

**DEVELOPMENT OF ACOUSTIC MATERIALS AND VALUE-ADDED
CHEMICALS FROM WASTE BIOMASS**

ASHUTOSH NEGI



**SCHOOL OF INTERDISCIPLINARY RESEARCH
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

JULY 2025

© Indian Institute of Technology Delhi (IITD), New Delhi, 2025

**Development of Acoustic Materials and Value-added Chemicals from
Waste Biomass**

by

Ashutosh Negi

School of Interdisciplinary Research

Submitted in fulfillment of requirements of degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2025

CERTIFICATE

This is to certify that the thesis entitled “**Development of Acoustic Materials and Value-added Chemicals from Waste Biomass**” being submitted by Mr. Ashutosh Negi in the fulfillment of the requirements for the award of the degree of **Doctor of Philosophy** to the Indian Institute of Technology Delhi (India) is an authentic record of work carried out by him. Mr. Ashutosh Negi has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which, to my knowledge, has reached the requisite standard.

The results contained in the thesis are original and have not been submitted in part or full to any other university or institute for the award of any other degree or diploma.



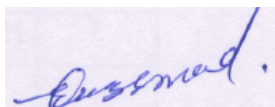
Dr. M. Ali Haider

Professor
Department of Chemical Engineering
Indian Institute of Technology Delhi



Dr. Shahab Fatima

Associate Professor
Centre for Automotive Research and Tribology
Indian Institute of Technology Delhi



Dr. Ejaz Ahmad

Assistant Professor
Department of Chemical Engineering
Indian Institute of Technology ISM Dhanbad

Acknowledgment

First and foremost, I would like to acknowledge my supervisors, Prof. M. Ali Haider, Prof. Shahab Fatima, and Prof. Ejaz Ahmed for their support and encouragement during the entire dissertation period. Further, I am very much thankful to my SRC members, Prof. Anushree Malik, Prof. Kamal Kishor Pant, and Prof. S. Wazed Ali, for their thoughtful questions and suggestions during the progress presentations. The questions and suggestions have certainly improved the quality of work. I am also grateful to Prof. Jason Hallett for supporting me and providing an opportunity to conduct research work at Imperial College London. Finally, I would like to convey warm regards to my family, friends, and lab members who have made this Ph.D. journey a memorable experience for me.

Ashutosh Negi

Abstract

Among the bio-based resources, agricultural residues are abundantly available across the globe, generally treated as waste. The transformation of agricultural residues to value-added products, thus provides an opportunity to develop novel processes for sustainability. Herein, a comprehensive waste biomass processing approach is presented to convert agricultural residues into acoustic materials and value-added chemicals. Towards this, the first part of the dissertation explores the sustainable utilization of rice straw for developing sound absorbing and insulating materials. A pretreatment was first applied to separate out the cellulosic component of the waste biomass. Cellulosic pulp obtained from rice straw was employed as a feedstock to fabricate sound absorbing materials. Impedance tube measurements were performed to test acoustic properties of the fabricated material by filling it in a 3-D printed polylactic acid cavity. The pretreated pulp consists of a porous structure, which provides opportunities for dissipation of sound energy within the material. The pretreatment has shown significant enhancement (25.45%) in noise reduction coefficient to 0.55 compared to 0.41 measured for the material fabricated from raw rice straw. In parallel, sound insulating biocomposites were developed by mixing rice straw with bio-based binders such as lignin and guar gum. The developed biocomposites were tested for sound transmission loss (STL) in an impedance tube setup. It measured an average STL in the range of 28-30 dB, which is significant for noise control applications. A techno-economic analysis (TEA) of the fabrication process was performed. Economic indicators such as net present value (NPV), internal rate of return (IRR), and payback period (PB) were estimated. Economic analysis results suggested the importance of keeping raw feedstock cost within permissible limits to ensure economically viable commercial-scale noise-control material production.

In the second part of the dissertation work, chemical processing routes were explored to valorize the leftover cellulosic biomass into value-added chemicals. Towards this, the chemical transformation of 2,5-dimethylbenzoic acid was explored experimentally. The results indicated that the acidic ionic liquids enhance the yield of 2,5-dimethylbenzoic acid due to the higher availability of HSO_4^- ions in the reactant. Moreover, trimellitic acid (TMLA) production TEA from biorenewable substrates was explored theoretically using ASPEN Plus. The TEA of the TMLA production suggested the importance of managing raw material cost and solvent recycling to achieve the desired economics for TMLA production.

