. When natural fibers are modified with nanocellulose, significant improvements occur in terms of dimensional stability, mechanical strength, and most importantly, the acoustic performance of the material. This modification allows the creation of more optimal microstructures for sound absorption [6].

The sound absorption mechanism in natural fiber-based materials with nanocellulose involves several complex physical processes [7]. When sound waves enter the material, the acoustic energy interacts with the porous structure of the natural fibers and nanocellulose. The absorption process occurs through the air viscosity mechanism, where the movement of air particles inside the material's pores encounters resistance and friction, converting kinetic energy into heat [8]. The presence of nanocellulose enhances the effectiveness of this process by increasing the contact surface area and creating more micro-pores capable of trapping and absorbing sound energy. Previous studies have shown that natural fiber-based acoustic materials with the addition of nanocellulose is capable of achieve sound absorption coefficients competitive with conventional synthetic materials. Several studies have indicated that these materials can achieve sound absorption coefficients up to 0.8-0.9 at specific frequency ranges, which indicates Excellent absorption capability. Additionally, this material also demonstrates stable performance under various environmental conditions, such as changes in temperature and humidity, which are important factors for practical applications [9].

The potential applications of natural fiber and nanocellulose-based acoustic materials are vast, ranging from use in residential and commercial buildings, motor vehicles, to industrial equipment [10]. In the construction sector, these materials is capable of be applied as wall panels, acoustic ceilings, or sound insulation to enhance room acoustic comfort. In the automotive industry, these materials can be used as cabin insulation to reduce engine and road noise. The flexibility in processing and the ability to be shaped into various configurations makes this material highly adaptable to various application needs [11]. Although the potential of natural fiber and nanocellulose-based acoustic materials is highly promising, comprehensive literature reviews are still required to deeply understand the acoustic effectiveness of these materials in various conditions and applications. A systematic review will help identify the factors affecting acoustic performance, appropriate characterization methods, as well as the challenges and opportunities in developing these materials in the future. A deep understanding of these aspects will provide a strong foundation for the research and development of sustainable acoustic materials in the future [12].

Based on the background outlined, there are several fundamental issues that need to be explored in depth related to the acoustic effectiveness of natural fiber-based nanocellulose. First, what are the acoustic characteristics of various types of natural fibers modified with nanocellulose, and what factors influence the sound absorption performance of these materials? Second, to what extent is the effectiveness of natural fiber and nanocellulose-based acoustic materials in different sound frequency ranges, and how does their performance compare with conventional acoustic materials already available on the market? Other issues to be examined include how the preparation and modification methods of natural fibers with nanocellulose affect the acoustic properties of the resulting materials, and what technical challenges are faced in the production process and industrial-scale application of these materials. Additionally, the sustainability and environmental impact of natural fiber and nanocellulose-based acoustic materials also need to be examined, including life cycle analysis and the potential for recycling these materials compared to conventional acoustic materials.

This study systematically evaluates conduct a comprehensive and systematic literature review on the acoustic effectiveness of natural fiber-based nanocellulose in sound isolation and absorption applications. The main objectives include an in-depth analysis of the acoustic characteristics of various types of natural fibers modified with nanocellulose, evaluation of the sound absorption performance of these materials across various frequency ranges, and identification of the factors influencing the acoustic effectiveness of these materials. Furthermore, this research also aims to examine the optimal preparation and modification methods to improve the acoustic performance of these materials. The secondary objective of this study is to analyze the potential applications of natural fiber and nanocellulose-based acoustic materials in various industrial sectors, identify the challenges and opportunities in the development of these materials, and provide recommendations for future research and development. This study also aims to provide a clear overview of the position of this technology in the context of sustainable acoustic materials and its contribution to environmentally friendly noise pollution solutions.

The theoretical benefits of this research are to provide a comprehensive understanding of the sound absorption mechanisms in natural fiber and nanocellulose-based materials, which is capable of serve as the foundation for the development of theories and models for predicting the acoustic performance of similar materials. This systematic literature review will generate a synthesis of knowledge that can help other researchers identify research gaps and determine the direction of future studies. Additionally, this research will contribute to the development of a database on the acoustic characteristics of natural materials, which can be used as a reference in the design and simulation of acoustic systems. The practical benefits of this research include providing information that can be used by industries to consider adopting natural fiber and nanocellulose-based acoustic materials as a more sustainable alternative. The results of this study can serve as a guide for engineers and designers in selecting the appropriate acoustic materials for specific applications, as well as providing recommendations for optimizing material performance under various operational conditions. Moreover, this research can also support the development of standards and regulations related to sustainable acoustic materials and contribute to global efforts to reduce the environmental impact of the construction materials industry.

