BIOBASED SOUND ABSORPTIVE PANEL SYSTEM DESIGN AND DEVELOPMENT USING FRUIT SEEDS

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By

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We certify that we have read this thesis and that, in our opinion, it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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In order to reduce the carbon footprint due to currently applied sound absorptive materials in the building construction field, alternative sustainable systems are investigated in this research. By re-using the waste fruit seeds that are abundant in the Central Anatolia region of Turkey, a composite panel system is developed to be applied in buildings as a fine finish surface, like a wall or ceiling panel. The raw material is composed of various fruit seeds, including cherry, watermelon, olive, etc. The tree resin is combined with wood fire ash as a natural adhesive. The efficacy of the adhesive property is the subject of biological adhesive research. Wood glue is utilized as an alternative to other adhesive materials; it is considered more efficient in material production due to its practicality and accessibility. The varied combinations of seeds, tree resin, and wood glue have been tested through impedance tube measurements, and sound absorption coefficient data are acquired. To test the efficiency of produced samples, one with the maximum sound absorption performance is tested in the design studio at Bilkent University based on the data obtained, which is a current acoustic problem due to very high reverberance. An acoustical model is generated replicating the problematic studio, and the panel system is tested through ray-tracing simulations. On the generated studio model, the panel system is applied to specific surfaces, and reverberation times for the current and adjusted state of the studio is compared. The results indicate that the panels out of seeds combined with proper adhesives have a potential to be applied as a sound absorptive decorative system in various architectural spaces.

Keywords: Sound Absorption Coefficient, Impedance Tube, Sustainable Materials, Biobased Materials, Sound Absorptive Panel, Fruit Seeds, Reuse

ÖZET

MEYVE ÇEKİRDEKLERİ KULLANARAK BİYOBAZLI SES YUTUCU PANEL SİSTEMİ TASARIM VE GELİŞTİRMESİ

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Eylül 2023

Bu araştırmada, yapı endüstrisinde hâlihazırda uygulanan ses yutucu malzemelerden kaynaklanan karbon ayak izini azaltmak için alternatif sürdürülebilir sistemler araştırılmaktadır. Türkiye'nin İç Anadolu bölgesinde bol miktarda bulunan atık meyve tohumlarının yeniden kullanılmasıyla, binalarda duvar veya tavan paneli gibi ince bir son yüzey olarak uygulanmak üzere bir kompozit panel sistemi geliştirilmiştir. Hammadde kiraz, karpuz, zeytin vb. gibi çeşitli meyve çekirdeklerinden oluşur. Doğal bir yapıştırıcı olarak odun reçinesi odun ateşi külü ile birleştirilir. Yapışkan özelliğinin etkinliği, doğal yapışkan araştırmalarının konusudur. Ahşap tutkalı, diğer yapışkan malzemelere alternatif olarak kullanılır; pratikliği ve erişilebilirliği nedeniyle malzeme üretiminde daha verimli olduğu düşünülmektedir. Çeşitli tohum, ağaç reçinesi ve ahşap tutkalı kombinasyonları, empedans tüpü ölçümleriyle test edilmiş ve ses emme katsayısı verileri elde edilmiştir. Üretilen örneklerin etkinliğini test etmek için, yüksek çınlama süresi sorununa sahip olan Bilkent Üniversitesindeki bir tasarım stüdyosunda, en yüksek ses yutma performansına sahip olan malzeme örneği test edilir. Akustik açıdan probleme sahip olan bu stüdyonun üç boyutlu modeli oluşturulur ve ışın izleme simülasyonları ile test edilir. Oluşturulan stüdyo modeli üzerinde belirli yüzeylere panel sistemi uygulanarak stüdyonun mevcut ve panel sistemi uygulanmış durumu için çınlama süreleri karşılaştırılır. Sonuçlar, uygun yapıştırıcılarla birleştirilen tohumlardan çıkan panellerin, iç mekânlarda ses yutucu dekoratif sistemler olarak uygulanma potansiyeline sahip olduğunu göstermektedir. Alternatif gözenekli yapıştırıcılarla ilgili çalışmalar devam etmektedir.

Anahtar sözcükler: Ses Yutma Katsayısı, Empedans Tüpü, Sürdürülebilir Malzemeler, Biyo-bazlı Malzemeler, Ses Yutucu Panel, Meyve Tohumları, Yeniden Kullanım

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CHAPTER 1

INTRODUCTION

1.1. Problem Statement

The use of environmentally hazardous products in the modern world has led the sustainable resources limit to be exceeded, and as a result, the world has been dragged towards an eventual catastrophe. This has allowed the annual demand for green technologies to grow substantially. To comprehend a substance's sustainability, its effects on nature, human health, and social justice must be assessed. In order to secure the sustainability of resources, the manufacturing process must generate as little waste as feasible, or waste products must be given a second life. Renewable energy is preferred over nonrenewable resources in this regard (Santoni et al., 2019). Consequently, if possible, ecologically friendly, and biodegradable products should be more common in construction industry.

Acoustic comfort in interior spaces refers to how sound quality and noise levels are perceived by users. This subject is crucial in architectural design and effects the overall well-being, comfort and productivity of the people using the space. Achieving acoustic comfort necessitates the creation of an environment in which sound is controlled, balanced, and tailored to meet the specific requirements of the space and its users. The type, composition, and thickness of the materials used for sound insulation, isolation and sound absorption are critical in room acoustics and building acoustics design. These materials are chosen with care and strategically arranged to regulate sound reflections, absorption, transmission, and diffusion.

The most prevalent sound-absorbative materials include perforated wood panels, perforated gypsum board, wood wool, and melamine foam. Mineral or glass wool backed perforated panels or fabric-covered glass, or mineral wool are frequently applied conventional sound-absorbing materials used in architectural applications. Because these materials release microscopic hazardous particles, even in small quantities, they may pose health problems in the future for employees who are in the process of material production (Buratti et al., 2016). It is known that exposure to dust poses an average health risk (Kupczewska-Dobecka et al., 2020). So as an alternative green and biodegradable materials should be searched. On the other hand, high manufacturing costs result in substantial carbon footprints and severe environmental repercussions (Buratti et al., 2016; Saldaña-Mendoza et al., 2021).

By applying green technology detrimental gas discharges can be restricted, building hygiene standards can be met and the capacity of recycled or reused materials in building systems can be increased (Bungau et al., 2022). As certain standard acoustic materials lack these characteristics, research has begun on an alternate form of sustainable material to help such environmental and health issues. Thus, one of the objectives of this study is to improve alternative biobased sound absorptive systems for use in room acoustics in order to lower the carbon footprint of acoustical materials currently used in the building construction sector.

Turkey has diverse ecological and geographical circumstances. Thus, several varieties of fruit are developed. A considerable proportion of Turkey's fruit production consists of fruit seeds, the majority of which are waste seeds. Cherry planting is common in the Central Anatolia region of the province of Konya, Turkey, and cherry seeds are abandoned as garbage in this location, which prompted this research as of the raw material. In this investigation to develop a diffusive-absorptive panel system, seeds are employed as raw materials, while wood glue and tree resin are used to bind the seeds together. The fundamental criterion for selecting appropriate seeds for the project is the preference of fruit seeds that are abundant in Turkey, while the proper size for the sound-absorbing panels to be manufactured in the project is also considered. Combining cherry seeds from separate batches with tree resin and, subsequently, wood glue results in the production of two distinct substances. In addition to cherry seeds, olive and watermelon seeds are also utilized to increase the diversity of accessible materials. The study also focuses on the fire resistance rating of the seeds, as the acoustic panels are intended for interior use. Zhou and Fu (2020) conducted a study wherein they applied nano-composite coatings to the surface of wood, resulting in an observed enhancement of wood's fire resistance. The inclusion of nano-composite-based materials in certain paints enhances the fire resistance of the surfaces on which they are applied. The cherry seeds that are used in this study are colored to improve their fire resistance, as the paint contains numerous compounds that are expected to promote fire resistance.

1.2. Aim and Scope of the Thesis

The primary objective of this research is to promote reuse of natural resources in architectural applications to increase acoustic comfort, which are specifically local waste fruit seeds. The specific focus is on enhancing acoustic comfort in indoor environments. For that reason, the potential use of local waste fruit seeds (cherry, olive, and watermelon seeds) is searched to provide acoustically comfortable spaces. The utilization of sound absorptive materials in the field of architectural acoustics presents a significant challenge to the principles of sustainable development, as they have detrimental effects on both human well-being and the environment. When recyclable materials and waste products are employed in the manufacturing process by reducing the amount of trash produced, it is possible to lessen the negative impacts on environment. For this reason, this research aims to develop a composite material that makes use of fruit seeds that are abundant in Turkey. The idea that sustainable acoustic materials are better for both human health and the health of the environment is the major motivation behind this research.

There is a variety of materials searched under sustainable acoustic materials in the literature to be discussed in the following sections, with natural and/or recyclable components. Despite this, the use of fruit seeds in the manufacturing of acoustic materials has been kept to a minimum. Some research in the literature has looked at how peach and apricot seeds may be used within the context of fruit seeds. These researchers are focused on raising the material's thickness in order to increase the sound absorption coefficient, but they do not consider various kind of seeds in the samples (Borrell et al., 2020, Sanchis et al., 2022).

This study initially starts with design and production steps of composite panel systems. Nine unique acoustic material samples are designed. These samples are obtained from various fruit seeds, which are often thrown away as trash, such as cherry, olive, and watermelon seeds. These examples are produced by mixing the fruit seeds with different amounts and combinations of tree resin and wood glue. Subsequently, the experimental investigation is performed using impedance measurements. Sound absorptive material choice in indoor applications is challenging because there are many factors affecting the decision-making process such as, aesthetic value, the level of providing air quality, sanitary conditions and fire resistance. The outcome of this research is aimed to be applied in a variety of environmental situations, such as restaurants, cafés, lobbies, workplaces, and retail outlets. For ease of application 30x30 cm sized panels that can be readily placed on a structural grid system can be applied over walls or can be suspended from the ceiling. An architectural studio is tested in its current circumstances to analyze the efficiency of the suggested samples in addressing practice of acoustical challenge. The purpose of this evaluation is to determine whether the proposed samples can effectively solve acoustic problems in speech related environments. After that, a comparison is made between the acoustical characteristics of the studio with and without the use of these samples. The objectives can be summarized as follows:

- To design and develop sound absorptive panel systems with waste materials based on fruit seeds to be applied in indoor environments, which has a potential in reverberation control and aesthetically appellant.

- To promote the use of recycled, biobased and/or waste materials in the field of architectural acoustic and thus to minimize the use of synthetic and industrial materials. To contribute the development of energy-efficient buildings by employing cost-effective construction materials.

1.2.1. Research Questions

How can waste fruit seeds of different combinations be utilized in acoustic systems to be applied in indoor environments?

- What are the criteria for selecting fruit seeds to be used in composite sound absorptive panel systems?

- How seed size and variety of seeds effect the sound absorption coefficient values of a composite panel system?

- What is the impact of different binders in sound absorption performance of biobased composite materials?

1.2.2. Hypotheses

- An efficient sound absorbing material can be developed by combining waste fruit seeds (cherry, olive, and watermelon seeds) with proper binders of adhesive materials (tree resin or wood glue) in suitable configurations, to be used in indoor spaces.
- Fruit seeds in different combinations can make a higher performance sound absorptive panel in comparison to panels with single type of seeds.
- Natural binders are more effective than chemical adhesives in increasing sound absorption performance of biobased material compositions.

1.3. Structure of the Thesis

In order to fulfil the aims of this research, the thesis has been structured into five distinct sections.

Chapter 1 addresses the existing research gap in architectural acoustics field and explores the utilization of biobased, recyclable and/or biobased sound-absorbing materials derived from fruit seeds.

Chapter 2 is comprised of two sub-sections. The first section provides a brief of the acoustic parameters utilized in the material analysis. The parameters that are presented in this study are defined, and their significance for the research is underscored. The second sub-chapter presents the current literature on natural and industrial recycled materials.

Chapter 3 explains the methodologies and procedures employed to assess the design and production process of the nine distinct material samples investigated in the thesis. The acoustic simulations conducted at the design studio of the Faculty of Architecture at Bilkent University are also presented in this section. By that, the impact of the recommended material on the acoustic comfort within the design studio is assessed.

Chapter 4, titled results cover the primary outcomes derived from the study. The analysis involves the examination of the outcomes obtained from impedance tube measurements and acoustic simulations. A comparative analysis is conducted on nine distinct material samples based on the impedance measurements obtained.

Chapter 5, the conclusion summarizes the research and emphasizes the main findings. This section also discusses potential future research steps that can be followed for a potential mass production of developed composite material samples.

CHAPTER 2

STATE OF THE ART

2.1. Basic Acoustic Terminology

The fundamental acoustic principles encompass the terms of acoustics that is essential for the purpose of designing spaces that offer optimal sound quality and comfort. The present chapter commences by providing a comprehensive explanation of the acoustic parameters employed in the research conducted for this thesis.

2.1.1. Sound Absorption, Reflection and Diffusion

When a sound wave encounters with a surface, the material either reflects, absorbs, and/or transmits some of sound energy (Long, 2014). So, the total energy is always conserved, but the ratio of absorption, reflection or transmission changes depending on the material characteristics. Due to friction and other mechanisms, sound energy is transformed into heat within the material during absorption. Sound absorption performance of a material is determined by its "sound absorption coefficient,"(Egan, 1988). It is the ratio of total sound energy that is released by a source and reaches to the surface of a material (E0) to the total sound energy that is absorbed by a material (E). In mathematics, it is written as: $\alpha = E/E_0$ (Liu & Chen, 2014). The sound absorption coefficient is used as an indicator to determine a material's sound absorption capacity. The parameter is unitless. Theoretically, the ideal (full) absorption of sound by a material is represented by a value of 1, whereas the absence (none) of absorption is represented by a value of 0.

Acoustic reflection occurs when sound waves encounter a surface and return to the room (either specular or diffuse) (Olson, 1967). This happens when the surface is incapable of absorbing the sound energy. In technical terms, acoustic reflection is the result of the velocity and pressure changes of the sound wave. The pressure change of the wave causes a change in the acoustic impedance of the medium (Dowling, 1983). This change at the interface with the reflecting surface in impedance causes the sound wave to return. Acoustic reflection is crucial especially in performance spaces (Beranek, 2012). The design of reflectors with their material choice is a significant step of acoustical design of concert halls.

There are two types of reflection one is specular reflection as discussed above. Second type is the diffuse reflection. Acoustic diffusion is the act of dispersing sound waves in several directions as opposed to reflecting them back to a single point. This may be accomplished by using specific materials, such as diffusive panels or specially shaped surfaces, that scatter and break up sound waves as they travel through them (Pohlmann and Everest, 2014b). In the design of concert halls, recording studios and other locations where sound quality is essential, acoustic diffusion is also critical for the even distribution of sound within spaces. By distributing sound waves in various directions, acoustic diffusion may assist to lessen the concentration of sound energy in certain sections of a place and produce a more uniform and natural acoustic environment (Beranek, 2012).

2.1.2. Reverberation Time

Reverberation time is the primary objective parameter to be assessed in room acoustics. and used in acoustical design and analysis of various types of spaces. Reverberance on the other hand corresponds to the subjective perception of reverberation time Maekawa (1994). The reverberance within a space should be optimum and should contribute to the function of the space. When there is excessive reverberation in a room, speech becomes less intelligible. If the reverberation time is too short the space will become dull, and sound strength may be unnecessarily reduced. In a music hall for instance, reverberation may create effective harmony between nearby notes and sounds from various instruments in a variety of musical styles. Moreover, it enhances the frequency of bass and the volume of tone in the hall (Gade, 2014). Reverberation Time is defined in Figure 1 through the use of a sample decay.

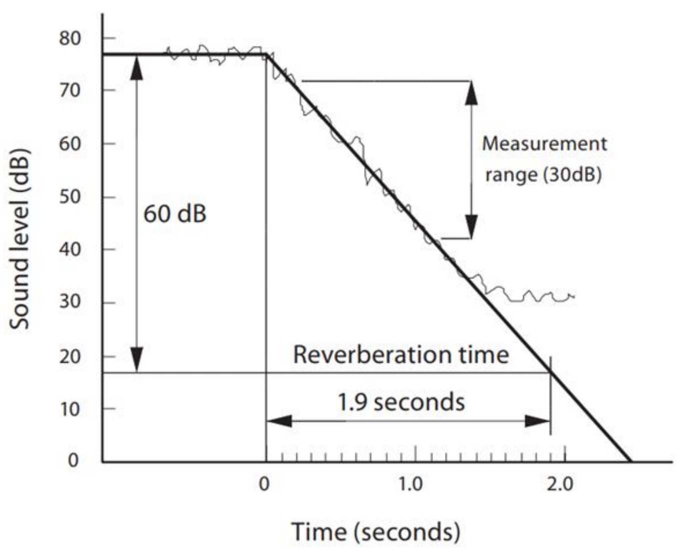


Figure 1. Reverberation time estimation over a sample decay (Barron, 2009, p. 28)

Reverberation time is the duration of time it takes for a sound to drop by 60 dB from its initial level after the sound source is ceased (Egan, 1988). In field measurements sometimes due to the inefficient sound source level and high background noise, it is not always possible to obtain a 60 dB drop with the required dynamic range. It can relate to the geometry and size the space. For this reason, parameters T20 and T30 are commonly utilized. T20, in accordance with ISO 3382-1, is takes in to account the decay in between -5 dB to -25 dB (then the decay duration is multiplied by 3), and T30, takes in to account the decay in between -5 dB and -35 dB (then the decay duration is multiplied by 2), below the direct sound level.

Estimation of reverberation time is necessary when a space/room is in the design phase or if it is not possible to do field measurements. W.C. Sabine observed that the total acoustic absorption ($A = \sum S\alpha_{av}$) and the room volume (V) both affect the reverberation time. Basically, as volume of an enclosed space increases reverberation time increases and as the total amount of absorption area of surface materials increase reverberation time drops.

For calculating reverberation time in a room, three main formulas are applicable. Sabine's formula, which is the first one, is appropriate for live rooms and applies to most of the real situations (Yap et al., 2007) as of design studios that are assessed currently in this research. The second and third ones are appropriate for dead rooms. These are Eyring's formula and Millington and Sette's formula. All three formulas assumes that the sound field is diffuse (Maekawa, 1994).

1) Sabine's Formula:

T = (0,163 V) / A in seconds, Where A = the equivalent sound absorption area in m^2

(= $\Sigma S\alpha_{av}$)

$\Sigma S\alpha av = S_1\alpha_1 + S_2\alpha_2 + . . . + S_n\alpha_n$

V = the volume in m^3 S = the surface area in m^2 α = sound absorption coefficient (Cremer et al., 1984).

2) Eyring Formula:

$\alpha_1 \approx \alpha_2 \approx \alpha_3 \approx ... \approx \alpha_n$,

T = (0,163 V) / [$-S\log_e (1 - \alpha)$] in seconds. Where, $\alpha = \Sigma S\alpha_{av} / S$

3) Millington & Sette Formula:

$\alpha_1 \quad \alpha_2$ /= α_3 /= ...α_n,

T = (0,163 V) / [$\Sigma -S_n\log_e (1 - \alpha_n)$] in seconds (Maekawa, 1994).