सारांश

जैव-आधारित संसाधनों में, कृषि अवशेष पूरी दुनिया में प्रचुर मात्रा में उपलब्ध हैं, जिन्हें आमतौर पर अपशिष्ट माना जाता है। कृषि अवशेषों को मूल्य वर्धित उत्पादों में परिवर्तित करना सतत विकास के लिए नए तरीकों को विकसित करने का एक अवसर प्रदान करता है। इस शोध में, कृषि अवशेषों को ध्वनि नियंत्रण सामग्रियों और मूल्य वर्धित रसायनों में बदलने के लिए एक समग्र अपशिष्ट बायोमास प्रसंस्करण दृष्टिकोण प्रस्तुत किया गया है। इस दिशा में, शोध प्रबंध के पहले भाग में ध्वनि-अवशोषक और ध्वनि-अवरोधक सामग्रियों के निर्माण के लिए धान की पुराली (राइस स्ट्रॉ) के सतत उपयोग की खोज की गई है। सबसे पहले, अपशिष्ट बायोमास के सेलुलॉसिक घटक को अलग करने के लिए एक पूर्व-उपचार (प्रीट्रीटमेंट) किया गया। धान की पुराली से प्राप्त सेलुलॉसिक पल्प को ध्वनि-अवशोषित सामग्री बनाने के लिए कच्चे माल के रूप में उपयोग किया गया। निर्मित सामग्री की ध्वनिक विशेषताओं का परीक्षण करने के लिए इसे 3D-मुद्रित पॉली लैक्टिक एसिड (PLA) गुहा में भरकर प्रतिबाधा ट्यूब (इंपीडेंस ट्यूब) में माप किए गए। पूर्व-उपचारित पल्प में एक छिद्रपूर्ण संरचना होती है, जो सामग्री के भीतर ध्वनि ऊर्जा के अपव्यय की संभावना प्रदान करती है। इस पूर्व-उपचार से ध्वनि न्यूनीकरण गुणांक में 25.45% की महत्वपूर्ण वृद्धि हुई, जिससे यह 0.55 हो गया, जबकि कच्चे धान के पुराली से बनी सामग्री के लिए यह मान 0.41 था। साथ ही, ध्वनि-अवरोधक बायोकोम्पोजिट, धान की पुराली को लिग्निन और ग्वार गम जैसे जैव-आधारित बाइंडर्स के साथ मिलाकर विकसित किया गया। विकसित बायोकोम्पोजिट को प्रतिबाधा ट्यूब सेटअप में ध्वनि संचरण हानि (Sound Transmission Loss - STL) के लिए परीक्षण किया गया, जहां इसका औसत STL 28-30 dB के दायरे में मापा गया, जो शोर नियंत्रण अनुप्रयोगों के लिए महत्वपूर्ण है। इसके निर्माण प्रक्रिया का एक तकनीकी-आर्थिक विश्लेषण (Techno-Economic Analysis - TEA) किया गया। आर्थिक संकेतक जैसे शुद्ध वर्तमान मूल्य (Net Present Value - NPV), आंतरिक प्रतिफल दर (Internal Rate of Return - IRR), और अदायगी अवधि (Payback Period - PB) का अनुमान लगाया

गया। आर्थिक विश्लेषण के परिणामों ने यह सुझाव दिया कि वाणिज्यिक स्तर पर आर्थिक रूप से व्यवहार्य शोर-नियंत्रण सामग्री के उत्पादन को सुनिश्चित करने के लिए कच्चे माल की लागत को अनुमेय सीमाओं के भीतर रखना आवश्यक है।