METHODS

Research Design

This study uses a qualitative approach with a systematic literature review method to analyze the acoustic effectiveness of natural fiber-based nanocellulose in sound isolation and absorption applications. This research design was chosen because it provides an in-depth and comprehensive understanding of the phenomena being studied through the analysis and synthesis of various relevant sources of literature. The qualitative approach allows the researcher to explore the complexity of the research topic in a holistic and contextual manner, leading to a rich and nuanced understanding of the acoustic effectiveness of the materials examined. A systematic literature review was selected as the primary research strategy because it enables the structured collection, evaluation, and synthesis of available evidence from scientific literature. This method follows a strict and transparent protocol to ensure that the research process is capable of be replicated and the results are reliable. This research design also allows for the identification of existing knowledge gaps and provides a strong foundation for future research recommendations, while ensuring that all important aspects of the research topic can be thoroughly explored.

Literature Search Strategy

The literature search strategy represents systematically designed to ensure that all publications relevant to the research topic are identified and collected. Searches will be conducted in several major electronic databases, namely Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar, using a combination of specifically defined keywords. The keywords used include "natural fiber," "nanocellulose," "acoustics," "sound absorption," "sound isolation," "acoustic materials," "natural fiber," "nanocellulose," and "sound absorption" in various combinations using Boolean operators AND and OR. The literature search will be limited to publications published within the last ten years to ensure the relevance and timeliness of the collected information. In addition to electronic database searches, manual searches will also be conducted on the reference lists of identified articles to find additional publications that may have been missed in the automated search. The search process will be documented in detail, recording the number of results from each database, the keywords used, and the filters applied to ensure transparency and the potential for replicating the research.

Inclusion and Exclusion Criteria

Inclusion criteria for this research include peer-reviewed journal articles published in reputable journals, articles that specifically discuss natural fibers modified with nanocellulose for acoustic applications, and studies that present quantitative data on the acoustic performance of these materials. Furthermore, articles that discuss sound absorption mechanisms, material characterization, and practical applications of natural fiber and nanocellulose-based acoustic materials will also be included in the review. Publications in both Indonesian and English will be the primary focus, with consideration given to publications in other languages that include English abstracts. Exclusion criteria include articles that only discuss natural fibers without nanocellulose modification, publications that do not present empirical data on acoustic performance, and articles focusing on non-acoustic applications of natural fiber and nanocellulose-based materials. Additionally, review articles without original data contributions, conference proceedings not published in journals, and publications that cannot be accessed in full text will also be excluded. Articles with poor methodology quality or insufficient information for analysis will also be excluded from the review.

Selection Process and Quality Assessment

The literature selection process will be carried out in several stages to ensure that only the most relevant and high-quality articles constitute included in the analysis. The first stage involves screening the titles and abstracts to identify articles potentially relevant to the research topic. Articles passing the initial stage will undergo further evaluation by full-text reading to ensure alignment with the established inclusion and exclusion criteria. Each article will be independently assessed by the researcher, and in case of discrepancies in assessment, discussions will be held to reach a consensus. Article quality will be evaluated based on established criteria, including the research methodology quality, clarity of data presentation, relevance to the research topic, and contribution to the knowledge in the field of acoustic materials. Articles will be categorized according to their quality and relevance, with higher weight given to those with robust methodology and comprehensive data. This quality assessment process will help identify the most reliable articles to be used in the analysis and synthesis of the research findings.

Data Extraction and Analysis

Data extraction will be systematically carried out by employing forms designed specifically to capture relevant information from each selected article. The data to be extracted includes complete bibliographic information, the characteristics of the materials studied, the preparation methods and modification of natural fibers with nanocellulose, the acoustic parameters measured, the results of acoustic performance testing, and the tested applications. Additionally, information about the research methodology, instrumentation used, testing conditions, and limitations mentioned by the authors will also be extracted. Data analysis will be performed qualitatively using a thematic approach to identify patterns, themes, and trends emerging from the collected literature. The analysis process includes categorizing data based on the type of natural fiber, nanocellulose modification methods, acoustic frequency range, and tested applications. The synthesis of results will be conducted by comparing and contrasting findings from various studies to identify consistencies and inconsistencies in results, as well as to develop a comprehensive understanding of the acoustic effectiveness of the materials studied. The analysis will also identify existing knowledge gaps and provide recommendations for future research.

Validity and Reliability

The validity of the study will be ensured through the application of a strict and transparent literature review protocol, including the use of clear inclusion and exclusion criteria, a comprehensive search strategy, and a systematic selection process. To ensure internal validity, source triangulation will be conducted using multiple databases and different search methods. Additionally, peer checking will be carried out by involving experts in the field of acoustic materials to verify the relevance and quality of the selected articles. External validity will be maintained by ensuring that the literature sample collected represents representative of the existing body of knowledge in the field of natural fiber and nanocellulose-based acoustic materials. The reliability of the study will be guaranteed through detailed documentation of every step of the research process, from the search strategy to data analysis, allowing the study to be replicated by other researchers. Consistency in the application of selection criteria and quality assessment will be ensured by using standard protocols and adequate training. Moreover, inter-rater reliability checks will be performed by involving multiple reviewers to ensure consistency in the assessment and selection of articles. The data analysis process will be documented in detail, with audit trail records stored to allow for verification and validation of the research findings.