2.1.3. Speech Transmission Index (STI)

According to Hongisto (2005), Speech Transmission Index (STI) is an objective metric parameter that is used to evaluate the ability to perceive what is being said. IEC 60268-16 (IEC, 2011) standardizes STI as a physical measure of speech intelligibility. The Speech Transmission Index (STI) assesses speech intelligibility while taking into account the articulation loss caused by reverberation as well as the background noise (Peters et al., 2013).

The range of speech intelligibility spans from an ideal rating of 1.00 to a complete lack of intelligibility at 0. This range is primarily determined by the level of reverberation, the signal to noise ratio and the number of early reflections between the speech source and the receiver (Van De Poll et al., 2014). High reverberance reduces speech intelligibility. Table 1 presents speech intelligibility quality ratings and the corresponding values of the Speech Transmission Index (STI).

Table 1. Speech intelligibility quality ratings and STI values (Beranek, 1988, p. 623)

Quality Rating	Bad	Poor	Fair	Good	Excellent
STI Value	0 to 0.32	0.32 to 0.45	0.45 to 0.60	0.60 to 0.75	0.75 to 1.00

2.2. Sustainable Acoustic Materials

Sustainability refers to the capacity of a system or process to continue operating indefinitely without depleting the necessary resources or harming the environment (Mrcgp, 1988). As human activities exert increased pressure on natural resources and ecosystems, resulting to problems such as climate change, biodiversity loss, and water scarcity, the significance of this concept is growing.

Sustainability involves harmonizing economic, social, and environmental factors to ensure that current demands are met without endangering future generations' capacity to fulfill their own needs. This necessitates a transition from the current linear model of production and consumption, in which resources are extracted, utilized, and then discarded, to a circular model that prioritizes resource efficiency, reuse, and recycling. World Commission on Environment and Development (1987) explains sustainability as the capability of a system or process to continue operating indefinitely without depleting the resources required for its operation or harming the environment. According to United Nations (2015), it involves harmonizing economic, social, and environmental factors to ensure that present requirements are met without jeopardizing the capacity of future generations to fulfill their own needs (United Nations, 2015).

In recent years, interest on "green" materials has been highly increased. Several construction industry research facilities have produced new eco-friendly materials. These substances possess fascinating thermal and auditory characteristics (Desarnaulds et al., 2005; Asdrubali et al., 2012). In addition, the sector has begun to assess these materials; metropolitan municipalities, for instance, make suggestions to building regulations in an effort to expand their usage. The utilization of eco-friendly materials in new buildings permits the mitigation of construction materials in the industry, therefore promoting sustainability.

2.2.1. Sustainability Evaluation of Eco-Friendly Products

Sustainability evaluation is the analysis of a product's or service's long-term effects on the environment, society, and on the economy. Eco-friendly items are ones that are meant to have minimum negative influence on the environment; consequently, sustainability assessment is crucial for determining the extent to which these products are environmentally friendly. There are several methodologies and instruments available to analyze the sustainability of eco-friendly goods, such as life cycle assessment (LCA), eco-design, and eco-labelling. LCA is a comprehensive method for analyzing the environmental effects of a product or service at all stages of production, starting with the extraction of raw materials to disposal. The advanced life cycle assessment (LCA) method exhibits a distinction from the conventional LCA procedure in that it involves the categorization of the input material prior to conducting the impact evaluation. The purpose of classification is to determine distinct phases of each material's life cycle. The impact assessment is conducted individually for each material, and the findings are subsequently consolidated at the conclusion of the analysis (Kim et al., 2013). Eco-design is a method of incorporating environmental factors into product design in an effort to minimize the product's environmental impact. Eco-labeling is a certification method that evaluates the environmental performance of a product in accordance with predetermined standards (Bovea and & Ibáñez-Forés, 2019).

To control sound and reduce noise levels in structures, vehicles, and other environments, acoustic materials are utilized. Nevertheless, many conventional acoustic materials are not sustainable, as they may be derived from nonrenewable resources, require substantial energy to manufacture, or produce detrimental emissions during production and disposal. Several of the currently employed acoustic materials are not proper in regard to energy use and greenhouse gas emissions. These substances may be detrimental to human health. Mineral wools are frequently utilized in applications such as heat and sound insulation due to their favorable combination of cost-effectiveness and superior performance. However, when breathed in, mineral wool fibers may lodge in the alveoli of the lungs and irritate the skin (WHO, 2002).

On the other side, polyurethane and melamine foams are utilized in acoustic applications. But they are quite costly to produce, and their manufacturing process relies on petrochemicals. In addition, the aromatic diisocyanatos used to create polyurethane foams consist of substances that might cause irritation to the respiratory system. In some cases, these substances have the potential to induce occupational asthma (Creely et al., 2006). To address these issues, there has been a growing interest in developing acoustic materials that are environmentally favorable and provide effective sound control while minimizing their impact on the environment. In the following, there are examples of sustainable acoustic materials: As acoustic insulation or sound-absorptive panels, recycled materials such as rubber, cork, and glass can be utilized. By repurposing materials that would otherwise be sent to landfills, these materials can reduce waste and energy consumption. Wool, cotton, and hemp are natural fibers that can be used in sound insulation or as sound-absorptive panels. Instead of synthetic fibers, it is advised to utilize natural fibers with high acoustic and thermal performance to safeguard health of people and the environment. Natural fibers are relatively low in toxicity, and the procedures used in their production help preserve the environment. (Joshi, 2004; Pervaiz and Sain, 2003; Bribián and Usón, 2011). Even recycled resources, such as repurposed plastic fibers and rubber granules, are sustainable since they contribute to a reduction in waste production. In addition, structures made from these materials include recycled natural fibers and granules in the form of porous substrates that permit plant growth. As sound-absorptive panels, mycelium-based materials, which are derived from the root-like structures of mushrooms, can be used (Pelletier et al., 2013). Furthermore, mycelium-based boards have potential as a bio-based composite alternative to conventional foam insulating boards. These materials are renewable, biodegradable, and have minimal impact on the environment. Beyond their environmental impact, sustainable acoustic materials offer numerous benefits. Such as; they can enhance indoor air quality, reduce energy consumption by enhancing insulation, and create healthier and more comfortable environments for occupants. Sustainability considerations in building design and construction, will enhance the use of sustainable acoustic materials, thereby decrease the ecological footprint of buildings and cities.

Natural fibers may be used thermally and acoustically in several ways. Coconut, kenaf, and hemp are commercially used mineralized wood fibers. The less processing natural materials undergo, the greater their energy efficiency and sustainability. For energy savings, locally accessible materials are generally preferable. Natural fibers have a positive effect on climate change and global warming because of their capacity to absorb CO2 during plant development (Pervaiz & Sain, 2003). In contrast to mineral fibers, vegetable fibers exhibit greater susceptible to fungal and parasite attacks, as well as worse fire resistance.

The sustainable sound absorptive and insulation materials may be categorized under two basic categories: Natural recycled materials and industrial recycled materials.

2.2.2. Natural Recycled Material

Natural sound absorptive materials are those derived from natural sources and can be used to control sound, by reducing high reverberance and noise levels. Due to their durability, low toxicity, and environmental friendliness, these materials are preferred over synthetic materials. Biodegradability and low-cost present opportunities for the design of natural materials for acoustic applications. Natural materials can be combined to produce composite materials, which can then be used to create a wide variety of material samples. Changing the composition, porosity, thickness, and other characteristics of a natural material can alter its acoustic performance (Bhingare, 2019).

There are two distinct types of natural acoustic materials: porous and fibrous. Porous materials, such as natural cork, have an open structure and can attenuate sound because of their internal surface area (Abenojar et al., 2013). Porous building materials are widely used within the domain of architectural acoustics due to their ability to facilitate the transmission of sound energy through their porous structure.

Fibrous materials, such as natural fibers and fabrics, are utilized for their sound absorption and attenuation properties. The fibers of these materials absorb sound by transforming sound energy into heat. Wool, flax, hemp, sisal and jute and other similar natural fibers are frequently utilized as reinforcement components in composite materials for acoustic wall and ceiling. (Hassan et al., 2020).

It is also possible to modify the acoustic properties of natural acoustic materials. Bamboo, for example, can be treated with natural compounds to enhance its sound-absorption performance (Koizumi et al., 2002). In addition, natural and synthetic fibers can be combined to create composites with improved mechanical and acoustic properties.

Natural acoustic materials are an environmental alternative to synthetic materials for pollution control and acoustic comfort. Their efficacy, low toxicity, and renewable nature make them desirable for a broad range of applications.

Additionally, in the construction sector, less treated and more natural the materials are, the greater their energy efficiency. To minimize energy consumption within the construction industry, it is advisable to prioritize the use of natural and/or plant-based materials. These materials also have minimal influence on climate change throughout their development. The utilization of these natural resources will reduce the use of synthetic and non-perishable items. In comparison to typical man-made materials, the drawbacks of natural materials include weak resistance to parasites and fungi, as well as fire. Natural materials may need to undergo a chemical procedure, which decreases their sustainability score. Recently, numerous natural substances have been developed and assessed for the application the field of architectural acoustics. The acoustic properties of materials that have been examined include impact sound insulation, sound absorption, and thermal conductivity. Table 2 provides a comparison of these properties with those of some natural and conventional materials.

Table 2. Acoustic and thermal characteristics of natural (from 1 to 8) and conventional (from 9 to 11) insulation materials (Desarnaulds et al., 2005)

	Material	Thermal conductivity (W/m.K)	Absorption coefficient as at 500 Hz	Index of reduction of impact noise DLW (dB)
1	Hemp	0.04	0.6(tc:300mm)	-
2	Kenaf	0.044	0.74(tc:50mm)	-
3	Coco fiber	0.043	0.42	23
4	Sheep wool	0.044	0.38(tc:60mm)	18
5	Wood wool	0.065	0.32	21
6	Cork	0.039	0.39	17
7	Cellulose	0.037	1(tc:60mm)	22
8	Flax	0.040	-	-
9	Glass wool	0.04	1(tc:50mm)	-
10	Rock woll	0.045	0.9(tc:50mm)	-
11	Expanded polystyrene	0.031	0.5	30

**tc: Thickness

The following section provides a comprehensive analysis of various natural materials that possess recyclable properties.

Kenaf:

Kenaf is a hibiscus plant that is linked to okra and cotton. Currently, it is mostly used for, canvas, burlap, and cordage. These plants have the capacity to generate two distinct categories of fibers. The fibers derived from the central part of the plant body are primarily employed as biomass, while the thicker fibers obtained from the stem find application in the production of paper, textiles, and ropes (D'Alessandro & Pispola, 2005). The average absorption coefficient of kenaf samples is 0.85 in from 500 Hz to 5000 Hz and 0.65 in between 100 Hz - 5000 Hz. Figure 2 depicts the usual sound absorption coefficient spectrum for a 50 mm Kenaf sample with a hard backing. This graph also includes the absorption coefficient value for commercial materials with comparable thickness (Asdrubali et al., 2012).

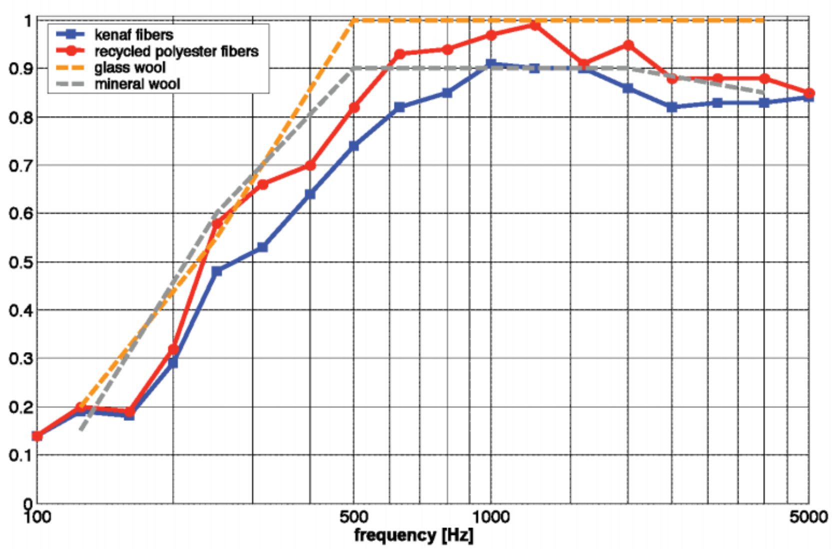


Figure 2. Absorption coefficient for a Kenaf sample with density 50 kg/m^3 and thickness 50 mm (D'Alessandro and Pispola, 2005)

Rice Husk:

The waste and residue materials from rice production have been widely used in scientific research due to their abundance. Buratti et al. (2018) examined the acoustic characteristics of rice husk as the primary component of acoustic panels and compared them to those of other acoustic panels composed of recycled materials, such as granulated rubber, cork scraps, coffee chaff, and wastepaper composite panels. For the sample preparation of rice husk panels, glued and unglued alternatives were produced, and at frequencies up to 4000 Hz, the acoustic performance of samples with a thickness of 15 mm was lower for unglued samples than for glued samples. As the thickness of the glued samples rose, the performance apex shifted to lower frequencies. Porosity was discovered to be a significant indicator of acoustic performance, and because rice husk, cork scraps, and granulated rubber all had higher porosity, they all performed similarly. It was observed that coffee chaff performed poorly. The acoustic performance of rice husk (cylindrical granules)-kenaf (lingo-cellulosic fiber) with polyvinyl alcohol binder was the subject of another investigation. The sound absorption coefficients observed for composite, 100% rice husk and 100% kenaf samples were 0.66, 0.61, and 0.5, respectively. Therefore, it can be concluded that mixing rice chaff with kenaf improved its acoustic performance (Samaei et al., 2021).

Date palm wastes:

The potential for converting agricultural waste into products with added value has attracted a growing amount of interest. The total date palm generated each year is 200,000 tons. This waste is either burnt or discarded as agricultural rubbish. In their study, Taban et al. (2021) examined the impact of density and thickness on the acoustic properties of panels composed from date palm trash. Four distinct sample thicknesses and two different sample densities were examined, as seen in Figure 3. Upon application of the substance, a decrease in reverberation time and early decay time and an increase in definition and clarity at frequencies over 500 Hz were detected. The increase in thickness and density has a considerable effect influence on sound absorption.

Figure 3. Prepared date palm waste samples for impedance tube test. (Taban et.al., 2021)

In another study, the acoustic performance of samples of coir and date palm waste materials was tested, and it was observed that both fibers exhibited poor and almost identical low-frequency sound absorption. Taban et al. (2019) found that in the middle frequency band the sound absorption dramatically rises to a maximum of 0.84 at 2000 Hz for 40 mm thickness.

Fruit Seeds:

Fruit seeds are being studied for the construction industry in a variety of sustainable disciplines, including energy efficiency (Bartocci et al., 2015), thermal insulation (Martínez et al., 2006), and the synthesis of activated carbon (Lussier et al., 1994). Borrell et al. (2020) examines the sound absorption coefficient of panels made of various fruit seeds. In this research, four distinct types of fruit seeds (olive-cherry-apricot- peach) with distinct density, shape, and porosity were chosen. As seen in Figure 4, cylindrical samples of varying wall thicknesses were produced and analyzed in a standing wave tube.

Olive

Cherry

Figure 4. Studied samples of olive, apricot, cherry and peach seeds (Borrell et al., 2020)

The results indicate that, sound absorption varied based on the variety of fruit seed and sample thickness. The samples have sound absorption coefficients that range from 0.70 to 0.95 between 550 Hz and 1500 Hz. In that research (Borrell et al., 2020) three-thickness of samples (olives, cherries, apricots, and peaches) were immersed in a bio resin adhesive to investigate the effect of porosity rate in Figure 5. The alpha values of samples with and without resin, are demonstrates in Figure 5. Due to the small diameters of their pores, the olive and cherry samples is not much affected by the resin. Regarding apricot seeds, the presence of resin hinders the fibrous structure, reducing the ability for sound absorption. Peach and apricot seeds have more gaps between the seeds because of their seed size. when the resin is applied into the samples, the samples which have a large size of seeds have more resin than other samples. therefore, the sound absorption performance diminishes after resin applied to the samples of peach and apricot. (Borrell et al., 2020).

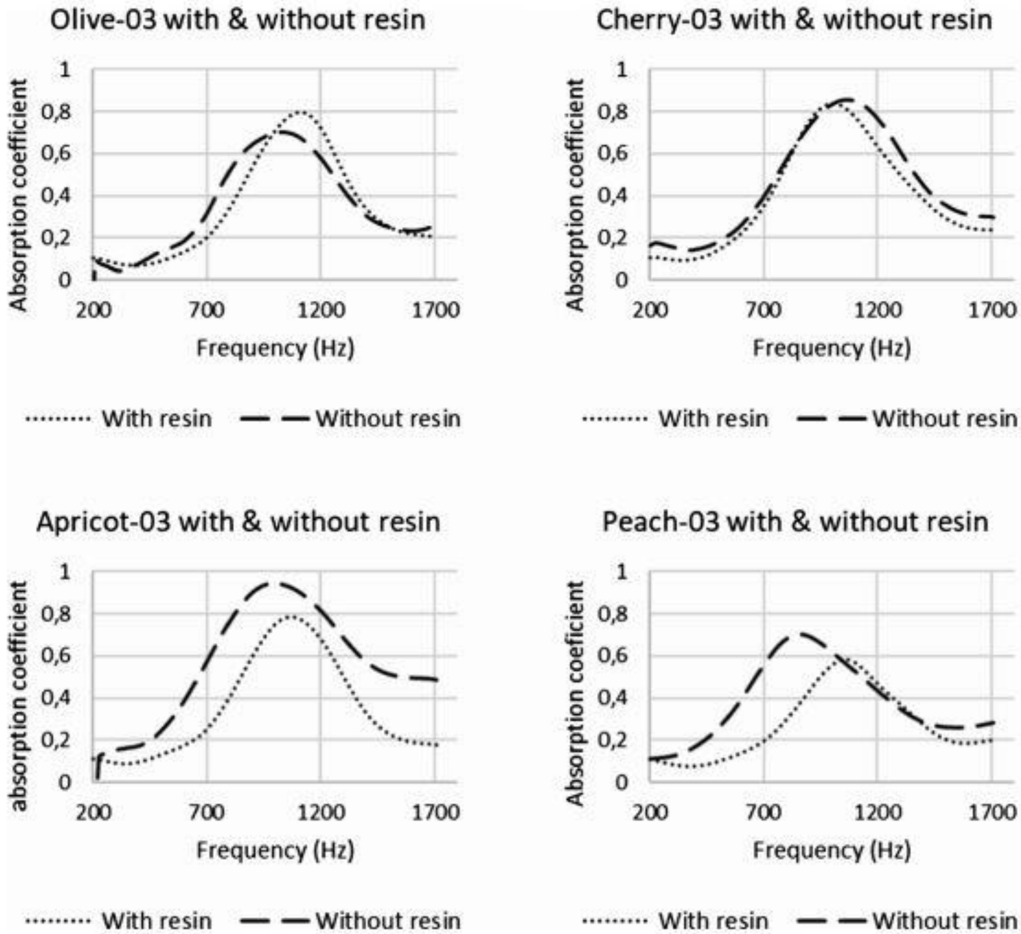


Figure 5. Sound absorption coefficients of the measured the samples with and without bio resin (Borrell et al., 2020)

Sanchis et al. (2022) evaluated the acoustic properties of olive, cherry, apricot, and peach seeds in a standing wave tube. The samples with varying air gaps per volume exhibited similar behavior. The coefficients of sound absorption for each sample are compared. The fruit seeds are adhered using cyanoacrylate adhesive as a binder. According to the investigation results, the configurations of the fruit seeds had an impact on the sound absorption. Additionally, the results demonstrate that seeds with a coarser surface have higher capacity for sound energy absorption compared to fruit seeds characterized by a porous surface. When various densities were compared, it was discovered that samples with a lower density performed better.