शोधकार्य के द्वितीय भाग में, अवशिष्ट सेलुलॉसिक बायोमास को मूल्यवर्धित रासायनिक उत्पादों में रूपांतरित करने हेतु संभावित रासायनिक प्रसंस्करण मार्गों का अन्वेषण किया गया। इस दिशा में, 2,5-डाईमिथाइल बेंजोइक एसिड के रासायनिक रूपांतरण को प्रयोगात्मक रूप से अध्ययन किया गया। परिणामों से संकेत मिला कि अम्लीय आयनिक तरल पदार्थ (Ionic Liquids) 2,5-डाईमिथाइल बेंजोइक एसिड की प्राप्ति को बढ़ाते हैं, क्योंकि इसमें HSO_4^- आयनों की अधिक उपलब्धता होती है। वहीं, जैव-नवीकरणीय अवशेषों से ट्राइमेलिटिक एसिड (TMLA) के उत्पादन का तकनीकी-आर्थिक विश्लेषण (TEA) सैद्धांतिक रूप से ASPEN Plus का उपयोग करके किया गया। TMLA उत्पादन के तकनीकी-आर्थिक विश्लेषण (TEA) ने यह सुझाव दिया कि वांछित आर्थिक लाभ प्राप्त करने के लिए कच्चे माल की लागत प्रबंधन और विलायक पुनर्चक्रण (Solvent Recycling) का महत्वपूर्ण योगदान है।

Table of Contents

CERTIFICATE.....	i
Acknowledgment	ii
Abstract.....	iii
सारांश	v
Table of Contents	vii
List of Figures.....	xiii
List of Tables.....	xvii
List of Abbreviations.....	xix
List of Symbols.....	xxii
Chapter 1 Introduction	1
1.1 Background.....	1
1.2 Objectives	18
1.3 Thesis organization	19
Chapter 2 Biorenewable Acoustic Materials and Chemicals.....	29
2.1 Background.....	29
2.2 Acoustical materials.....	30
2.2.1 Sound absorbing materials.....	30
2.2.2 Sound insulating materials.....	47
2.3 Bio-based chemicals	54
2.3.1 Production of selected aromatics from biorenewable resources.....	59

2.4	Research gap	64
Chapter 3 Materials and Methods		75
3.1	Background	75
3.2	Raw materials.....	75
3.2.1	Sound absorbing material	75
3.2.2	Sound insulating material	77
3.2.3	Dimethylbenzoic acid production	77
3.3	Transformation of waste lignocellulosic biomass to noise control materials	77
3.3.1	Transformation of rice straw to sound absorbing materials.....	78
3.3.2	Transformation of rice straw to sound insulating biocomposites	80
3.4	Characterizations.....	82
3.4.1	Fourier transform infrared spectroscopy (FTIR)	82
3.4.2	X-ray diffraction (XRD)	84
3.4.3	Thermogravimetric analysis (TGA).....	85
3.4.4	Brunauer-Emmett-Teller (BET).....	87
3.4.5	Field emission scanning electron microscopy (FESEM).....	88
3.4.6	Energy dispersive X-ray spectroscopy (EDX).....	89
3.4.7	Universal testing machine (UTM)	90
3.4.8	Thermal conductivity	92
3.4.9	Shore D hardness	93
3.4.10	Gas chromatography-mass spectrometry (GC-MS).....	94

3.4.11	Compression molding	95
3.4.12	Impedance tube set-up	97
3.5	Techno-economic analysis	98
Chapter 4 Sound Absorbing Materials from Waste Biomass.....		105
4.1	Background.....	105
4.2	Experimental procedure	105
4.3	Characterizations.....	106
4.3.1	Sound absorption coefficient testing.....	107
4.4	Results and discussion	109
4.4.1	FTIR of raw and pretreated rice straw samples	109
4.4.2	XRD of raw and pretreated rice straw samples	112
4.4.3	TGA of raw and pretreated rice straw samples	113
4.4.4	BET of raw and pretreated rice straw samples	115
4.4.5	FESEM of raw and pretreated rice straw samples	115
4.4.6	Density of raw and pretreated rice straw samples	116
4.4.7	SAC of raw and pretreated rice straw samples	118
4.5	Conclusion	122
Chapter 5 Development of Sound Insulating Biocomposites.....		127
5.1	Background.....	127
5.2	Experimental procedure	128
5.2.1	Sound transmission loss testing	131

5.3	Results and discussions.....	134
5.3.1	FTIR of raw powders and developed biocomposites.....	134
5.3.2	XRD of raw powders and developed biocomposites.....	136
5.3.3	FESEM of developed biocomposites.....	137
5.3.4	TGA of raw powders and developed biocomposites	139
5.3.5	Thermal conductivity of developed biocomposites	140
5.3.6	Flammability of developed biocomposites	141
5.3.7	Mechanical properties of developed biocomposites	142
5.3.8	Biodegradation of developed biocomposites	145
5.3.9	Density of developed biocomposites	147
5.3.10	Sound transmission loss of developed biocomposites	147
5.4	Conclusion	149
Chapter 6 Techno-economic Analysis of Acoustic Material Fabrication		155
6.1	Background.....	155
6.2	Methodology.....	156
6.3	Results and discussion	158
6.3.1	Sound absorbing materials.....	158
6.3.2	Sound insulating materials.....	162
6.4	Conclusion	167
Chapter 7 Chemical Transformation of Cellulose-derived Platform Chemicals to Valorized Products.....		171
7.1	Background.....	171