Conceptual Framework of the Research

The conceptual framework of this research represents built upon the integration of material acoustics theory, the properties of natural fibers, and nanocellulose technology to provide a strong theoretical foundation for the literature analysis. This framework illustrates the relationship between the physical and chemical characteristics of natural fibers, modification with nanocellulose, and the resulting acoustic performance. The key components of the conceptual framework include input variables such as the type of natural fiber and nanocellulose modification methods, the transformation process through physical-chemical interactions, and the output in the form of the acoustic characteristics of the material produced. This framework also integrates environmental and application factors that may influence the acoustic effectiveness of the material, such as temperature conditions, humidity, and the frequency of sound applied. Additionally, the framework considers sustainability and environmental impact as important dimensions in the evaluation of natural fiber and nanocellulose-based acoustic materials. This conceptual framework will serve as a guide in the literature analysis and synthesis process, ensuring that all essential aspects of the research topic are explored systematically and comprehensively.

Research Ethics

This research adheres to the applicable principles of research ethics, particularly in terms of proper usage and citation of literature sources. All articles and publications used in this study will be accurately and completely cited in accordance with the prevailing scientific citation standards. The researcher represents committed to maintaining academic integrity by avoiding plagiarism, data fabrication, or manipulation of information from the literature sources used. Additionally, this research will comply with copyright laws and open-access policies of various academic journal publishers that provide the literature sources. Transparency in the research process is a top priority, with detailed documentation of all research steps and providing access to the extracted data to the scientific community in accordance with applicable regulations. The researcher is also committed to reporting all research findings objectively and without bias, including reporting findings that may not align with the initial hypothesis or the researcher's expectations. Any conflicts of interest will be openly declared, and this research will be conducted with a strong commitment to the values of integrity, objectivity, and scientific accountability.

RESULT AND DISCUSSION

Characteristics of Natural Fiber and Nanocellulose-based Acoustic Materials

Recent studies have significantly strengthened the scientific basis for using natural fiber-based acoustic materials modified with nanocellulose [13]. The fiber morphology, chemical composition, and porosity have been shown to play a decisive role in determining acoustic performance, particularly in low-frequency applications. Additionally, the integration of cellulose nanocrystals (CNC) into luffa-based matrices has been found to enhance sound absorption across mid-to-high frequency ranges due to hierarchical porosity and increased surface interaction. The fibrous structure of micro- and nanocellulose has also been found to allow broader acoustic band coverage, making them suitable for versatile architectural applications. This is further supported by a comprehensive review outlining how microstructural parameters such as tortuosity, pore size distribution, and airflow resistivity influence overall acoustic performance. Collectively, this evidence affirms that integrating nanocellulose into natural fibers is not only structurally feasible but also acoustically advantageous for sustainable building technologies [14].

Based on the literature review conducted, natural fiber-based acoustic materials modified with nanocellulose exhibit demonstrates high potential characteristics for sound isolation and absorption applications. The most widely studied natural fibers include coconut coir, hemp fiber, banana pseudostem, rice straw, and cotton, each of which has a natural porous structure that allows for effective sound wave absorption. Modification with nanocellulose has been shown to improve the dimensional stability of the material by 35-40% compared to unmodified natural fibers, while maintaining the biodegradable properties that are the primary advantage of these materials. The physical characteristics of materials modified with nanocellulose show a significant improvement in terms of mechanical strength and resistance to environmental degradation. The material density ranges from 150-300 kg/m³, which still falls within the lightweight category but provides sufficient strength for structural applications [15]. The porosity of the material reaches 70-85%, with a more homogeneous pore size distribution compared to unmodified natural fibers. Microstructure analysis using SEM shows that nanocellulose forms a network that fills the spaces between fibers, creating a hierarchical structure optimal for sound absorption. The chemical properties of the material indicate that nanocellulose modification does not alter the fundamental properties of the natural fibers, but enhances stability under extreme environmental conditions. FTIR analysis shows that hydrogen bonds between nanocellulose and natural fibers are well-formed, resulting in a chemically stable composite material. The content of lignin and hemicellulose in the modified natural fibers has decreased in a controlled manner, producing a material with lower hygroscopic properties while maintaining the flexibility required for acoustic applications. Resistance to fungi and biological degradation has also significantly increased compared to unmodified natural fibers [16].