Based on the empirical findings presented in the research conducted by Sanchis et al. (2022), it can be said that an increase in the extent of surface roughness of fruit seeds leads to a rise in the absorption of sound energy. Seeds with a coarser surface exhibit a significant increase in energy absorption compared to fruit seeds characterized by a less coarse surface, a phenomenon seen in several porous materials. However, Borrell et al. (2020) examines the sound absorption coefficient of four distinct fruit seed samples. Comparing the findings of the four categories of fruit seeds with resin, the sound absorption coefficients of small seeds are generally higher, since the amount of resin that fill the cherry seeds are smaller than other seeds. According to Borrell et al. (2020), the result of the four categories of fruit seeds without resin demonstrate that samples with the apricot seeds has the highest sound absorption coefficient values.

Flax:

In the textile industry, only around 20% of the plant mass is made up of high-quality textile fibers. Some components are considered inexpensive by-products. The shortest fibers have mostly been utilized to create a unique material for thermal insulation and sound absorption. Around fifty percent of the bulk of the flax-tow is flax shaves. During the removal and recombination of its internal plant compounds through heating processes, this material is self-linked. Hajj et al. (2011) measured the sound absorption of two flax-tow samples (2 mm and 10 mm) using impedance tube. Figure 6 illustrates the findings. Above 500 Hz, the 10 mm fibre sample exhibited a sound absorption coefficient greater than 0.5. The 2mm-fibre sample has somewhat poorer absorption qualities than the 1mm-fibre sample, but both samples are suitable for sandwich panel construction (Hajj et al., 2011).

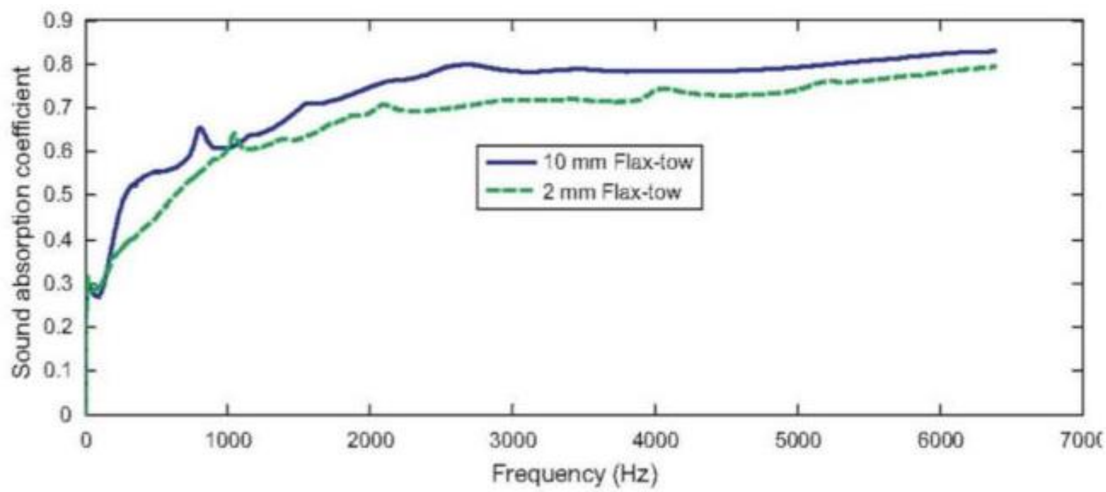


Figure 6. Alpha values (α) of measured two samples of the shortest fibers (Thormark, 200)

Further research was conducted to determine how the flax shaving size and proteinic binder affects sound absorption for samples with a thickness of 50 mm. The findings showed that samples with coarser flax shavings and less binder perform better in regard to thermal insulation and sound absorption (Figure 7), but are also softer (Hajj et al., 2012).

Tea Leaf:

The feasibility of using tea leaf fiber as a sound absorptive material is studied by Wong et al. (2017). Fiber made from used tea leaves is a byproduct of the tea plant. The spent tea leaf fibers exhibit a significant abundance of polyphenols, specifically tannins, which contribute to their notable resistance against fungal and termite attacks, as well as their exceptional fire resistance. Moreover, spent tea leaf structures exhibit a hollow and cellular composition, which makes them highly effective in terms of acoustic and thermal insulation. The study focused on three distinct grades of spent tea leaf, examining their acoustic properties through the analysis of sound absorption coefficient. The sound absorption coefficient in an impedance tube was measured through experimental methods. The study revealed that the highest quality spent tea leaf fiber grade demonstrates superior acoustic performance compared to other grades.

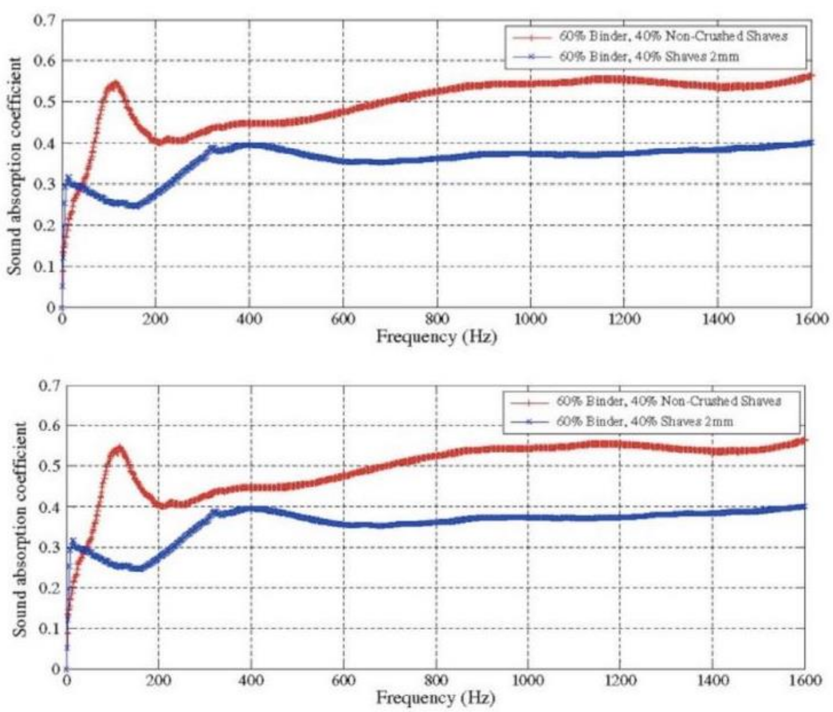


Figure 7. Evaluation of alpha (α) values of measured two flax samples (Hajj et al., 2012)

Ersoy and Küçük (2009) studied the potential of utilizing industrial tealeaf fiber for sound absorption purposes. The sound absorption characteristic exhibits a substantial enhancement when a solitary layer of cotton fabric is employed to provide support to the rear surface of the material. In addition, it is observed that tealeaf fiber exhibits superior sound absorption characteristics in comparison to non-woven fibers derived from polyester and polypropylene.

Coffee waste:

Coffee residues are produced as a byproduct of rising coffee consumption. Yun et al. (2020) investigated the efficacy of an acoustic panel manufactured from coffee waste in a café setting. Urea resin was utilized as the binder for the samples, and panels with varying densities (0.4, 0.5, and 0.6 g/cm^3) and particle sizes were examined and compared. Both the thickness and diameter of the panels were maintained at their respective settings of 50 and 45 mm. The results of this experiment led to the conclusion that, as a result of the porous properties of the coffee waste, the sound absorption coefficient rise with increasing frequency. This research indicates that the noise levels in the cafe are effectively diminished through the implementation of a recycling process for the coffee waste, which is a byproduct generated within the same building. Furthermore, this study introduces an innovative building material derived from coffee waste, which is subsequently utilized in the construction of cafes where the waste coffee is produced. To enhance the acoustic comfort within architectural design studios, Sel et al., (2021) employ the utilization of recyclable coffee waste to create panels that can be fixed to the ceilings and walls of said studios. To facilitate the identification of the optimal variation, three distinct samples, denoted as A, B, and C, have been prepared. The three samples exhibit variations in composition and, simultaneously, display distinct amounts of time within the oven. The samples designated as A and B comprise of desiccated remnants of coffee waste and tea leaves. Sample A is subjected to a cooking duration of one hour, whereas sample B is subjected to a cooking duration of two hours. Sample C exclusively comprises coffee waste and is subjected to the process of airborne drying. The images of the samples are depicted in Figure 8. Based on the outcome of the study, it is evident that 20 mm thick samples, accompanied by a 30 mm air gap, exhibit superior sound absorption characteristics in comparison to conventional suspended ceiling panels. Upon comparing the samples, it is observed in Figure 9 that sample B exhibits superior sound absorption properties.

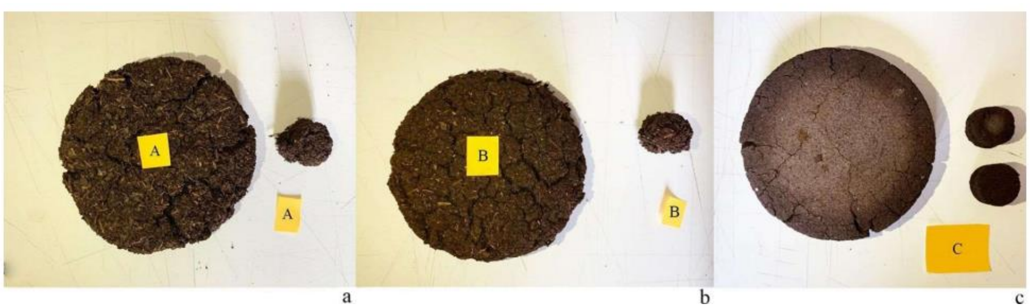
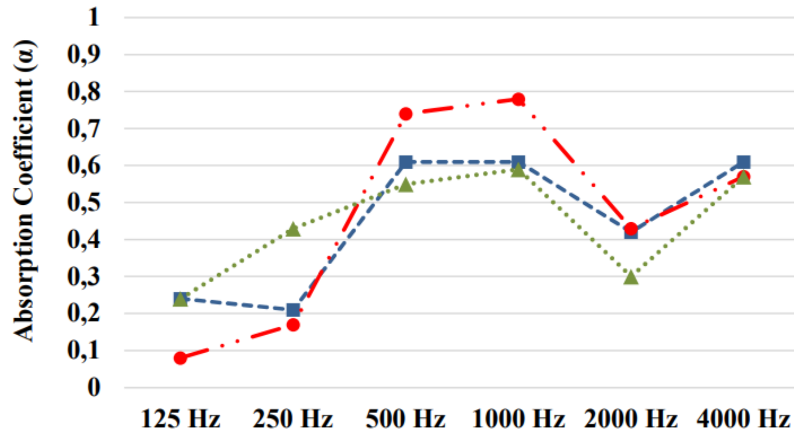


Figure 8. a) Sample A (baked for one hour), b) Sample B (baked for two hours), c) Sample C (dried) (Sel et al., 2021)



	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Sample A [a]	0.24	0.21	0.61	0.61	0.42	0.61
Sample B [b]	0.08	0.17	0.74	0.78	0.43	0.57
Sample C [c]	0.24	0.43	0.55	0.59	0.30	0.57

Figure 9. Alpha(α) values from impedance tube test measurments of the developed products (Sel et al., 2021)

2.2.3. Industrial Recycled Materials

The utilization of recycled materials in architectural design, with a focus on acoustics, has witnessed a notable increase in recent years. Several designers and architects acknowledge the environmental and economic advantages associated with the utilization of recycled materials in construction. Consequently, they are increasingly adopting these materials to develop buildings that are more environmentally friendly and sustainable. Recycled materials serve as a viable substitute for natural resources as they effectively mitigate waste generation and minimize the consumption of raw, unrefined materials. There exist numerous examples of materials that can be categorized within this classification. In this section industrial recycled materials including recycled rubber, plastic, textile fibers, and solid waste materials are discussed in detail.

Rubber:

Recycled rubber is a versatile and durable substance that exhibits resilience and adaptability, rendering it suitable for a diverse range of acoustic purposes such as sound insulation, vibration isolation, and reduction of impact noise. Recycled rubber is commonly sourced from discarded tires, undergoing a pulverization and processing procedure to yield diverse manifestations such as mats, pavers, and rolls. Maderuelo Sanz et al. (2013) researched the various sizes of ground tyre rubber particles. The primary constituent utilized was the shredded rubber fibers derived from car tires. Vermiculite expanded polystyrene (EPS), and polyurethane (5-25% concentration) were incorporated into the mixture. Two different grain thicknesses, ranging from 0.2 to 3.5 mm, were subjected to testing. The low-frequency absorption was found to be enhanced by an increase in thickness and grain size. Furthermore, in their study, Khan et al. (2017) conducted an evaluation of the impact of the ratio between bio binder and tire shred residue on the absorption coefficient. Materials containing binder percentages ranging from 10% to 60% have an alpha of 0.5 at 500 Hz, whereas materials without binder have an alpha of 0.3.

The utilization of binders resulted in a decline in the performance of sound absorption. Used tires poses significant challenges within the realm of waste management. In the year 2010, the continent of Europe produced a total of more than 3.3 million metric tons of used tires. The management options for end-of-life tires include landfill disposal, energy recovery, and utilization as a material in construction field or other applications, or exportation (ETRMA, 2011). According to the Resource Management Agency (RMA, 2011), the United States generated approximately 5.2 million tons of end-of-life tires in the year 2009. A considerable portion of this waste material was effectively utilized for energy recovery purposes. Based on research in the end-of-life tires the presence and reasonable cost of this resource suggest its potential efficacy in the context of acoustic applications. Lastly, the utilization of rubber's damping properties in end-of-life tires, as suggested by Schiavi (2006), advocates for its application as an elastic material in the construction of floating flooring.

Plastics:

The seawater has experienced contamination from polymers, specifically plastics. The retrieval of plastics from marine environments presents significant challenges, primarily due to the presence of sediment and biota contamination. Globally, oceans have been identified as one of the regions that are heavily contaminated by polymers, including both microplastics and macroplastics (Alimba & Faggio, 2019). Moreover, the recycling of these collected plastics may pose potential risks to human health. Consequently, the contaminated plastics are gathered within designated disposal sites and subsequently fragmented into smaller fragments, commonly referred to as microplastics. Caniato et al. (2020) conducted research investigating a foam material that was synthesized using microplastics derived from both industrial and domestic waste sources. The microplastics were obtained from polyethylene terephthalate (PET) bottles, which were processed into flakes and powder, as well as expanded polystyrene in flake form. A comparative analysis was conducted by Caniato et al. (2020) on six samples exhibiting varying powder percentages. These samples have more plastic concentrated on the top surface. Figure 10 demonstrates the sample photographs. Sample 1 illustrate a lack of uniformity in the vertical dispersion of plastic particles. Specifically, there is a concentration of black particles seen on the top surface, whereas light blue particles are mostly found on the bottom side. Sample 2 exhibits a higher level of homogeneity, but with the presence of black particles on the top and the settling of PET powder at the bottom. Sample 3 is generated using a singular plastic material, hence eliminating any potential for color stratification. Due to their similarity to example 3, the descriptions of sample 4 and 5 are omitted in the sake of conciseness. In Sample 6, conversely, one can see bigger fragments of PET flakes on the top surface. The presence of powder buildup in the bottom layer is readily apparent (Caniato et al., 2020).

Figure 10. Lower surface visuals: a)Sample1, b)Sample2, c)Sample3, d)Sample6, Section macro-graphic visuals: e)Sample1, f)Sample2, g)Sample3, h)Sample6 (Caniato et al., 2020)

The findings showed that the amount of powder and alginate added to the biomatrix has an impact on the acoustic performance of the samples. The introduction of the powder resulted in an increase in the tortuosity of the porous structure, consequently leading to an enhancement in performance. The samples exhibited satisfactory performance across various frequency ranges, thereby enabling the customization of acoustic performance according to specific requirements. The variations in the powder composition and the resulting changes in microstructural characteristics among the samples are the main reason for obtained outcomes.

Sample 1 exhibits the highest absorption level at 3400 Hz, whereas sample 2 demonstrates maximum absorption at 2600 Hz (Caniato et al., 2020). The observed discrepancy may be attributed to variations in cellular shape. Sample 1 exhibits elongated cellular morphology, while sample 2 has a uniform microstructural arrangement. The performances in Sample 3, 4, and 5 exhibit variations due to the elevated concentration of microplastic particles. The absorption peaks exhibit a downward change in frequency when the distribution of powder was concentrated in the outer layer. Upon comparing the samples with conventional glass wool materials, it was observed that they exhibit comparable performance to standard insulators such as rockwool and polyurethane foams (Caniato et al., 2020).

Textile:

Each year, a significant quantity of clothes and textiles, totaling millions of tons, is disposed of in landfills, resulting in substantial environmental contamination. In the United States, textile waste of over 16 million tons were generated in the year 2014. Out of this total, around 10.46 million tons were disposed of in landfills (Leblance, 2018). The disposal of large quantities of textile waste in landfills leads to a range of environmental degradation issues, including the contamination of groundwater and the release of greenhouse gases during decomposition (Dissanayake et al., 2018). Furthermore, textile waste accounts for approximately 6% of the total waste generated worldwide (Sezgin et al., 2021). According to Wang (2010), the process of decomposition of biodegradable textile waste cause in the production of methane, which is a potent greenhouse gas that contributes to the phenomenon of global warming. However, the environmental impact of synthetic materials disposed in landfills is significant owing to their non-biodegradable and poisonous properties. The objective is to recover the energy and resources that are expended during textile production processes. The production of sound insulating materials from textile waste is considered to be an efficient and sustainable recycling method. Zach et al. (2012) found that the physical characteristics of textile waste closely resemble those of typical building insulation materials. previous research suggests use of textile waste as a raw material to produce insulation materials in construction industry (El Wazna et al., 2017).

Hassani et al. (2021) conducted a research investigation on the sound absorption capabilities of post-consumer denim. The significance of denim waste in the production of eco-friendly acoustic panels arises from its 3D irregular internal structure and cost-effectiveness in manufacturing. In this experimental study, a series of samples were generated with variable bulk densities of 61 to 102 kg/m^3 and resin contents of 10 to 35%. The observation revealed that the fiber of denim with a smooth surface, characterized by a fiber with a 14.8 mm average diameter, underwent a transformation upon resin bonding. This transformation resulted in the development of a rough surface, with a fiber diameter of 19 mm on average, accompanied by the formation of a porous structure. Various areal and bulk densities were examined for the samples, and it was determined that an augmentation in these parameters resulted in enhanced acoustic performance. Moreover, it was observed that samples with higher resin concentrations exhibited enhanced performance when the bulk densities were held constant. Upon analysis of samples containing 30-35% resin content and having a bulk density of 76 kg/m^3, it was observed that these samples exhibited superior performance compared to the commercially available glass wool samples.