7.2	Experimental procedure	172
7.2.1	Reactants	172
7.2.2	Acid-base ratio determination	172
7.2.3	HSQC NMR spectroscopy	172
7.2.4	GC-MS analysis	173
7.2.5	Theoretical modeling	174
7.3	Results and discussion	176
7.3.1	Effect of temperature and acidity of ionic liquid	176
7.3.2	Effect of acrylic acid concentration	179
7.3.3	Inferences from hybrid DFT/MD studies	181
7.4	Conclusion	183
Chapter 8 Techno-economic Analysis of a Chemical Process to Produce Value-added Chemicals.....		187
8.1	Background	187
8.2	Methodology	189
8.2.1	Simulation parameters	190
8.3	Results and discussion	195
8.3.1	Simulation of the double reactor and single reactor processes for TMLA production	195
8.3.2	Techno-economic analysis of TMLA production in a double reactor system	196
8.3.3	Techno-economic analysis of TMLA production in a single reactor system.....	199
8.4	Conclusion	201

Chapter 9 Conclusion and Future Scope of Work.....	205
9.1 Key conclusion.....	205
9.2 Future scope of work	206
Appendix.....	208
Biodata of Candidate.....	230

List of Figures

Figure 1.1: Agricultural residues types and their potential utilization routes	1
Figure 1.2: a) Major agricultural crop production, b) Comparative rice production in India....	3
Figure 1.3: Effects of noise exposure on human health.....	4
Figure 1.4: a) Schematic of sound absorbing and insulating material in a closed space, b) Noise control material market growth	7
Figure 1.5: Applications of noise control materials	8
Figure 1.6: Lignocellulosic biomass pretreatment methods	13
Figure 1.7: Phase diagram of deep eutectic solvents	14
Figure 1.8: Selected HBA and HBD used in the literature studies	15
Figure 1.9: Transformation routes for HMF and DMF from biomass.....	16
Figure 1.10: Potential value-added chemicals from 5-hydroxymethylfurfural	17
Figure 2.1: Schematic of sound absorbing materials.....	30
Figure 2.2: Schematic of distance traveled by low and high-frequency sound waves	40
Figure 2.3: Effect of pretreatment of the straw cell wall structure	43
Figure 2.4: Schematic of sound insulating materials.....	47
Figure 2.5: Schematic of insertion loss a) With wall, b) Without partition wall	48
Figure 2.6: Schematic for noise reduction	48
Figure 2.7: Production of p-xylene, TPA, toluene, and TMLA from a) Fossil route, b) Biorenewable route	56
Figure 2.8: Reaction mechanism for the production of p-xylene, TPA, toluene and TMLA (adapted from ^{120, 121, 122, 123}).....	57
Figure 3.1: Schematic overview of investigated processes	76
Figure 3.2: a) IKA heating plate b) NADES prepared for rice straw pretreatment	78

Figure 3.3: Images of raw and pretreated rice straw.....	79
Figure 3.4: Step-by-step synthesis, fabrication, and testing of bio-renewable sound absorbing materials.....	80
Figure 3.5: Fabrication of rice straw biocomposites.....	82
Figure 3.6: Schematic of a) FTIR, b) ATR.....	83
Figure 3.7: Schematic of TGA.....	86
Figure 3.8: Schematic of FESEM.....	89
Figure 3.9: Schematic of a) UTM, b) Sample in tensile test, c) Sample in flexural test	91
Figure 3.10: Schematic of thermal conductivity meter.....	92
Figure 3.11: Schematic of the Shore D hardness meter.....	94
Figure 3.12: Schematic of GC-MS	95
Figure 3.13: Schematic of compression molding	96
Figure 4.1: Schematic of two-microphone impedance tube setup.....	108
Figure 4.2: FTIR spectra of raw and pretreated rice straw samples	111
Figure 4.3: XRD pattern of raw and pretreated rice straw samples.....	112
Figure 4.4: TGA curve of raw and pretreated rice straw samples	114
Figure 4.5: FESEM micrographs of a) Raw rice straw, b) 1hr, 120°C, c) 1hr, 140°C , d) 3hr, 120°C, e) 3hr, 140°C pretreated rice straw. Values in brackets indicate cavity diameter and crack spacing.....	116
Figure 4.6: Effect of pretreatment on SAC and NRC of raw and pretreated rice straw samples	119
Figure 4.7: Effect of thickness on SAC and NRC of raw and pretreated rice straw samples	121
Figure 4.8: Effect of air gap on SAC and NRC of a) Raw rice straw, b) 1hr, 120°C, c) 1hr, 140°C d) 3hr, 120°C, e) 3hr, 140°C pretreated rice straw	122