Acoustic Performance of Materials at Different Frequency Ranges

The analysis of the acoustic performance of natural fiber and nanocellulose-based materials demonstrates excellent sound absorption characteristics at specific frequency ranges. At low frequencies (250-500 Hz), the material shows an average sound absorption coefficient of 0.4-0.6, which is significantly higher than unmodified natural fibers, which only reach 0.2-0.3 [17]. This improvement is attributed to the more orderly microstructure and more homogeneous pore distribution resulting from the nanocellulose modification. The absorption mechanism at low frequencies is dominated by the air viscosity process inside the pores of the material, where nanocellulose acts as an additional barrier that enhances energy dissipation. At mid frequencies (500-2000 Hz), the material shows optimal performance with a sound absorption coefficient reaching 0.7-0.9, which is comparable to commercial acoustic materials such as fiberglass and mineral wool [18]. This frequency range is particularly important for practical applications, as it covers most of the sound spectrum produced by human activity and machinery [19]. The hierarchical structure formed from the combination of natural fibers and nanocellulose creates multiple mechanisms for sound absorption, including pore resonance, thermal viscosity, and wave scattering. The optimal material thickness for this frequency range is between 20-40 mm, where further thickness increases do not provide significant improvements in the absorption coefficient. At high frequencies (2000-6000 Hz), the material shows relatively stable absorption coefficients in the range of 0.6-0.8, with a tendency to decrease at very high frequencies. This is consistent with the theory of porous material acoustics, where sound absorption effectiveness tends to decrease at high frequencies due to shorter wavelengths. However, nanocellulose modification proves to maintain good acoustic performance at high frequencies compared to conventional materials. Factors influencing performance at high frequencies include pore size, tortuosity, and air flow resistance, all of which is capable of be controlled through optimization of nanocellulose concentration and application methods [20].

Preparation and Modification Methods of Natural Fibers with Nanocellulose

The literature review identifies several effective natural fiber preparation methods to improve compatibility with nanocellulose [21]. Alkali treatment using NaOH at concentrations of 2-5% has proven to be most effective in removing lignin and hemicellulose, which may interfere with the bonding between fibers and nanocellulose. A bleaching process using sodium hypochlorite or hydrogen peroxide is conducted to improve the color and remove residual impurities that may affect the acoustic properties of the material [22]. The optimal treatment time ranges from 2-4 hours at temperatures of 80-90°C, where excessive treatment can damage the cellulose structure and reduce fiber strength. Nanocellulose modification can be carried out through several methods, with dip coating and spray coating being the most commonly used. The dip coating method provides a more homogeneous distribution of nanocellulose with a nanocellulose solution concentration ranging from 0.5-2% w/v. This process involves immersing the prepared fibers in the nanocellulose solution for 30-60 minutes, followed by gradual drying at temperatures of 60-80°C. Spray coating offers better control over the amount of nanocellulose applied, with higher material efficiency, however requires more complex equipment and results in less homogeneous distribution on the fiber surface. Process parameter optimization shows that a nanocellulose concentration of 1- 1.5% w/v gives optimal results in terms of improving the acoustic and mechanical properties of the material. Too low a concentration does not provide significant improvement, while too high a concentration may form a film that covers the fiber pores and reduces air permeability [23]. The pH of the nanocellulose solution in the range of 6-7 has been shown to be optimal for maintaining dispersion stability and preventing nanocellulose aggregation. Curing at temperatures of 100-120°C for 2-4 hours is necessary to ensure strong bonding between nanocellulose and natural fibers, as well as to remove any moisture residues that may affect the acoustic properties of the material [24].

Comparison with Conventional Acoustic Materials

The comparison of acoustic performance between natural fiber and nanocellulose-based materials and conventional materials shows very competitive results [25]. Fiberglass, with a density of 32 kg/m³, has an average sound absorption coefficient of 0.8-0.9 in the 500-2000 Hz frequency range, while natural fiber and nanocellulose-based materials, with a density of 200-250 kg/m³, can achieve sound absorption coefficients of 0.7-0.9 in the same frequency range. Although natural fiber-based materials have higher density, they still fall under the category of lightweight materials and offer advantages in terms of sustainability and environmental impact. Furthermore, natural fiber-based materials demonstrate more stable performance under various humidity conditions compared to fiberglass, which may degrade under humid conditions. When compared to polyurethane foam, natural fiber and nanocellulose-based materials have a broader effective frequency range [26]. Polyurethane foam, with a density of 30-40 kg/m³, shows a high sound absorption coefficient (0.8-0.95) at mid to high frequencies, however its performance at low frequencies is relatively low (0.2-0.4). In contrast, natural fiber and nanocellulose-based materials show more balanced performance across the entire frequency spectrum, with absorption coefficients that do not drop drastically at low frequencies [27]. This provides an advantage for applications that require sound absorption across a wide spectrum, such as in concert halls or recording studios. Mineral wool, as the industry standard, shows sound absorption coefficients of 0.7-0.9 in the 250-4000 Hz frequency range with a density of 100-150 kg/m³. Natural fiber and nanocellulose-based materials demonstrate comparable performance with slightly higher density but with a significant advantage in terms of health safety and environmental impact. Mineral wool can cause skin and respiratory irritation, while natural fiber-based materials are safe for health and fully recyclable. In terms of cost, natural fiber and nanocellulose-based materials have the potential to be more economical due to their use of agricultural waste and relatively simple production technology [28].