In addition, the alpha values between 500 Hz - 4000 Hz exceed 0.94. Hence, it can be inferred that utilizing denim waste as a substitute for synthetic resources, which have detrimental effects on the environment, presents a viable solution. In accordance with the findings of Sezgin et al. (2021), it was determined that cotton fibers derived from discarded denim fabrics exhibited the capacity to effectively attenuate structure-borne noise. Furthermore, these fibers demonstrated compatibility as support materials for panel sound absorbers when reinforced with polypropylene/polyethylene granules sourced from bottle caps commonly found on food and cleaning containers. In this experimental study, a consistent quantity of denim fibers was employed across all samples. Varying levels of pressure were applied to achieve different thicknesses, resulting in diverse fiber densities within the samples. The samples with 20 mm thickness exhibited higher values compared to those with lesser thicknesses (Sezgin et al., 2021).

CHAPTER 3

METHODOLOGY

3.1. Design and Production

The collection of fruit seeds is a significant step of this research to evaluate their potential positive effects on the environment and the potential for recycling of biobased materials for their later incorporation into the manufacturing process. The cherry, olive, and watermelon seeds are collected during their respective seasons for utilization in the fabrication of sound-absorptive panel samples. Once the seeds have been harvested, they are exposed to sunlight for duration of one month in order to undergo complete desiccation and to reduce their moisture content. Figure 11 shows the collected seeds of cherry, olive, and watermelon to be used in the composition of panel samples.

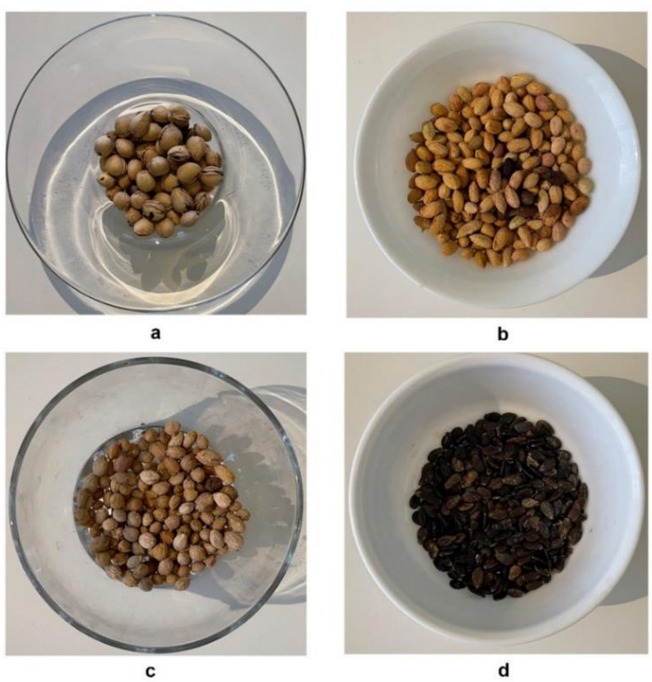


Figure 11. Raw materials: a) Cherry seeds b) Large olive seeds c) Small olive seeds d) Watermelon seeds

This study aims to investigate the effect of altering the seed size and shape on the sound absorption performance of material samples, while keeping the material thickness constant. This objective can be achieved by altering the fundamental composition of the substance. In order to determine the most optimal variant, a total of nine different samples are prepared.

The impedance tube, consisting of two cylinders of varying diameters, is utilized in sound absorption coefficient measurements in this study. Initially, wooden molds are produced in sizes of impedance tube diameters (100 mm large tube, 28 mm small tube). These molds are designed to possess a cylindrical shape and a depth of 20 mm (Figure 12.) 9 different material composition are prepared within molds. All samples have a thickness of 20 mm. The nine samples exhibit variations in terms of ingredient compositions, as indicated in Table 3. The utilization of tree resin and wood glue has been employed in the research as binding agents. Initially, the process involves subjecting wood resin, which serves as an organic binder, to a moderate level of heat at the cooker, Natural resin and heated resin are seen in Figure 13. Subsequently, wood ash is introduced into the mixture to enhance the adhesive properties and density of the resin. Later, the mixture of resin and wood ash is added into the cherry seeds in order to generate the initial sample (A). However due to practical difficulties of using resin and wood ash later wood glue is used as a binding agent for the subsequent eight samples (Figure 14).

Figure 12. Prepared moulds

a b

Figure 13. Tree Resin: a) Natural resin b) Heated resin

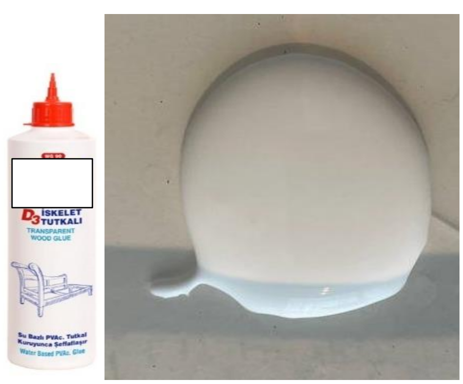


Figure 14. Wood glue

Table 3. Description of produced materials

Material Sample			A	B	C	D	E	F	G	H	I
Raw Material	Cherry		++ ++	++ ++	-	++	-	-	+	+	++ ++
	L. olive		-	-	++	-	++ ++	++	++	+	-
	S. olive		-	-	-	-	-	++	-	+	-
	Watermelon		-	-	++	++	-	-	+	+	-
Adhesive Material	Tree resin		+	-	-	-	-	-	-	-	-
	Wood glue		-	+	+	+	+	+	+	+	+
Add.	Dye		-	-	-	-	-	-	-	-	+

Figure 15 shows various stages involved in the manufacturing process of Material I. Wood glue appears white in its liquid state, but upon drying, it turns into transparent (see Figure 14). The final trial of material samples (I) is composed of cherry seeds that have been coated with red spray paint and cherry seed paste derived from wood glue. This combination is employed for investigating the impact of paint on the sound absorption coefficient of the material, and to increase the samples fire resistance. Later all samples are tested in impedance tube as described in the following chapter.

a b c

d e

Figure 15. Preparation steps of material I: a)Painted cherry seeds b)Addition of wood glue c)Mixing wood glue and red cherry seeds d)The prepared mixture in the mold e)Mixture upon drying

3.1.1. Impedance Tube Measurements

The S.C.S. Kundt Tube is utilized for the conducting impedance tube measurements. The 'Kundt Tube' configuration, as specified in ISO 10534- 2:1998 (International Organization for Standardization, 1998; Yazıcı and Gül, 2021), represents the primary and standardized arrangement for quantifying absorption coefficient and acoustic impedance. This configuration involves the utilization of two microphones and the transfer function technique. The sound absorption measurement technique employs a twin tube configuration, consisting of both small and large tubes within its design (See, Figure 16). Tubes with a diameter of 100 mm are employed for low frequency measurements, spanning from 50 Hz to 1200 Hz. and tubes with a diameter of 28 mm are employed for high frequency measurements, ranging from 1200 Hz to 8000 Hz.

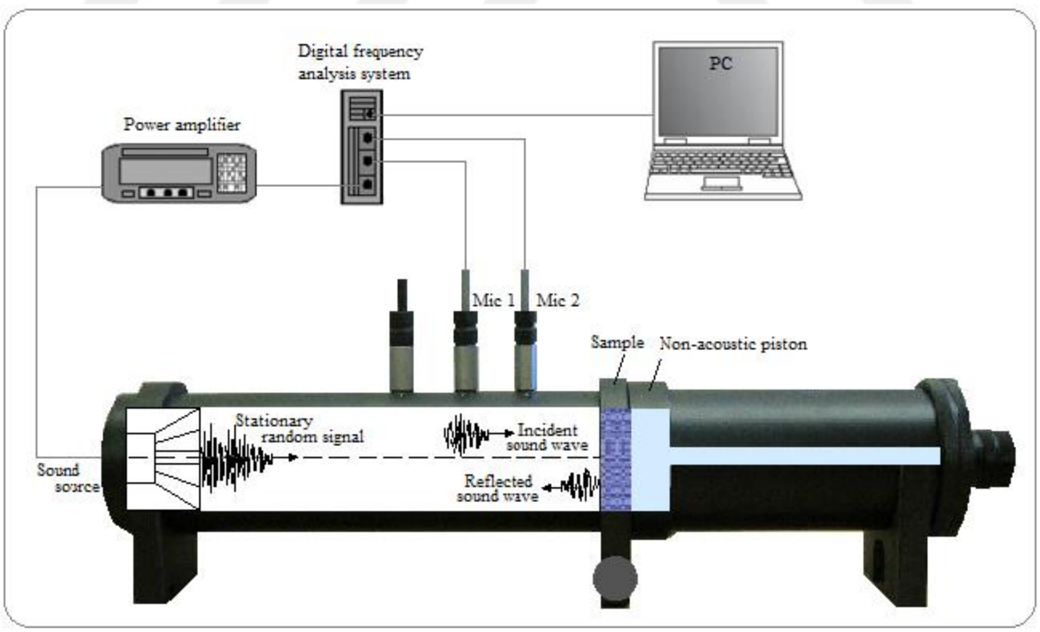
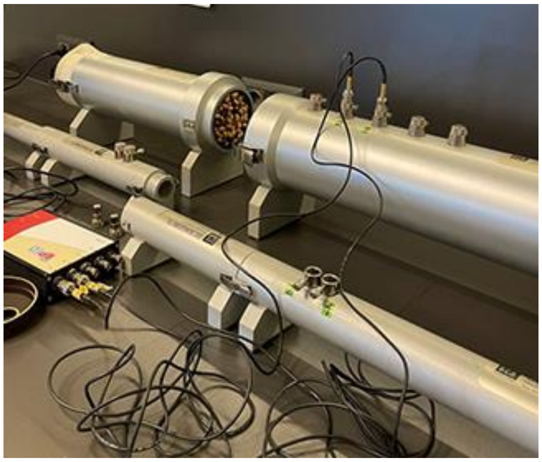
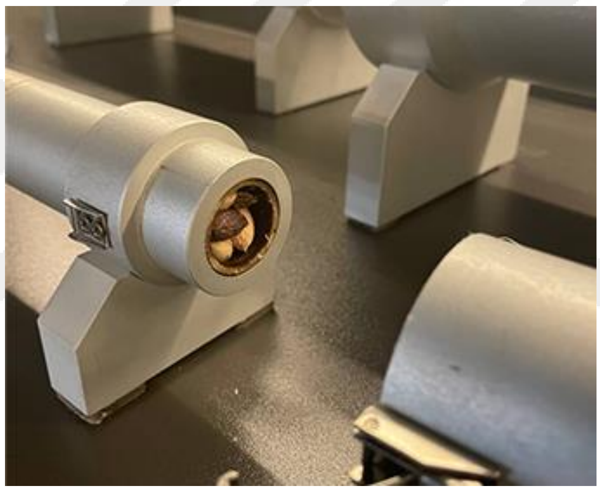


Figure 16. Impedance tube measurement set-up (Adapted from Brüel&Kjaer Sound and Vibration Measurement, 2016)



a

b



c

Figure 17. During the measurement of proposed products

All samples placed in tubes A-I (Figure 18) are 20 mm thick and measured with a 30 mm air gap. Additionally, the samples C-H are measured in the absence of any air space positioned behind them. The impedance tube's configuration is depicted in Figure 17, illustrating the placement of Sample C within the tube. The accuracy of the data is verified through conducting multiple tests on each composition. The outcomes of numerous tests are computed as an average, and any extreme values from these multiple tests are excluded from the analysis as a deviation.

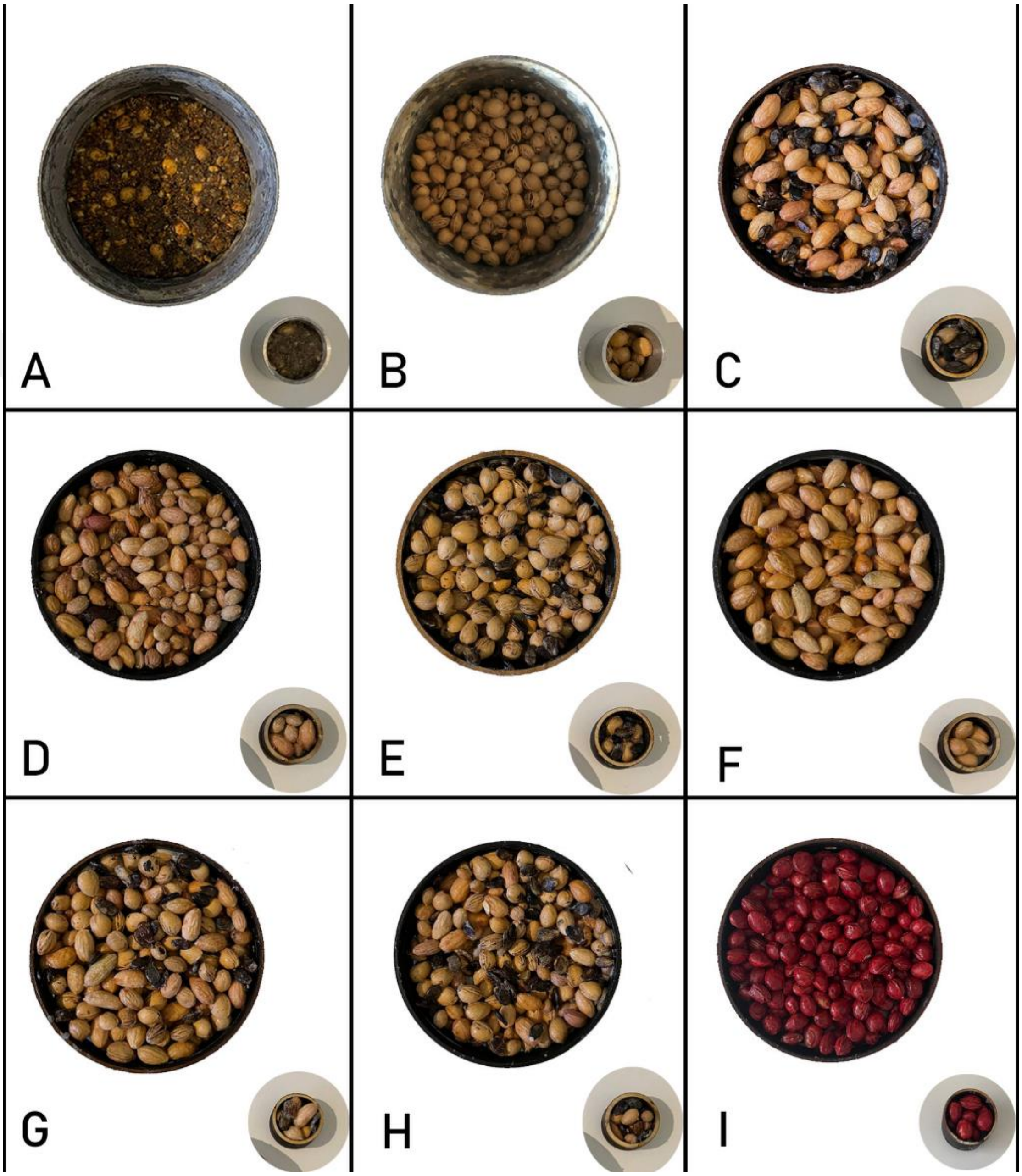


Figure 18. The material samples casted within tube ring

3.1.2. Room Acoustics Simulations

In the last stage of this study, an acoustic simulation is conducted using the proposed materials, focusing on a design studio (FB-06) that presents challenges in terms of acoustic comfort at Bilkent University Faculty of Art, Design and Architecture. The purpose of these simulations is to assess the efficacy of the proposed material. Sound absorption coefficients of current finishing materials of the design studio are listed in Table 4. Accordingly, all walls are paint over brick, ceiling is painted concrete floor is ceramic and there are windows. In its current condition allow surfaces are reflective, thus the reverberance is very high and discomforting. The use of material units, which consist of a composite material of tree resin and cherry seeds, has been suggested as a potential solution for addressing the problem of excessive reverberation time in the design studio. The larger sized panels are thought to be mounted on walls in a modular fashion. The panels positioned at a range of 130 to 150 cm in height (corresponding to the typical speaking level of individuals). The material suggested for an area of 87 m^2 is applied to the walls of the simulated studio. The primary objective of this rhythmic pattern is to increase the effective acoustic area of sound absorptive panel systems (as in a dashboard pattern). In addition, the system incorporates the units that can offer the flexibility of being replaced with a diverse range of colors, thereby accommodating aesthetic considerations. The primary objective of conducting acoustic simulations is to evaluate the acoustic parameters that can be calculated from simulated room impulse responses, before and after the studio's intervention.

As an initial step of the simulations, the 3d acoustic model of studio FB-06 is generated to be imported into ODEON Room Acoustics Software version 17.10. After the models have been generated using the 3D investigate rays option, the models are examined to ensure that there are no gaps so that simulations can be carried out precisely. The ray-tracing model of the studio FB-06 is presented in Figure 19 and 3D OpenGL views of the studio FB-06 are shown in Figures 20. The location of the sound source is130 cm above the ground. The floor surface is mapped to assess overall receiver area in a grid form within the studio. In order to analyze speech intelligibility index, it is assumed that the background noise does not exceed the NC30 threshold.