Figure 5.1: a) Images of developed samples used for sound transmission loss testing, b) Schematic of 4-microphone impedance tube setup	132
Figure 5.2: FTIR of a) Raw powders and b)Rice straw biocomposites.....	135
Figure 5.3: XRD pattern of a) Raw powders and b) Rice straw biocomposites.....	136
Figure 5.4: FESEM micrographs of a) RS 0, b) RS A, c) RS B, d) RS C, e) RS D, f) RS E	138
Figure 5.5: TGA profile of a) Raw powders and b) Rice straw biocomposites.....	139
Figure 5.6: Thermal conductivity of rice straw biocomposites	140
Figure 5.7: a) Tensile, b) Flexural, c) Shore D hardness of rice straw biocomposites	143
Figure 5.8: Biodegradability of rice straw biocomposites	146
Figure 5.9: Normal incidence STL a) Predicted using theoretical mass law, b) Measured using four-microphone impedance tube setup.....	148
Figure 6.1: Schematic on the perspective of circular knowledge translation ¹⁰	155
Figure 6.2: Process flow diagram for techno-economic analysis of (a) Sound absorbing material, (b) Sound insulating biocomposite	158
Figure 6.3: a) Operating cost components in sound absorbing material fabrication, b) Effect of variation in lactic acid, choline chloride, and rice straw cost on unit production cost, c) Plant profitability with variation in production cost, d) Plant profitability with variation in sale price	159
Figure 6.4: a) Operating cost components in sound insulating material fabrication, b) Effect of variation in rice straw, lignin, and guar gum cost on unit production cost, c) Plant profitability with variation in production cost, d) Plant profitability with variation in sale price.....	163
Figure 7.1: a) Reaction flow diagram, b) Image of reaction vials at different stages of reaction	173
Figure 7.2: Yield of 2,5-dimethylbenzoic acid with varying temperature and acidity of [DMBA][HSO ₄].....	178

Figure 7.3: Effect of AA concentration (mmol) on 2,5-dimethylbenzoic acid yield at A/B = 1.02	179
Figure 7.4: Reaction pathway for 2,5-dimethylbenzoic acid formation	181
Figure 7.5: Free energy profiles from hybrid DFT/MD calculations for the different reaction steps: (A) Diels-Alder addition, (B) Ring-opening, and (C) Dehydration reaction with the corresponding structure of reactant, transition state, and product used in MD simulations. The energies are shifted to use the reactant of that reaction step as a reference for comparing the solvent effects. Here, SN, SB, and SA represent the neutral, basic, and acidic solvent environments, respectively.....	182
Figure 8.1: TMLA production from (a) Conventional and (b) Biorenewable resources	188
Figure 8.2: Schematic for evaluating the economic viability of TMLA production from biorenewable substrates	190
Figure 8.3: Plausible reaction pathways for TMLA production in (a) Two-step double reactor setup and (b) One-step single reactor setup	190
Figure 8.4: Process flow diagram for TMLA production from HMF via DMF in double reactor setup	192
Figure 8.5: Process flow diagram for TMLA production from HMF in single reactor setup	194
Figure 8.6: Comparative of case-wise raw material price and total operating costs	197