Practical Applications and Industrial Potential

The application of natural fiber and nanocellulose-based acoustic materials in the construction sector shows great potential, especially for buildings emphasizing the green building concept and sustainability [29]. These materials can be applied as acoustic wall panels with thicknesses ranging from 20-50 mm, providing a noise reduction coefficient (NRC) between 0.6-0.8, meeting international standards for building acoustic materials. Installation of these materials is relatively easy as they can be cut and shaped as needed, and they are lightweight, requiring no complex supporting structures [30]. The application on acoustic ceilings also yields satisfactory results, with the ability to reduce reverberation time by 40-50% compared to conventional ceilings. The automotive sector shows high interest in natural fiber and nanocellulose-based acoustic materials as an alternative for cabin insulation. These materials can reduce noise levels in the cabin by 8-12 dB in the 500-2000 Hz frequency range, which is highly effective for reducing engine and road noise. The advantages of these materials in automotive applications include their lightweight, contributing to fuel efficiency, resistance to high temperatures, and the absence of harmful gases under heat conditions. Several automotive manufacturers have conducted trials using these materials on door panels and floor mats, with results showing acoustic performance comparable to conventional materials however with much lower environmental impact [31]. The audio equipment and acoustic room industries show promising application potential for natural fiber and nanocellulose-based materials. These materials can be used in the manufacturing of acoustic panels for recording studios, home theaters, and concert halls, where high acoustic quality is required. The ability of these materials to provide uniform sound absorption across various frequencies makes them ideal for applications requiring precise acoustic treatment. Additionally, the aesthetic properties of the material, which can be modified with natural dyes or attractive surface textures, add value to architectural acoustic applications. The market potential for these applications is vast, particularly with the increasing awareness of the importance of acoustic quality in various spaces and the trend of using environmentally friendly materials [32].

Challenges and Limitations of the Material

One of the main challenges in the development of natural fiber and nanocellulose-based acoustic materials is the variability in raw material quality, which is capable of affect the consistency of acoustic performance [33]. Natural fibers from different sources or harvested at different times may have varying physical and chemical characteristics, such as fiber length, diameter, lignin content, and moisture. This variability can lead to differences in sound absorption coefficients of up to 15-20% in materials produced using the same method. Standardization of the preparation process and strict quality control are required to address this issue, including the development of rapid and accurate characterization methods for raw material screening [34]. Long-term durability of the material under extreme environmental conditions remains a concern in practical applications. Although nanocellulose modification improves material stability, exposure to UV, extreme temperature fluctuations, and high humidity conditions over extended periods can lead to degradation that affects acoustic performance. Accelerated aging tests show that the material can experience a reduction in the sound absorption coefficient by 10-15% after exposure to UV and high-temperature conditions for 1000 hours. The development of additives to improve resistance to environmental degradation, such as UV stabilizers and natural antioxidants, still requires further research [35].

The scalability of production for natural fiber and nanocellulose-based acoustic materials faces several technical and economic challenges. The production process of nanocellulose is still relatively expensive and complex, which is capable of impact the cost-effectiveness of the material, especially for applications requiring large-scale production. Additionally, the modification process of natural fibers with nanocellulose requires precise control of process parameters, which can be a challenge in industrial-scale implementation. The development of more efficient and economical production technologies, as well as optimization of the supply chain for natural fiber raw materials, is necessary to support the commercialization of this material. Standardization of testing methods and material certification is also still required to facilitate the adoption of these materials in various industrial applications [36].

Development Prospects and Recommendations for Future Research

The development prospects for natural fiber and nanocellulose-based acoustic materials are demonstrates high potential with the global trend toward sustainable materials and green technology [37]. Future research should focus on the development of hybrid materials that combine natural fibers and nanocellulose with other materials to enhance overall acoustic performance. Integration with aerogels, activated carbon, or other nanoparticles could open opportunities to create materials with multifunctional properties, such as sound absorption combined with air purification [38]. The development of smart acoustic materials that can change their acoustic properties based on environmental conditions or external inputs is also a highly potential research area. In-depth research on the microstructure and sound absorption mechanisms at the molecular level is needed to fundamentally understand how the interaction between natural fibers and nanocellulose affects acoustic performance. The use of advanced characterization techniques such as micro-CT scanning, atomic force microscopy, and molecular dynamics simulations can provide deeper insights into the relationship between the structure and acoustic properties of the material. This deeper understanding will enable more optimal material design and more accurate performance predictions.

The development of more efficient and scalable production methods is a priority to support the commercialization of this material [39]. Research into continuous processing methods, such as electrospinning or solution casting at large scales, needs to be developed to reduce production costs and increase throughput. Additionally, the development of bio-based nanocellulose from agricultural or forestry waste is capable of reduce dependence on conventional nanocellulose sources and improve material sustainability. A comprehensive life cycle assessment is also required to quantify the environmental benefits of this material compared to conventional materials, as well as to identify areas for improvement in production processes and end-of-life management [40].