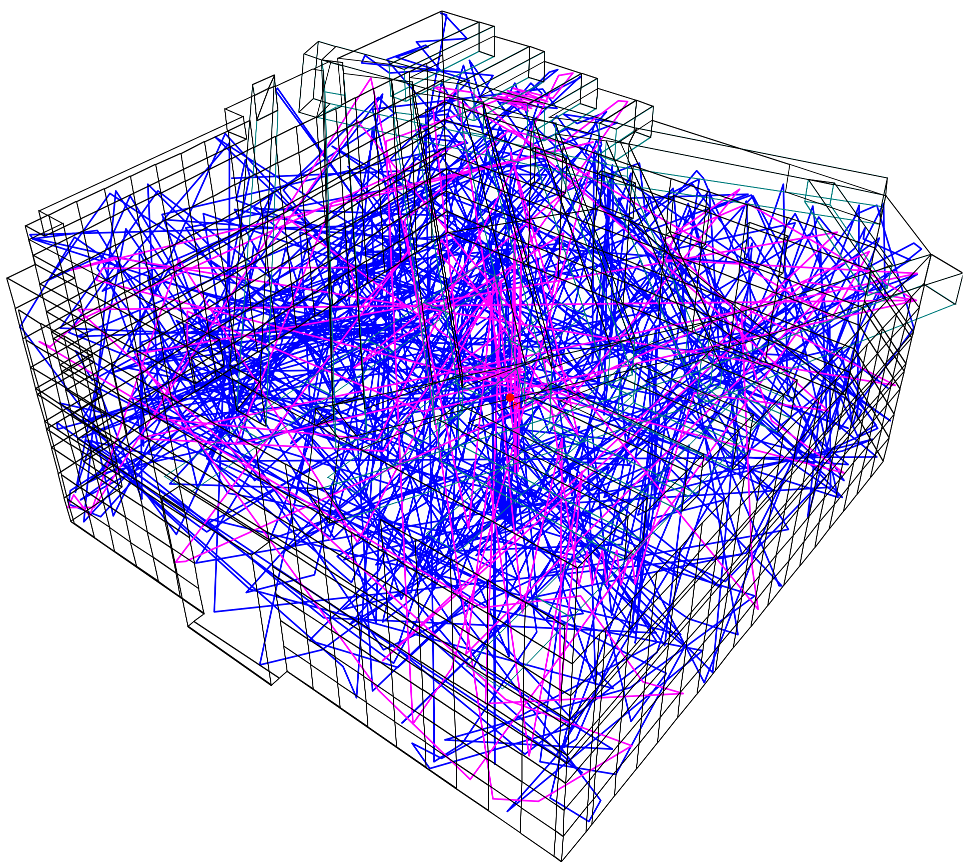


Figure 19. Ray tracing of the studio (FB-06)

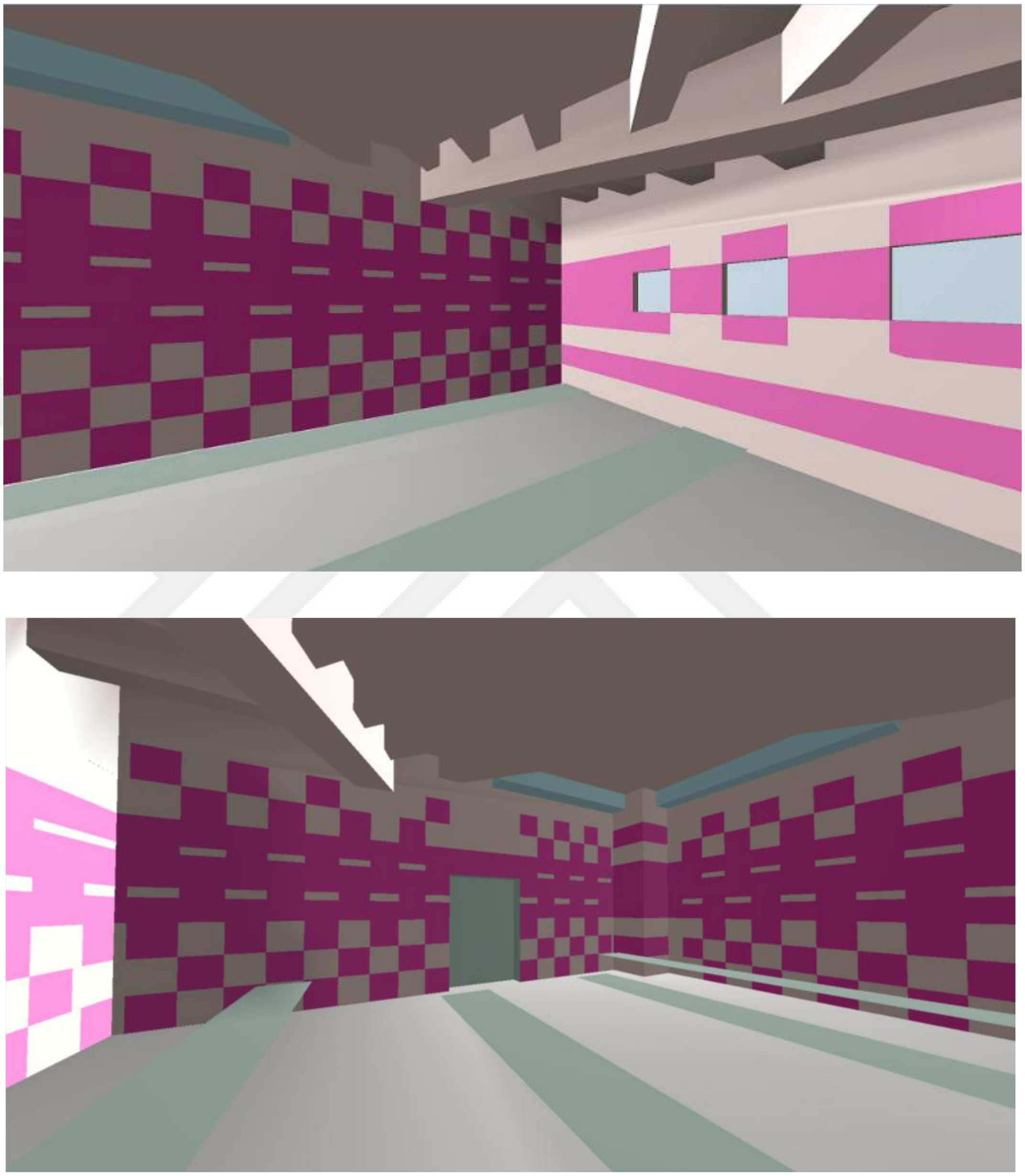


Figure 20. 3D OpenGL view of the studio (FB-06)

Table 4. Sound absorption coefficients over octave bands of existing finishing materials

Location	Material Names	125	250	500	1000	2000	4000
Wall Surfaces	Painted plaster on brick wall	0.09	0.09	0.09	0.10	0.10	0.15
Ceiling surfaces, columns	Painted concrete	0.01	0.01	0.01	0.01	0.02	0.03
Floor Surfaces	Ceramic tiles	0.01	0.01	0.01	0.02	0.02	0.02
Windows	Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04
Door	Solid timber door	0.14	0.10	0.06	0.08	0.10	0.10
Tables	Wood	0.25	0.18	0.11	0.08	0.07	0.06

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Impedance Tube Measurement Results

This section presents the impedance tube measurement results of the developed biobased material composite samples. These samples consist of different combinations of the components outlined in Table 2. In order to assure repeatability and dependability of the results, every configuration is tested10 times. The sound absorption coefficient (α) values between 50 Hz and 5000 Hz for the measured samples A-I are presented in Figure 21 to Figure 24.

Figure 21 depicts the samples A and B tested with 30 mm air gap formed by changing the binder. Accordingly, sample A, whose binder is resin, has greater absorption efficiency from 500 Hz to 2000 Hz than sample B, whose binder is wood glue. The graph shows sample A's alpha value reaches its maximum (0.7) at 800 Hz. At low frequencies (below 250 Hz), the measurement findings for these two materials demonstrate a remarkably similar pattern and low sound absorption. This can easily be related to the air gap thickness. If the thickness of the air gap is increased, the effective frequency range can move towards lower octave bands for both samples.

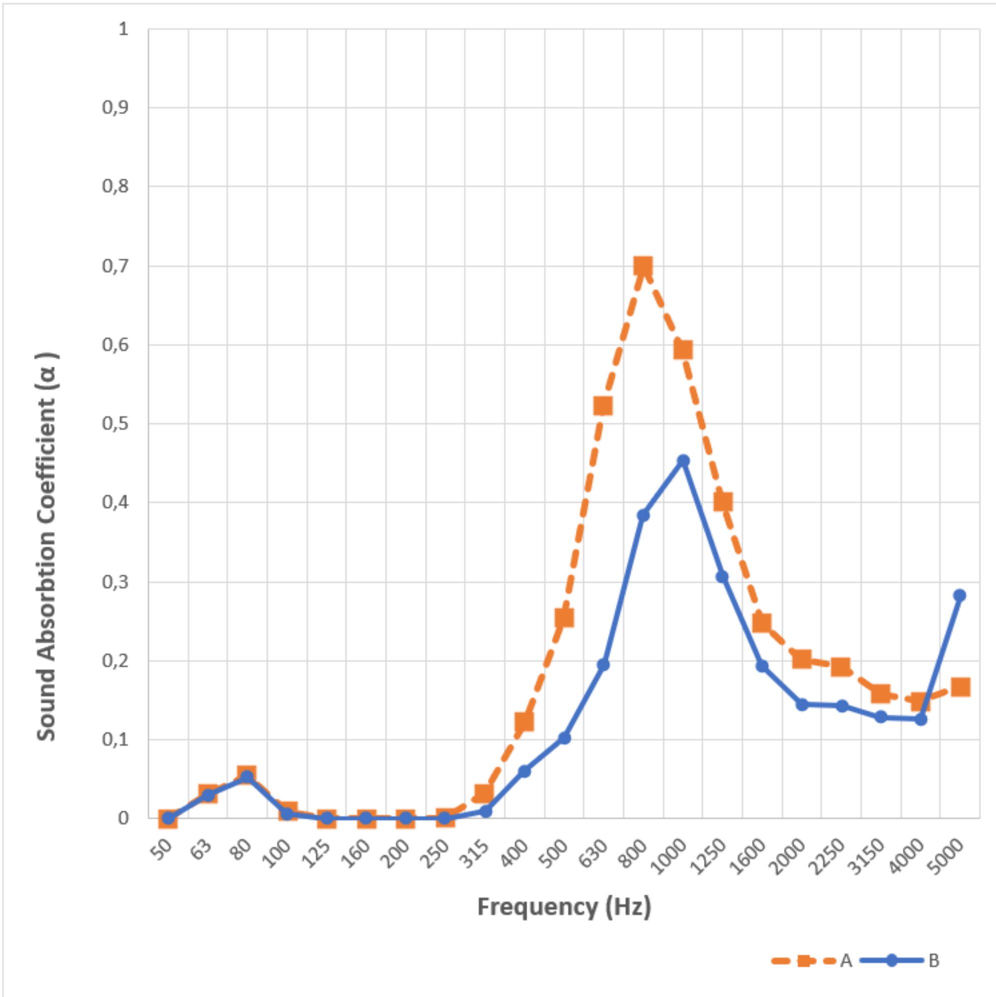


Figure 21. Sound absorption coefficients over 50 Hz to 5000 Hz for samples A and B with a 30 mm air gap backing

Figure 22 displays the sound absorption coefficient measurement results for 20 mm thick B- H samples with a 30 mm air gap backing. When the results are analyzed, it is observed that all seven samples exhibit greater sound absorption between 500 Hz and 2000 Hz. The alpha values over octave bands between 125 Hz and 4000 Hz for A-I are also presented in Table 5. According to Figure 22, samples H and C have the highest sound absorption performance in their effective ranges; with alpha values reaching up to 0.70 at mid frequencies. On the other hand, samples B and I have comparatively much lower alpha values over the measured frequency range. While samples B and I include solely cherry seeds, sample H has cherry, large-small olive, and watermelon seeds; therefore, it can be concluded that the material's ability to absorb sound rises as the diversity of seeds (with different diameters) within the sample increases.

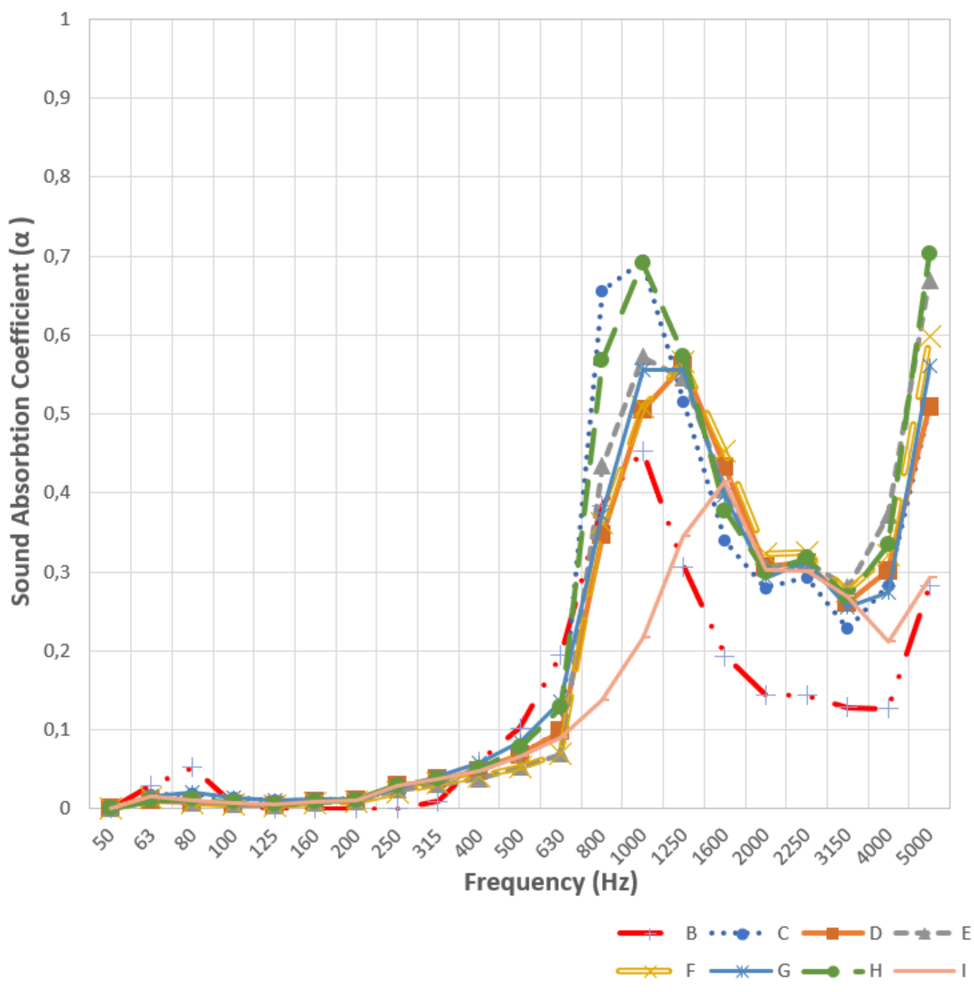


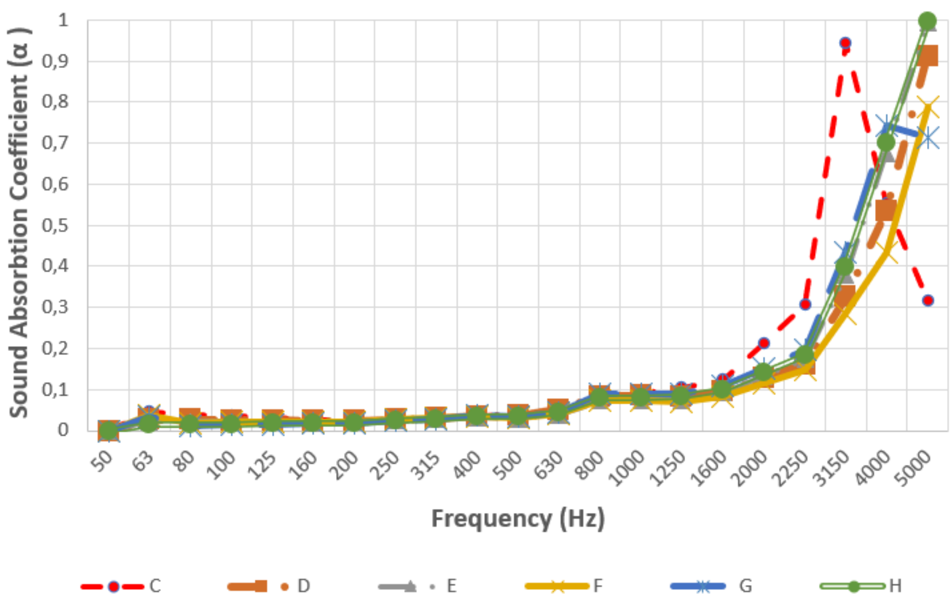
Figure 22. Sound absorption coefficients over 50 Hz to 5000 Hz for samples B-I with a 30 mm air gap behind.

Table 5. Sound absorption coefficients (α) values over 1/1 octave bands (Hz)

SAMPLE	125 HZ	250 HZ	500 HZ	1000 HZ	2000 HZ	4000 HZ
A	0,01	0,01	0,25	0,59	0,20	0,15
B	0,01	0,01	0,10	0,45	0,14	0,13
C	0,01	0,02	0,07	0,69	0,28	0,28
D	0,01	0,03	0,07	0,50	0,31	0,30
E	0,01	0,02	0,05	0,57	0,30	0,37
F	0,01	0,02	0,05	0,51	0,32	0,32
G	0,01	0,03	0,08	0,56	0,29	0,27
H	0,01	0,03	0,08	0,7	0,3	0,33
I	0,01	0,03	0,06	0,22	0,30	0,21

The results for samples C, D, E, F, G, and H with no air gap behind are depicted in Figure 23a. The range of speech tones is 500 Hz to 2000 Hz differs within the range. Without an air gap, the effective sound absorption of the samples is in between 2000 Hz–4000 Hz, indicating high frequencies. To provide effective sound absorption, especially consideringthe intended speech frequencies for indoor custom environments, it is recommended that the panels to be applied with minimum a 30 mm air gap behind. This can be readily provided with a supporting bracket for hanging the panels on walls.

a)



b)

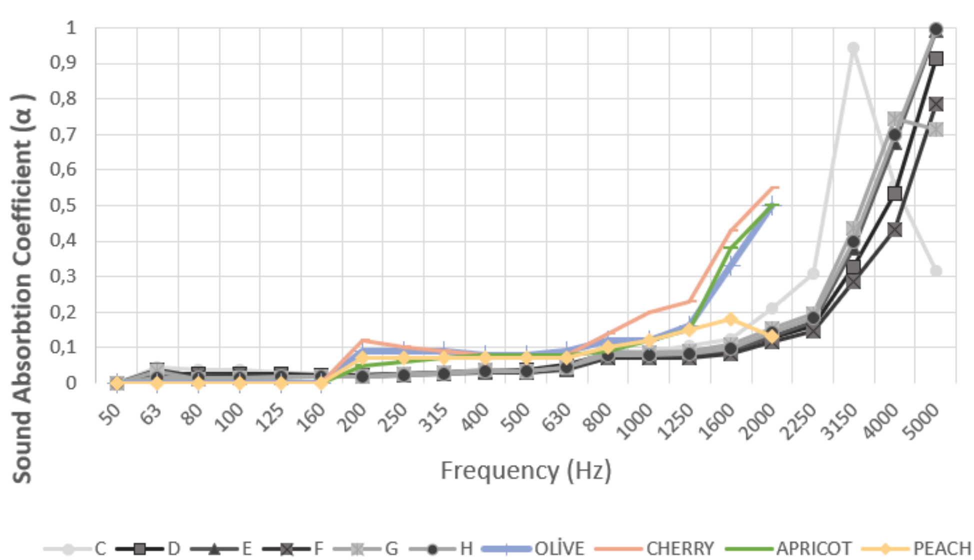


Figure 23. a) Sound absorption coefficients over 50 Hz to 5000 Hz obtained for samples C-H without air gap behind b) The alpha values comparison to from 200 Hz to 1800 Hz between C-H and olive, cherry, apricot, peach sample from the literature (Borrell et al., 2020)

When the research by Borrell et al. (2020) is revisited, it can be stated that four distinct material samples (olive, cherry, apricot, and peach) were created by employing only a single kind of seed in those samples. From those tested samples, without a gap behind, that are 22 mm thick in Borrel et al. (2020)'s study is compared to the material samples C, D, E, F, E, G, and H (see Figure 23b) developed within the framework of this study. However, the research by Borrell et al. (2020) only provides sound absorption coefficient data up to 1800 Hz, most probably due to measurement set-up limitations. Thus, values over 1800 Hz could not be compared. The effective absorption starts only after 800 Hz goes up-to 2000 Hz, after 2000 Hz the data is not provided. From Figure 23b it can be observed that there is a shift to the lower octave bands in Borrell et al. (2020)'s study in comparison to this research. The major rise in the alpha values of the materials in this study starts around 2000 Hz, and this is valid only for the samples tested without airgap. The samples tested with air-gap behind provide higher sound absorption in comparatively lower octave bands.