List of Tables

Table 1.1: Continent-wise global agricultural residue generation (Mt) from major crops	2
Table 1.2: WHO guidelines for noise pollution in specific environments.....	5
Table 1.3: Maximum noise exposure limits in India.....	6
Table 1.4: Noise control approaches for source-path-receiver	8
Table 1.5: Chemical composition of rice straw	11
Table 1.6: Chemical composition of rice straw generated from Indian cultivars	11
Table 1.7: Ultimate analysis of rice straw from different countries.....	12
Table 2.1: Comparison of sound absorption test methods	32
Table 2.2: Sound absorbing materials developed from bio-based feedstocks	33
Table 2.3: Chemical pretreatment of rice straw	41
Table 2.4: Comparison of sound insulation test methods	50
Table 2.5: Sound insulating materials developed from bio-based feedstocks	51
Table 2.6: Fossil derived p-xylene, terephthalic acid, toluene and trimellitic acid	58
Table 2.7: Production of biomass-derived p-xylene, TPA, toluene and TMLA	62
Table 3.1: Concentration of rice straw, lignin, and guar gum in developed biocomposites	80
Table 3.2: Proportional share of direct costs and indirect costs for sound absorbing material fabrication	99
Table 3.3: Proportional share of direct costs and indirect costs for sound insulating material fabrication	100
Table 4.1: FTIR peak and associated functional group of raw and pretreated rice straw samples.....	109
Table 4.2: Density, porosity, and tortuosity of raw and pretreated rice straw samples.....	117
Table 4.3: Comparative NRC of commercial sound absorbing materials	119

Table 5.1: Flammability properties of developed biocomposites	142
Table 5.2: Tensile and flexural modulus of rice straw biocomposites	144
Table 6.1: Major equipment cost with annual electricity consumption	157
Table 6.2: Effect of variation in production costs of sound absorbing material fabrication..	160
Table 6.3: Variation in sale costs of sound absorbing material fabrication.....	161
Table 6.4: Variation in production cost of sound insulating biocomposite fabrication.....	165
Table 6.5: Variation in sale price of sound insulating material fabrication.....	166
Table 7.1: Composition of the simulation mixture used for estimating the solvation-free energy under neutral conditions	175
Table 7.2: Previous studies on 2,5-dimethylbenzoic acid production	180
Table 8.1: Boiling point and molecular weight of components used in the study from Aspen plus property database.....	192
Table 8.2: Project parameters for economic analysis.....	195
Table 8.3: Case-wise material cost for the input feed	198
Table 8.4: Economics of single reactor setup at varying TMLA sale price	200

List of Abbreviations

AA	Acrylic Acid
Aq	Aqueous
ASPEN	Advanced System For Process Engineering
ASTM	American Society For Testing and Materials
ATR	Attenuated Total Reflection
BET	Brunauer-Emmett-Teller
CEPCI	Chemical Engineering Plant Cost Index
CrI	Crystallinity Index
DA	Diels-Alder
dB	Decibel
DES	Deep Eutectic Solvents
DMF	2,5-Dimethylfuran
EDX	Energy Dispersive X-Ray Spectroscopy
FESEM	Field Emission Scanning Electron Microscopy
FTIR	Fourier Transform Infrared Spectroscopy
GC-MS	Gas Chromatography-Mass Spectrometry
GSM	Grams Per Square Metre
HBA	Hydrogen Bond Acceptor
HBD	Hydrogen Bond Donor
HMF	5-Hydroxymethyl Furfural
HSQC	Heteronuclear Single Quantum Coherence
IL	Insertion Loss
IRR	Internal Rate of Return

ISO	International Organization For Standardization
kWh	Kilowatt Hours
mM	Milimoles
Mt	Million Tons
NADES	Natural Deep Eutectic Solvents
NPV	Net Present Value
NR	Noise Reduction
NRC	Noise Reduction Coefficient
PB	Payback Period
PLA	Polylactic Acid
PP	Polypropylene
PU	Polyurethane
PVA	Polyvinyl Acetate
RPM	Rotation Per Minute
SAA	Sound Absorption Average
SAC	Sound Absorption Coefficient
SDG	Sustainable Development Goals
STC	Sound Transmission Class
STL	Sound Transmission Loss
TDEC	Total Delivered Equipment Cost
TEA	Techno-Economic Analysis
TGA	Thermogravimetric Analysis
TMLA	Trimellitic Acid
TPA	Terephthalic Acid
UF	Urea Formaldehyde

UTM	Universal Testing Machine
WHO	World Health Organization
XRD	X-Ray Diffraction

List of Symbols

ρ	Density
θ	Diffraction Angle
ϕ	Porosity
α	Sound Absorption Coefficient
τ	Sound Transmission Coefficient
k	Thermal Conductivity
a_{∞}	Tortuosity
ψ	Transfer Function Phase
η	Viscosity
λ	Wavelength