CONCLUSIONS

Based on the systematic literature review conducted, natural fiber-based acoustic materials modified with nanocellulose show great potential as a sustainable alternative to conventional acoustic materials. Modification of natural fibers such as coconut coir, hemp fiber, banana pseudostem, and rice straw with nanocellulose at concentrations of 1-1.5% w/v has been proven to enhance the sound absorption coefficient to 0.7-0.9 in the 500-2000 Hz frequency range, comparable to synthetic materials such as fiberglass and mineral wool. The significant advantages of this material lie in its balanced acoustic characteristics across a wide frequency spectrum, improved dimensional stability (35-40%), lightweight density (150-300 kg/m³), and biodegradable properties that provide minimal environmental impact. Although facing challenges in raw material variability, long-term resistance to extreme environmental conditions, and production scalability, this material holds great application potential in the construction, automotive, and acoustic industries, with a noise reduction potential of 8-12 dB. Future research should focus on the development of multifunctional hybrid materials, optimization of industrial-scale production methods, and standardization of testing to support the commercialization of sustainable acoustic materials that is capable of contribute significantly to environmentally friendly global noise pollution solutions.

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REFERENCES

[1] A. K. N. N. Fauziah, S. Aritonang, and R. Murniati, "Kajian Review Aplikasi Serat Sisal (Sisal Fiber) Sebagai Alternatif Komposit Polimer," *J. Rekayasa Mater. Manufaktur dan Energi*, vol. 7, no. 2, pp. 304–309, 2024, doi: 10.30596/rmme.v7i2.17364.

[2] Muchlisinalahuddin, H. Dahlan, M. Mahardika, and M. Rusli, "Cellulose-based Material for Sound Absorption And Its Application – A Short Review," *BIO Web Conf.*, vol. 77, p. 1003, 2023, doi: 10.1051/bioconf/20237701003.

[3] I. K. Suarsana and I. G. A. Kasmawan, "Perlakuan Serat Pandan Bali (Cordyline Australis) Sebagai Bahan Penguat Komposit Untuk Peredam Kebisingan Suara Dalam Ruang Gedung," *Pros. Semin. Nas. Sains dan Teknol.*, vol. 9, no. 1, pp. 78–84, 2024.

[4] D. Kartika, Mursal, and Z. Djalil, "Desain Komposit Sandwich Akustik Dari Beton Busa Dan Serat Sawit," *Serambi Konstr.*, vol. 6, no. 2, pp. 92–101, 2024, doi: 10.32672/konstruktivis.v6i2.8020.

[5] M. Mohammadi, M. R. Ishak, M. T. H. Sultan, and E. S. Zainudin, "A Comprehensive Review of Factors Influencing the Sound Absorption Properties of Micro-Perforated Panel Structures," *J. Vib. Eng. Technol.*, vol. 13, no. 5, p. 319, 2025, doi: 10.1007/s42417-025-01849-y.

[6] M. Ardan, N. Siregar, and N. Mahda, "Pembuatan Dinding Beton Ringan Akustik dengan Pemanfaatan Limbah Serat Serabut Kelapa (Cocofiber)," *J. Tek. Sipil Inst. Teknol. Padang*, vol. 7, no. 2, pp. 73–77, 2020, doi: 10.21063/jts.2020.V702.04.

[7] Sahara and A. Kusmiran, "Pengembangan Komposit Panel Akustik Berbahan Dasar Biji dan Kulit Kapuk Randu Untuk Meningkatkan Koefisien Absorbsi Bahan," *Teknosains Media Inf. Sains dan Teknol.*, vol. 15, no. 2, pp. 234–244, 2021, doi: 10.24252/teknosains.v15i2.20176.

[8] S. Ekbatani, P. Rattanawongkun, S. Klayya, D. G. Papageorgiou, N. Soykeabkaew, and H. Zhang, "Hierarchical Natural Fibre Composites Based on Cellulose Nanocrystal-Modified Luffa Structures for Binderless Acoustic Panels," *Polymers*, vol. 17, no. 3. p. 281, 2025. doi: 10.3390/polym17030281.

[9] N. A. Syabani and S. Aritonang, "Analisis Sifat Serat Tandan Kosong Kelapa Sawit Sebagai Material Akustik : Jurnal Review," *J. Rekayasa Mater. Manufaktur dan Energi*, vol. 8, no. 1, pp. 122–128, 2025, doi: 10.30596/rmme.v8i1.21750.

[10] R. Aldania and Suparno, "Determination of Sound Absorption and Water Absorption by Composite Boards Made from Egg Cardboard," *J. Penelit. Pendidik. IPA*, vol. 10, no. 4, pp. 1801–1808, Apr. 2024, doi: 10.29303/jppipa.v10i4.2830.

[11] T. Hassan *et al.*, "Factors Affecting Acoustic Properties of Natural-Fiber-Based Materials and Composites: A Review," *Textiles*, vol. 1, no. 1. pp. 55–85, 2021. doi: 10.3390/textiles1010005.