By maintaining the same composition with material sample B (cherry seeds), material sample I is formed only by an additional spray-painting on to improve the fire resistance of the panel. Although the primary function of paint is to enhance fire resistance, the influence of paint on the material's sound absorption is investigated. According to Figure 24, the paint shifted the effective frequency range from 1000 Hz to higher frequencies, 1600 Hz–5000 Hz. At 1600 Hz, the maximum alpha of painted sample is 0.42. Application of paint to other samples should be tested in the future to derive a better conclusion of the effective frequency range of samples that are painted for fire resistance.

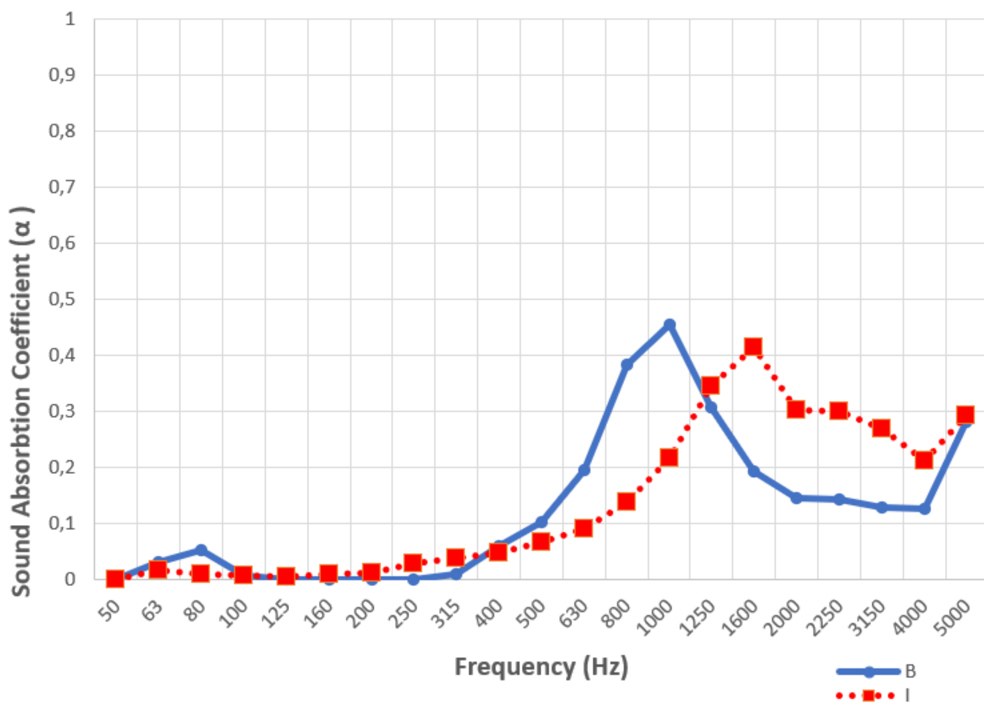


Figure 24. Sound absorption coefficients over 50 Hz to 5000 Hz for obtained for samples B and I with a 30 mm air gap behind

In brief, the material sample containing tree resin, as a binder, is observed to be superior to that of the same sample with wood glue binder. When the numbers of seed types and thus the seed sizes, are varied, the sound absorption performances of the samples are improved. The use of waste fruit seeds (cherry, olive, and watermelon) in the design and production of sound absorptive acoustic panels indicates considerable promise. Another outcome is that the spray-on paint application to increase the fire resistance of one sample panel, has shifted the effective frequency range towards higher octaves. The developed panel systems, can find different grounds of application in indoor spaces where control of speech sound and absorption is critical, such as open-plan offices, meeting rooms, living rooms, or public places such as cafés, restaurants, etc. Further research is necessary to investigate more biodegradable binder types, as well as to observe the effects of different paints over different material samples. In the following section most effective sample in speech frequencies (that is sample A) is applied in a design studio through ray-tracing simulations to check its effectiveness in reverberation control.

4.2. Ray Tracing Simulations

In this section Design Studio FB-06 is used as a control setup, to test the effectiveness of developed material samples. Among 9 samples, Sample A, which has the highest sound absorption performance at speech frequencies is used. As described in the methodology section in detail, initially the acoustical model is developed using archived drawings provided by the Department of Construction Works of Bilkent University. The present state of the studio includes all reflective surfaces painted walls and ceramic floor. After attaining the absorption coefficients in ODEON Room Acoustics Software room impulse responses are collected for individual receiver points defined in a grid layout over 130 cm high from ground. From RIRs both decay rates and energy based acoustic metrics can be calculated. The absorption area of current materials over octave bands are presented in Figure 25.

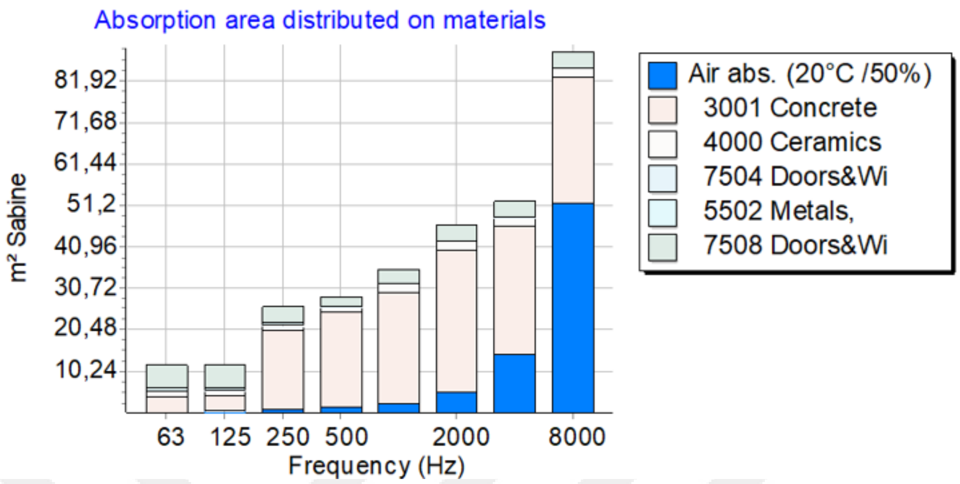
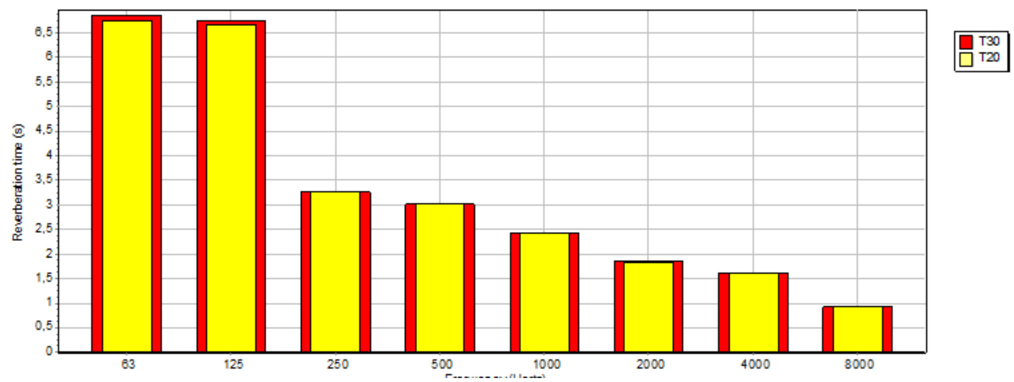


Figure 25. Distribution of absorption area on materials for the current state of Studio FB-06

The evaluation of the acoustical characteristics of a space frequently depends on the reverberation time (T30), which is considered as a primary parameter in this context. For this reason, initially the T30 values are checked for the current state of FB-06. As can be observed from Figure 26, global estimate of reverberation times (T30) of the FB-06 studio room for its current state: at 500 Hz and 1000 Hz are 3.01 s and 2.43 s, respectively. The average mid-frequency (average T30 values of 500 Hz and 1000 Hz) reverberation time is 2.72 s.



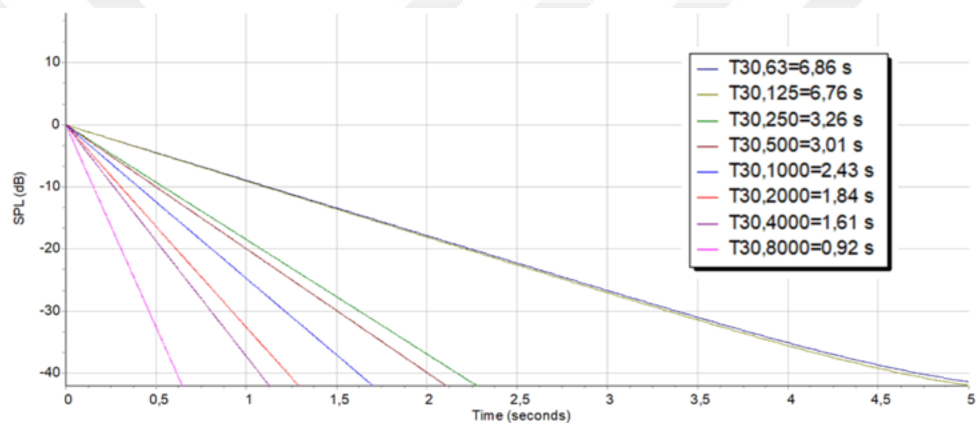


Figure 26. Estimated global reverberation times bar graph (above) and energy decay curves (below) for FB-06 design studio, initial state

Figure 27 to 30 present the T30 distribution maps and cumulative distribution graphs for 500 Hz and 1000 Hz. According to cumulative distribution graphs, T30 at 500 Hz is approximately 3,00 s while at 1000 Hz it is 2,43 s on average. The average mid-frequency reverberation time is 2.71 s, over grid points for the current state of for FB-06 design studio.

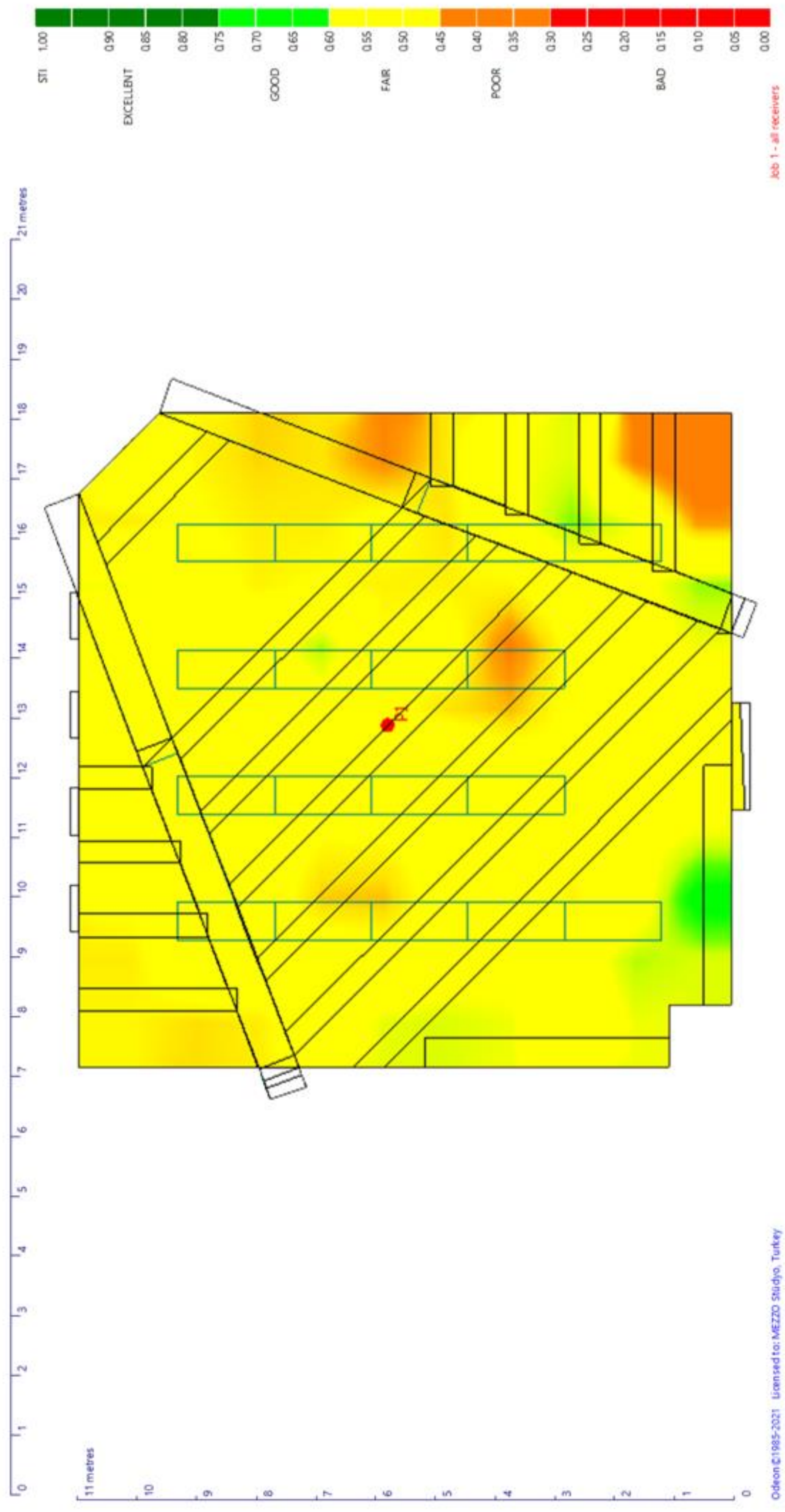


Figure 27. T30 distribution map of FB-06 design studio at 500 Hz, current state500 Hz, current state

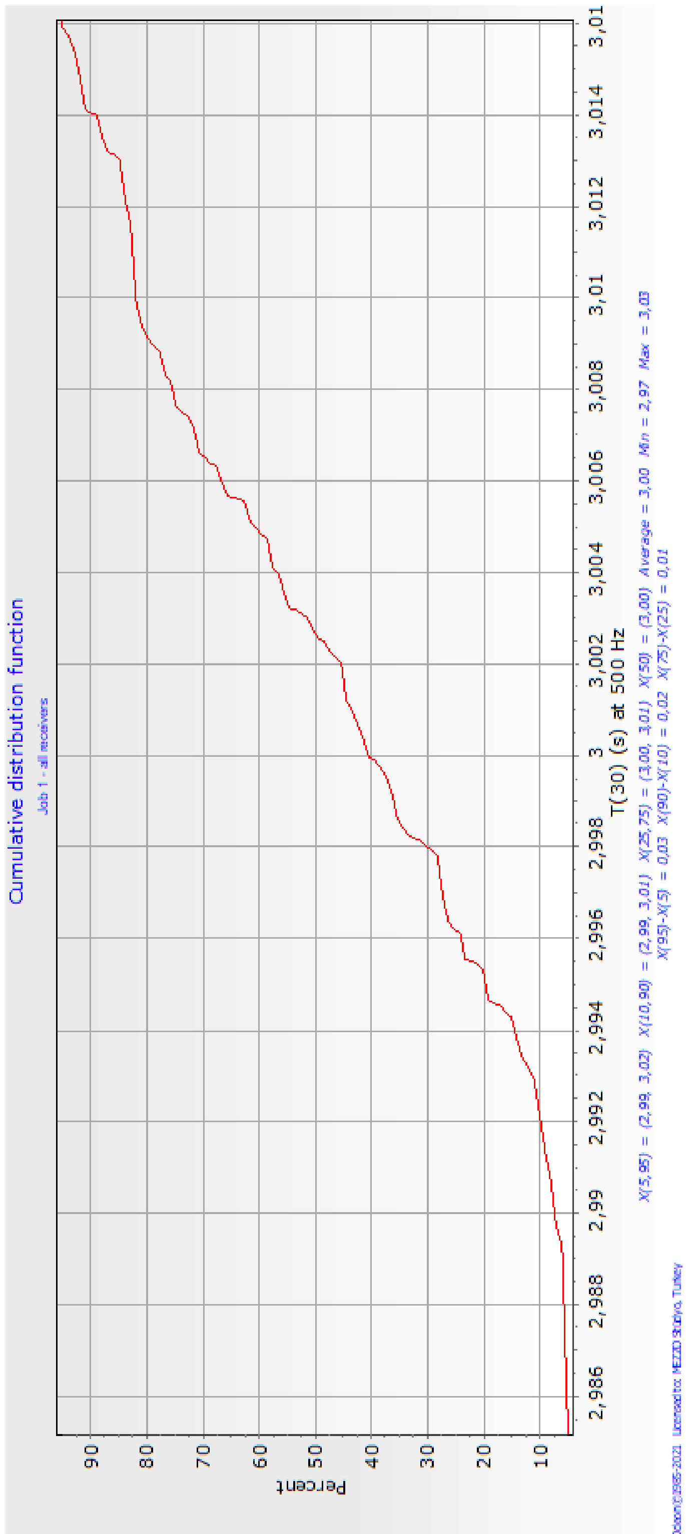


Figure 28. T30 cumulative distribution graph of FB-06 design studio at 500 Hz, current state