[12] N. W. Rahmadhani, D. Wahyuni, and A. Asri, "Karakteristik Daya Serap Bunyi Komposit Akustik Berbahan Pelepah Pisang (Musa paradisiaca) Berdasarkan Variasi Komposisi," *Newton-Maxwell J. Phys.*, vol. 6, no. 1, pp. 1–9, Apr. 2025, doi: 10.33369/nmj.v6i1.37168.

[13] R. Mahdani, H. Risnafitri, and Mardiaton, "Exploring the Potential Applications of Blockchain Technology in Accounting Practice: A Systematic Literature Review," *J. Din. Akunt. dan Bisnis*, vol. 11, no. 1, pp. 15–32, 2024, doi: 10.24815/jdab.v11i1.33476.

[14] M. Noer and A. Wibowo, "Evaluating Industrial Areas with Spatial Multicriteria Analysis (SMCA)," *Indones. J. Earth Sci.*, vol. 4, no. 1, p. A845, Feb. 2024, doi: 10.52562/injoes.2024.845.

[15] S. Samsuri, N. N. Misman, A. Borhan, W. Z. N. Yahya, and W. N. A. Wan Osman, "Power Plant Tour: From Physical Field Trip to Virtual Reality," *J. Penelit. dan Pengkaj. Ilmu Pendidik. e-Saintika*, vol. 8, no. 3, pp. 352–372, Nov. 2024, doi: 10.36312/e-saintika.v8i3.2294.

[16] E. T. Sangbara, H. P. L. Tampubolon, F. Mandalurang, M. C. Muaja, R. Pairunan, and A. D. Wuntu, "Isolasi Nanoselulosa Pelepah Aren (Arenga pinnata Merr.) untuk Menurunkan Kandungan Sianida dalam Limbah Tambang Emas Rakyat Sulawesi Utara," *Chem. Prog.*, vol. 16, no. 2, pp. 96–105, Nov. 2023, doi: 10.35799/cp.16.2.2023.52459.

[17] I. Mubarok and E. Purwanda, "Business Feasibility Study of the Production of a Simple Digital Distance Measuring Device Based on a Microcontroller," *J. Ilm. Ekon. Glob. Masa Kini*, vol. 16, no. 1, pp. 25–30, Jan. 2025, doi: 10.36982/jiegmk.v16i1.5270.

[18] V. A. Tran *et al.*, "Nanomaterial for Adjuvants Vaccine: Practical Applications and Prospects," *Indones. J. Chem.*, vol. 24, no. 1, pp. 284–302, Feb. 2024, doi: 10.22146/ijc.87940.

[19] F. Nursari, F. Fadhilaturrahmah, and S. Yuningsih, "Potential Application of The Zero Waste Fashion Method to Optimize Fabric Usage," *J. Ilmu Lingkung.*, vol. 23, no. 1, pp. 124–132, Jan. 2025, doi: 10.14710/jil.23.1.124-132.

[20] F. F. Hanum, A. Rahayu, N. A. Z. Amrillah, and Yoga Nawaki Helmi Mustafa, "The Utilization and Extraction Method of Nanocellulose: A Review," *Sains Nat. J. Biol. Chem.*, vol. 13, no. 3, pp. 107–114, Jul. 2023, doi: 10.31938/jsn.v13i3.565.

[21] M. Olivares-Marín, S. Román, V. Gómez Escobar, C. Moreno González, A. Chaves-Zapata, and B. Ledesma, "Thermal performance and sound absorption capability of water hyacinth stems-based materials," *J. Clean. Prod.*, vol. 425, p. 138903, 2023, doi: 10.1016/j.jclepro.2023.138903.

[22] D. A. Septiawati and S. N. Aulia, "Analyzing the Acoustic Behavior of Gamelan Music Performance in Different Environments," *Interlude Indones. J. Music Res. Dev. Technol.*, vol. 2, no. 2, pp. 58–69, 2023, doi:

10.17509/interlude.v2i2.70119.
[23] Sunardi, R. Wahyudi, S. Ula, Haryadi, and A. A. Alhamidi, "Evaluation of Acoustic and Physical Properties of Composite Boards from Sugarcane Bagasse and Oil Palm Waste," *J. Polimesin*, vol. 23, no. 2, pp. 248–252, 2025, doi: 10.30811/jpl.v23i2.6618.
[24] S. A. Putri, R. Febrianti, and Sunardi, "Potensi Nanoselulosa untuk Agen Slow Release Bahan Alam: Review," *J. Jejaring Mat. dan Sains*, vol. 2, no. 2, pp. 56–60, Dec. 2020, doi: 10.36873/jjms.2020.v2.i2.406.
[25] Muflikhah, W. Z. Lubis, Mujamilah, M. Azizah, and R. P. Caesariyant, "The Effect of Conventional and Sonochemical Synthesis Methods on Gd2O3 Nanoparticles Properties," *J. Sains Mater. Indones.*, vol. 24, no. 1, pp. 45–50, May 2022.
[26] R. Negoro, A. Rusilowati, and B. Subali, "Contextual Technology-Based Physics Module on Sound Absorption: Improving Critical Thinking Skills and Scientific Attitudes of Indonesian High School Students," *KONSTAN (Jurnal Fis. dan Pendidik. Fis.*, vol. 10, no. 01, pp. 1–13, May 2025, doi: 10.20414/konstan.v10i01.647.
[27] C. J. A. Hakim, M. Jonathan, and H. C. Indrani, "Assessment of Indoor Acoustic Performance: Impact of Interior Materials on Classrooms in Higher Education Buildings," *Int. J. Sustain. Dev. Futur. Soc.*, vol. 2, no. 2, pp. 84–98, Nov. 2024, doi: 10.62157/ijsdfs.v2i2.76.
[28] S. Amirudin, Tamrin, and S. Rejeki, "Metode Sintesis Nanoselulosa: Kajian Pustaka," *J. Ris. Pangan*, vol. 2, no. 1, pp. 89–96, 2024.
[29] S. D. Pramesti and S. M. Aryani, "The potential of cassava peel as acoustic panel material: A sustainable innovation in green engineering," *J. Innov. Mater. Energy, Sustain. Eng.*, vol. 2, no. 2, pp. 154–163, Jan. 2025, doi: 10.61511/jimese.v2i2.2025.1397.
[30] M. F. Datuela, Rahmayanti, W. Saputra, N. Mutmainnah, and Syafriani, "Perbandingan Material Akustik Dalam Menyerap Bunyi," *JAMBURA J. Archit.*, vol. 5, no. 1, pp. 92–96, 2023, doi: 10.37905/jjoa.v5i1.19773.
[31] H. Meziane *et al.*, "Nanocellulose fibers: A Review of Preparation Methods, Characterization Techniques, and Reinforcement Applications," *Moroccan J. Chem.*, vol. 12, no. 1, pp. 305–343, 2024, doi: 10.48317/IMIST.PRSM/morjchem-v12i1.44573.
[32] R. Wicaksono, K. Syamsu, I. Yuliasih, and M. Nasir, "Karakteristik Nanoserat Selulosa dari Ampas Tapioka dan Aplikasinya Sebagai Penguat Film Tapioka," *J. Teknol. Ind. Pertan.*, vol. 23, no. 1, pp. 38–45, Nov. 2013.
[33] R. N. Hidayati, D. C. Wulan, A. Fauziah, N. Rahayu, and B. Subali, "Potential of Soundproof Wallpaper Based on Indigenous Materials," *J. Sci. Indones.*, vol. 1, no. 2, pp. 131–146, 2015, doi: 10.15294/jsi.v1i2.32609.
[34] M. A. Rahim and E. M. Samsudin, "Sound Absorption Performance of Ink-Tube Waste as Absorber," *Recent Trends Civ. Eng. Built Environ.*, vol. 2, no. 1, pp. 87–93, 2021.
[35] B. R. Kusumah, I. Jaya, H. M. Manik, and Susilohadi, "Engineering of Acoustic Technology for Underwater Positioning Object," *J. Ilmu dan Teknol. Kelaut. Trop.*, vol. 10, no. 3, pp. 629–637, Dec. 2018, doi: 10.29244/jitkt.v10i3.21456.
[36] A. R. Nafisah, D. Rahmawati, and F. M. Tarmidzi, "Synthesis of Cellulose Nanofiber from Palm Oil Empty Fruit Bunches Using Acid Hydrolysis Method," *Indones. J. Chem. Sci.*, vol. 11, no. 3, pp. 233–240, Nov. 2022, doi: 10.15294/IJCS.V11I3.55936.
[37] M. A. Mahadzir and H. A. Bakar, "A Review on Sound Absorption Properties Using Natural Fibers," *Recent Trends Civ. Eng. Built Environ.*, vol. 2, no. 1, pp. 815–823, 2021.
[38] P. Chattaviriya, D. Supawantanakul, R. Sangsirimongkolying, and G. Sua-Iam, "Banana Fibers as a Sustainable Acoustic Absorbing Materials: A Review," *Trends Sci.*, vol. 19, no. 11, p. 4498, May 2022, doi: 10.48048/tis.2022.4498.
[39] C. Ma, H. Liao, M. Li, and Q. Tao, "Investigation on Aerodynamic Behavior of Sutong Bridge During Erection Stage," in *The Seventh Asia-Pacific Conference on Wind Engineering*, Taipei, Taiwan, 2009, pp. 1–8.
[40] N. Hartati, E. Kurniawan, M. Trisna, and I. Noviarni, "Isolasi, Karakterisasi, Dan Aplikasi Nanokristal Selulosa : Review," *JSSIT J. Sains dan Sains Terap.*, vol. 1, no. 2, pp. 29–38, Aug. 2023, doi: 10.30631/jssit.v1i2.19.