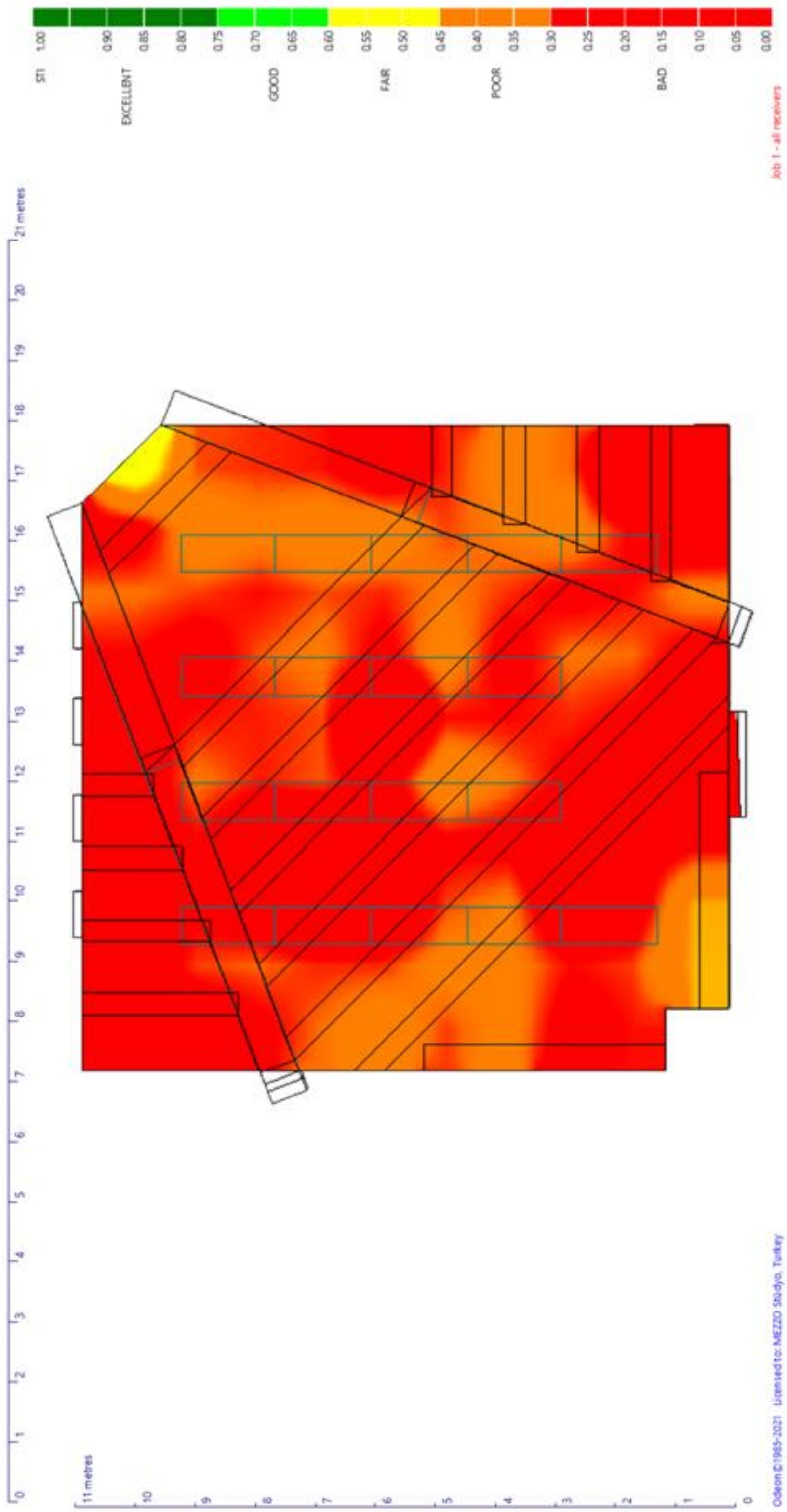


Figure 29. T30 distribution map of FB-06 design studio at 1000 Hz, current state

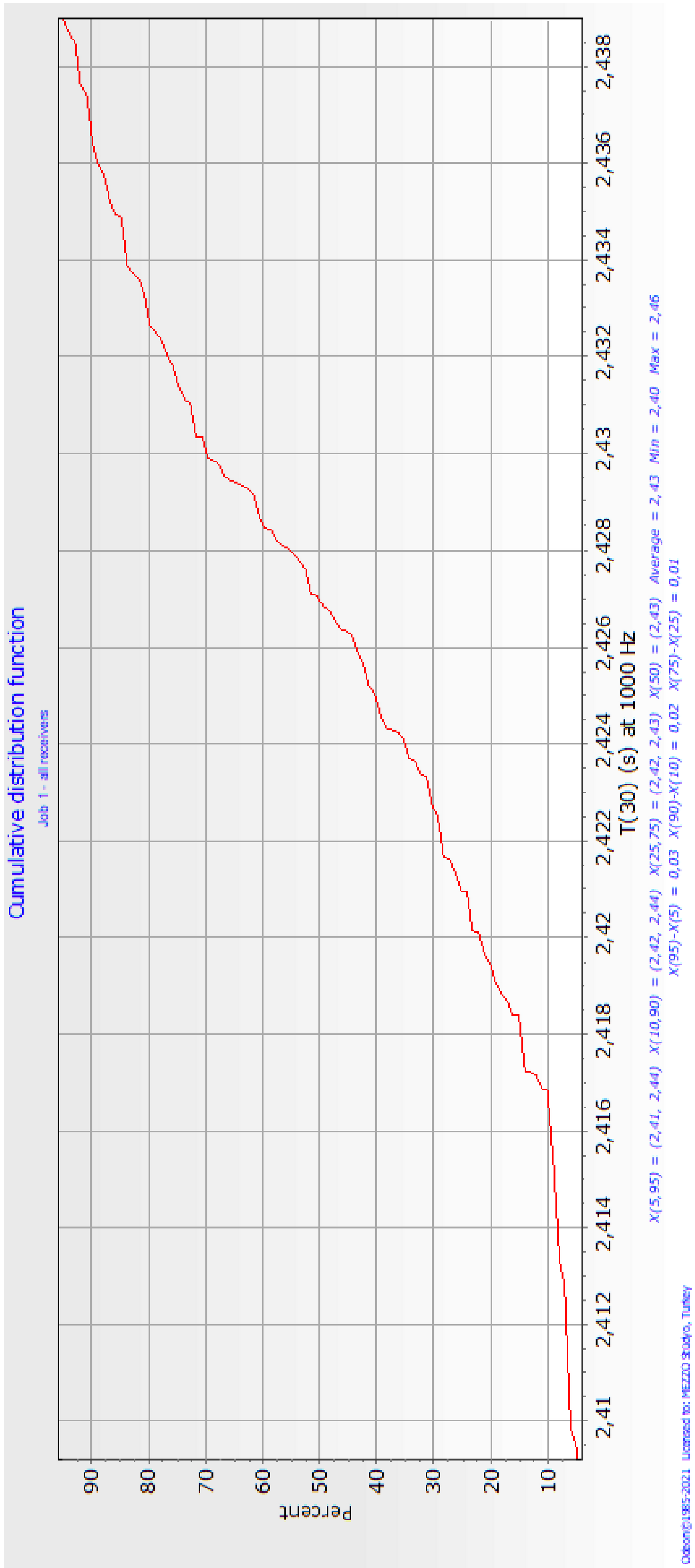


Figure 30. T30 cumulative distribution graph of FB-06 design studio at 1000 Hz, current state

As can be observed from the T30 graphs the current state of the studio is highly reverberant, and this much of lingering sound interferes with speech intelligibility. On the other hand, high T30 values causes tiredness of both instructors and students. For this reason, for some years the classes are cancelled in this studio. In order to provide some improvement in T30 values, as discussed previously, sample A is applied to wall surfaces in a dashboard pattern over 87 m^2. The absorption area of current materials over octave bands are presented in Figure 31. With the proposal the simulations are return, and the results are presented in the following.

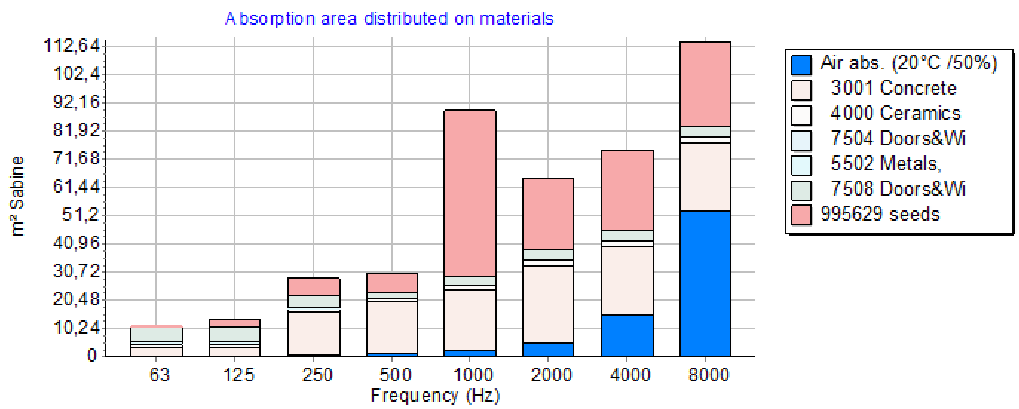


Figure 31. Distribution of absorption area on materials for FB-06 design studio, acoustical design proposal

As can be observed from Figure 32, global estimate of reverberation times T30 of the FB-06 studio room for acoustical design proposal: at 500 Hz and 1000 Hz are 2.92 s and 0.84 s, respectively. The average mid-frequency (average T30 values of 500 Hz and 1000 Hz) T30 is 1.88 s.

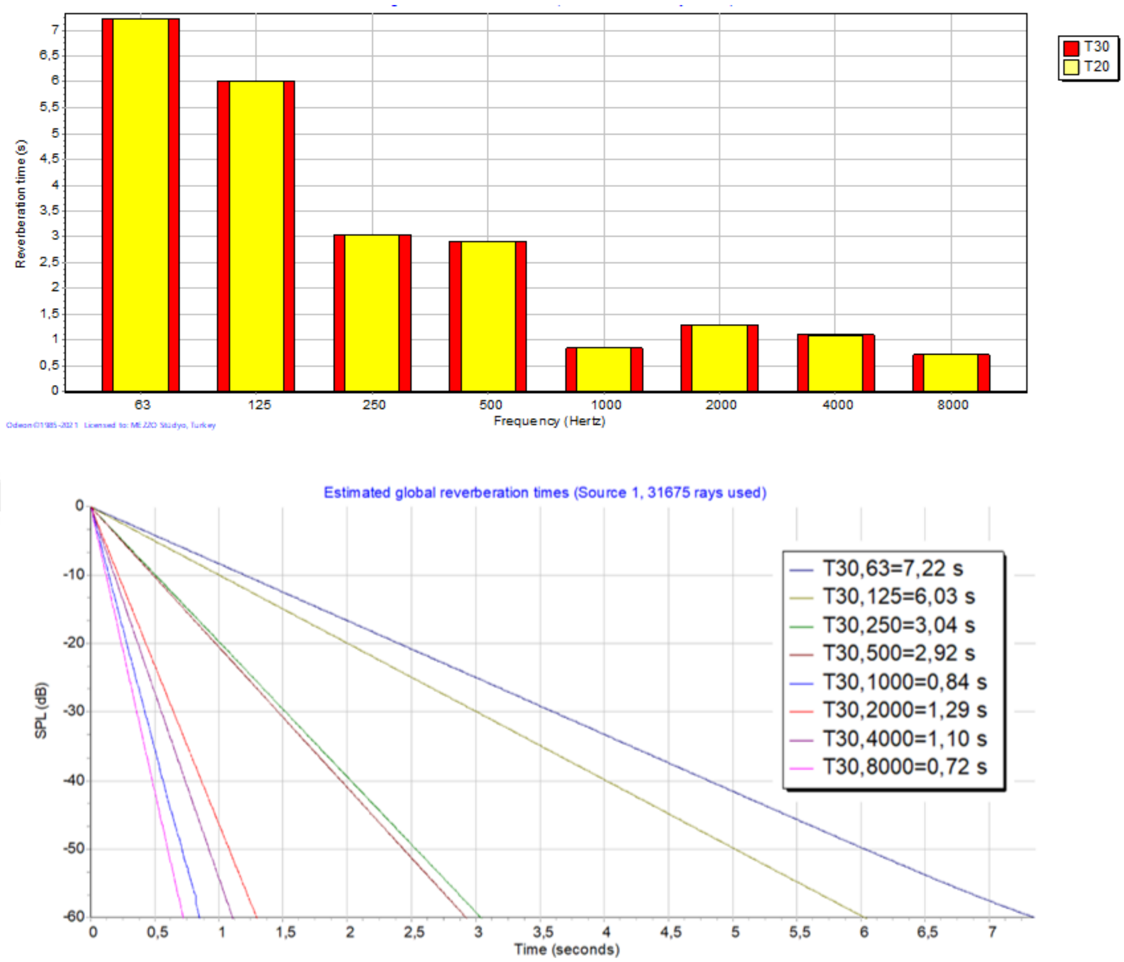


Figure 32. Estimated global reverberation times bar graph (above) and energy decay curves (below) for FB-06 design studio, acoustical design proposal.

Figure 33 to 36 present the T30 distribution maps and cumulative distribution graphs for 500 Hz and 1000 Hz. According to cumulative distribution graphs, T30 at 500 Hz is approximately 2,94 while at 1000 Hz it is 0,83 on average. The average mid frequency reverberation time is 1,88 s, over grid points for the acoustical design proposal of FB-06 design studio.

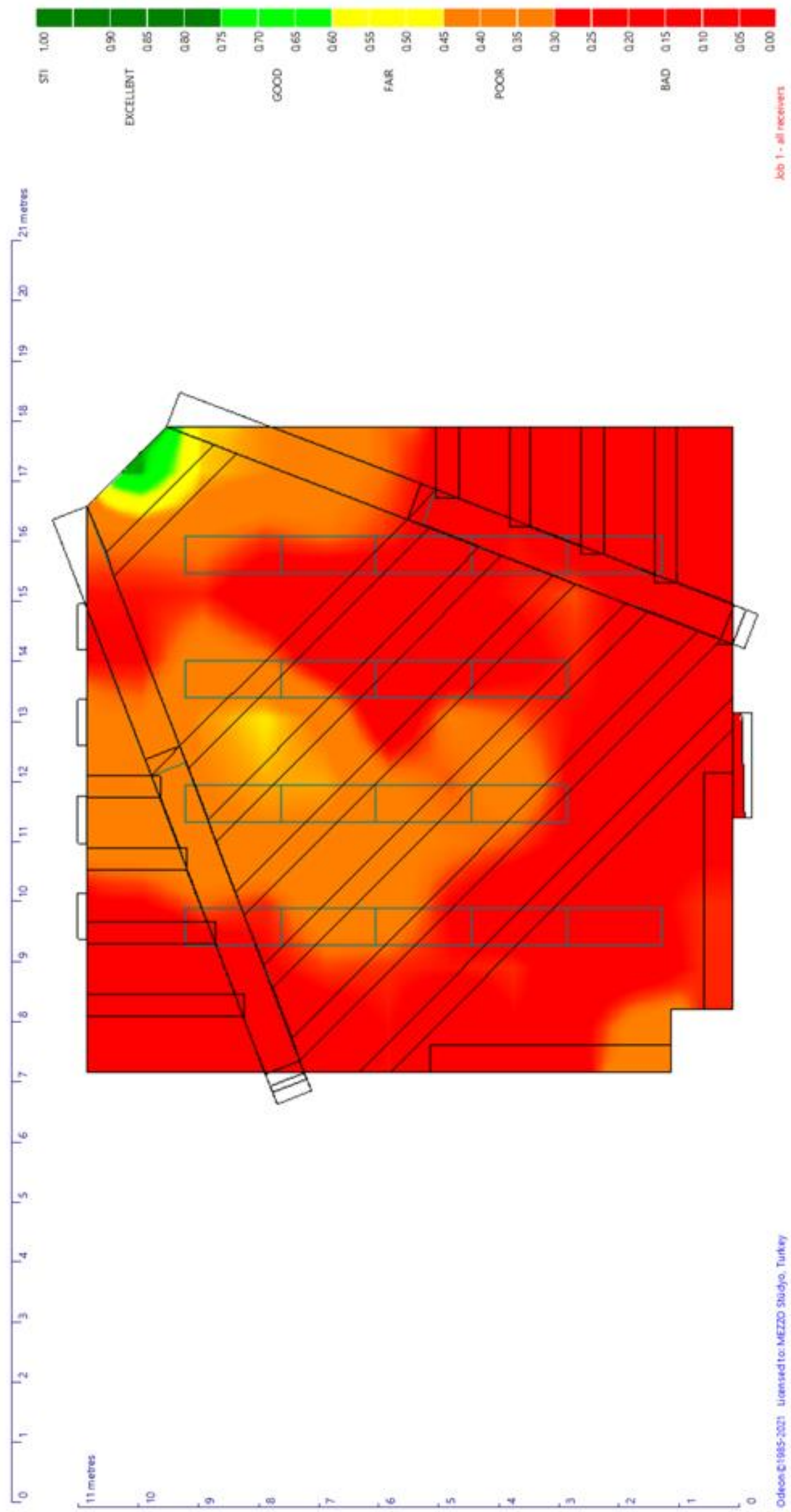


Figure 33. T30 distribution map of FB-06 design studio at 500 Hz, acoustical design proposal.

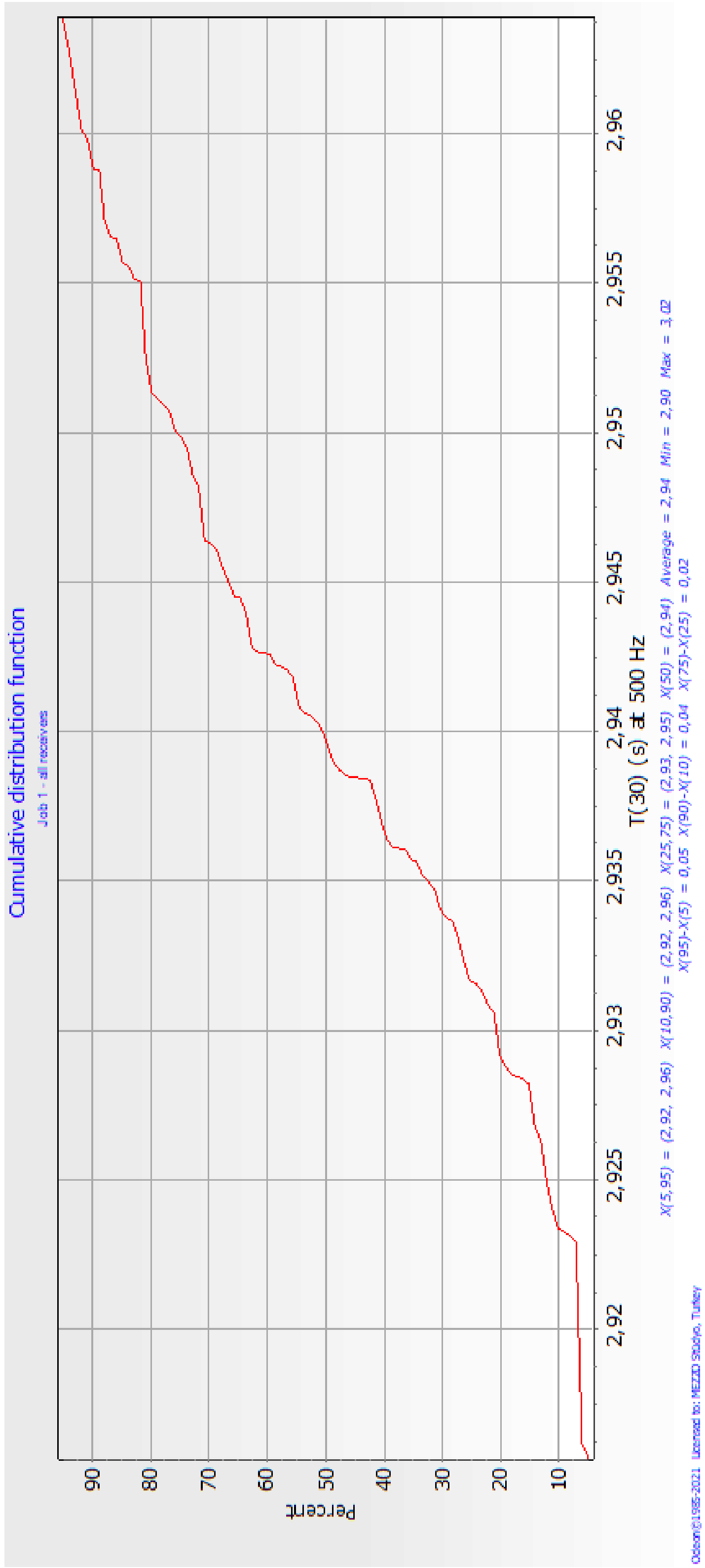


Figure 34. T30 cumulative distribution graph of FB-06 design studio at 500 Hz, acoustical design proposal

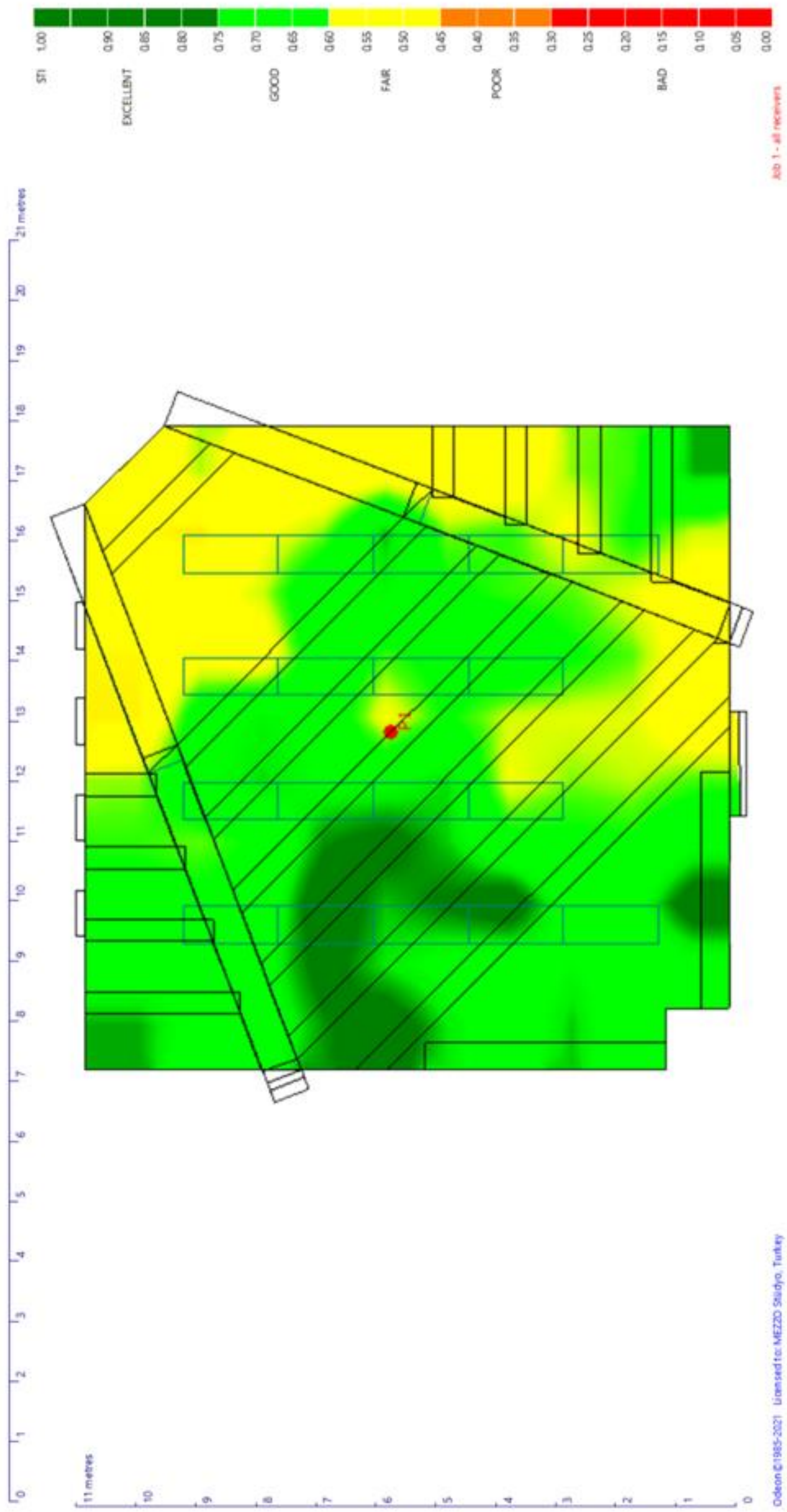


Figure 35. T30 distribution map of FB-06 design studio at 1000 Hz, acoustical design proposal

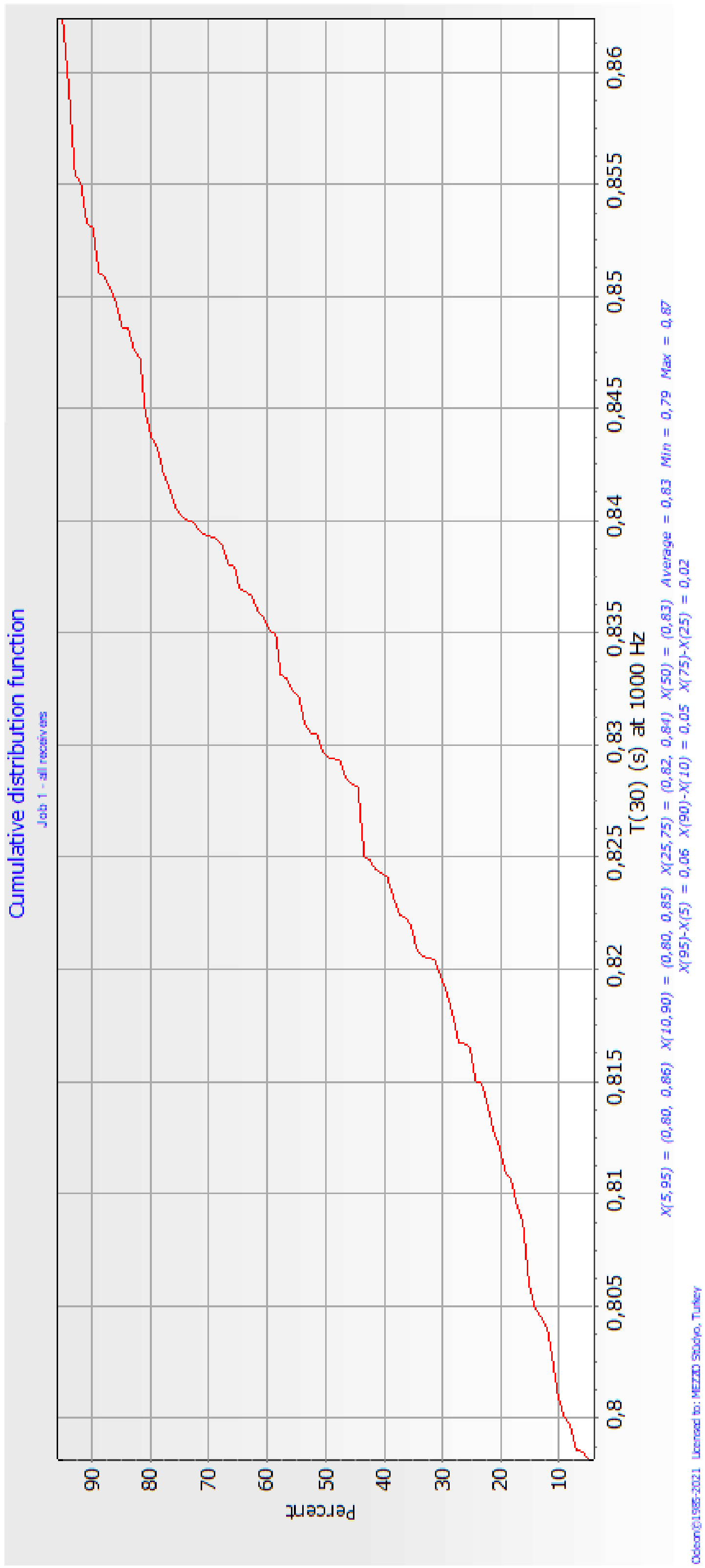


Figure 36. T30 cumulative distribution graph of FB-06 design studio at 1000 Hz, acoustical design proposal

In Figure 37 T30 values of current state is compared to the T30 values after application of Sample A, overall, 87 m^2, in FB-06 design studio. In overall the T30 values are reduced, but the reduction is not sufficient for mid to low frequencies. The highest improvement is at 1000 Hz. This is since Sample A has highest sound absorption coefficient with 0,59 at this octave band. In result the mid frequency average of T30 values is 2,71 s for current state and 1,88 s after the application of design proposal. At 1000 Hz after the application of Sample A T30 values of the studio decreased sharply from 2.93 s to 0.85 s.

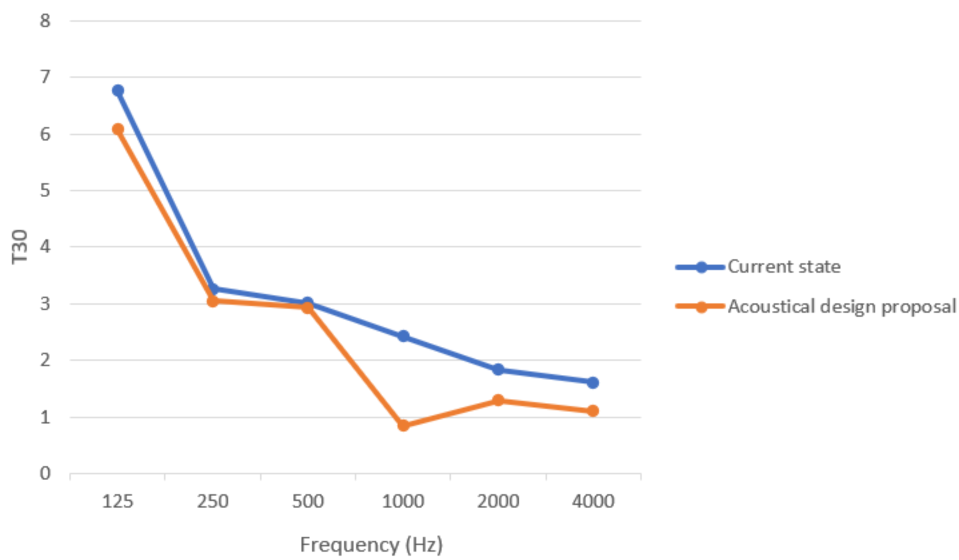


Figure 37. T30 values of FB-06 studio room over octave bands from 125 Hz to 4000 Hz, comparing simulated current results, and simulated results after acoustical design proposal

Figure 38 and Figure 39 presents STI distribution maps and cumulative distribution graphs in current state. According to cumulative distribution graphs, STI values is 0,43 on average and the speech intelligibility is in the range of “POOR” quality metric; from 0,32 – 0,45.

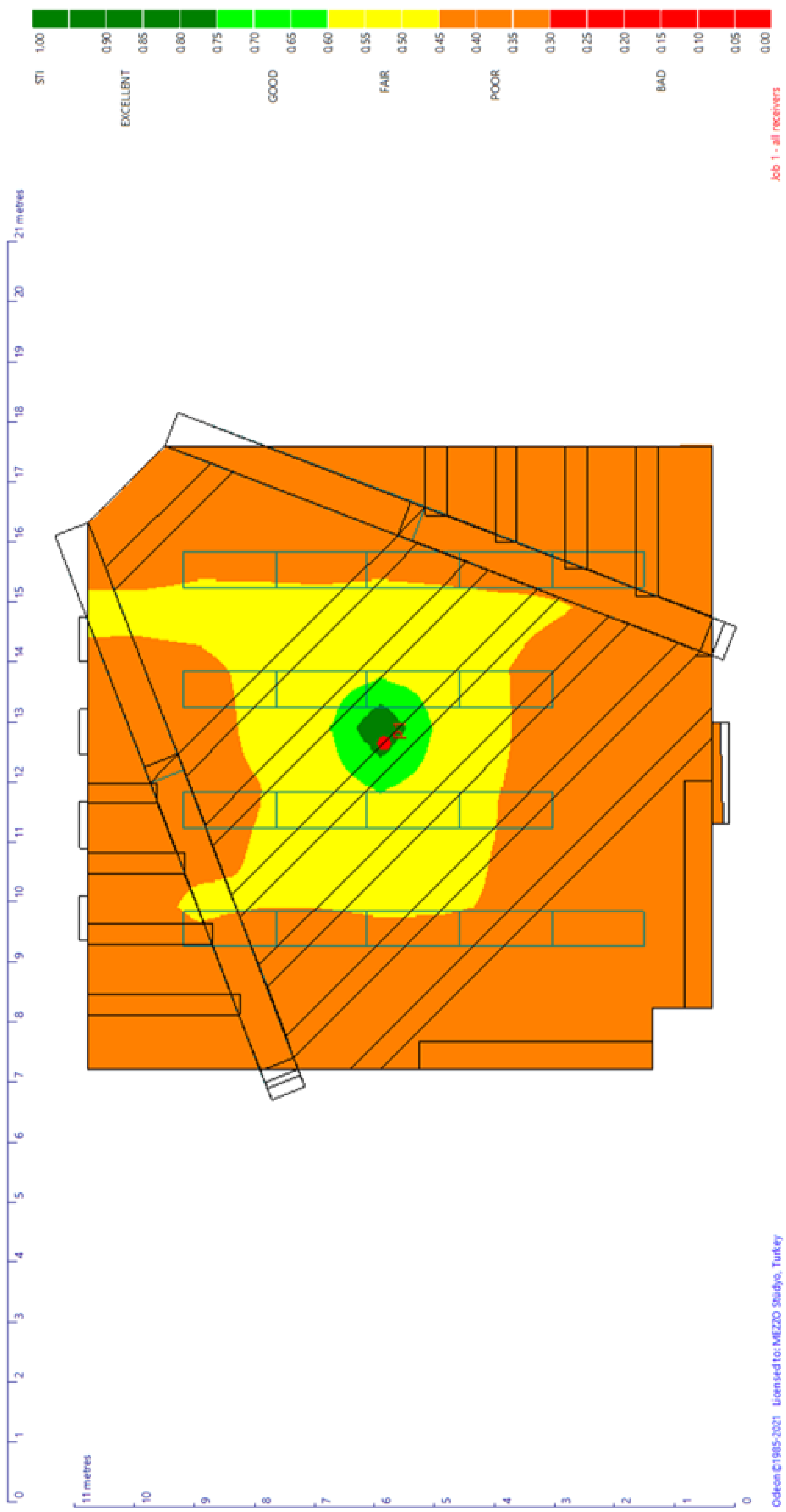


Figure 38. STI distribution maps of FB-06 design studio, current state

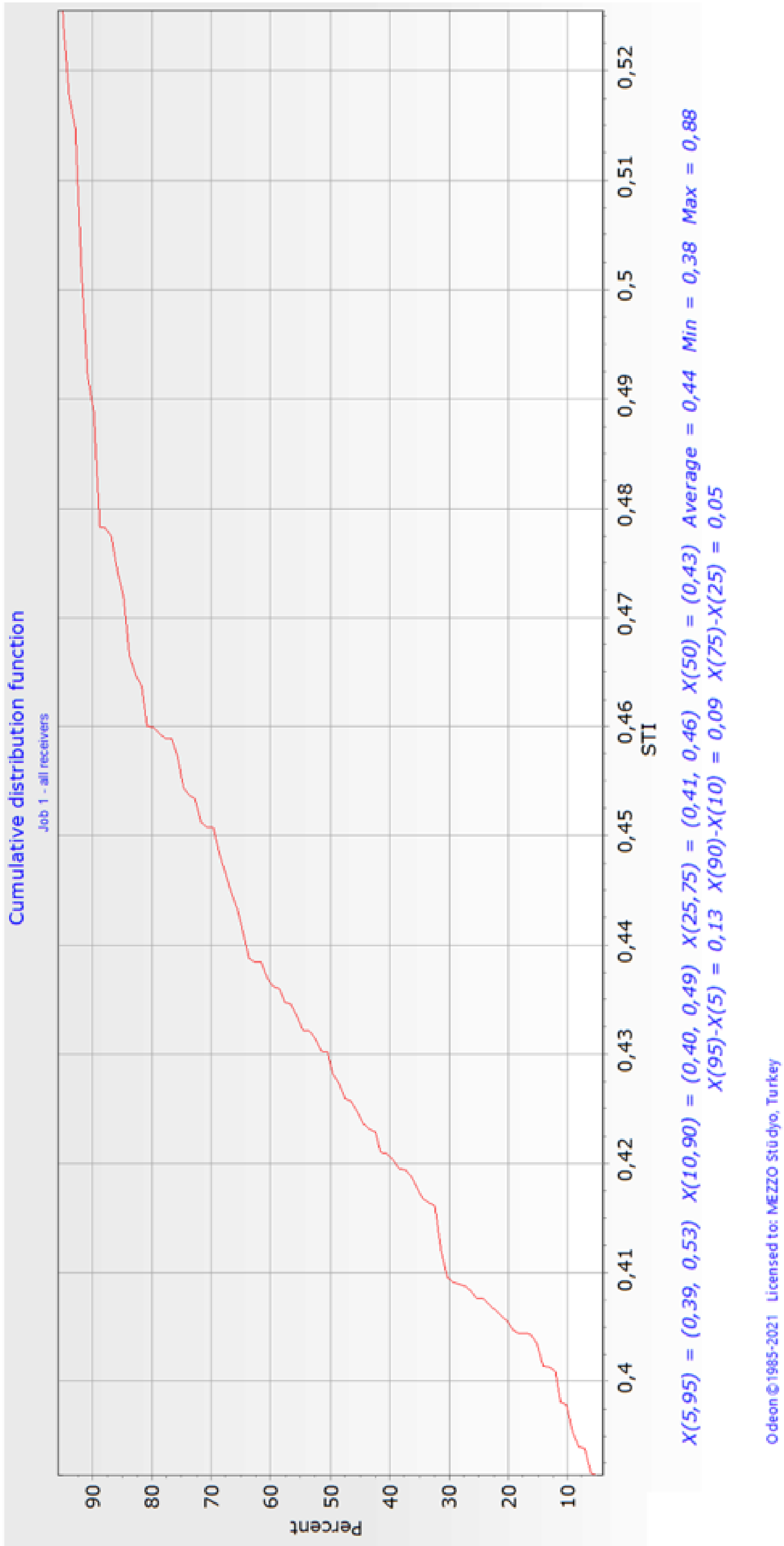


Figure 39. STI cumulative distribution graphs of FB-06 design studio, current state

Figure 40 and Figure 41 presents STI distribution maps and cumulative distribution graphs in acoustical design proposal. According to cumulative distribution graphs, STI values is 0,48 on average and the speech intelligibility indicates “FAIR” fair quality rating with a range of 0,45 – 0,60. According to STI values, after design proposal the quality of speech intelligibility is improved, from “Poor “quality to “FAIR” quality rating, and average value of STI is increased from 0,43 to 0,48. Additional application area of sample material will increase the STI ratings even further.

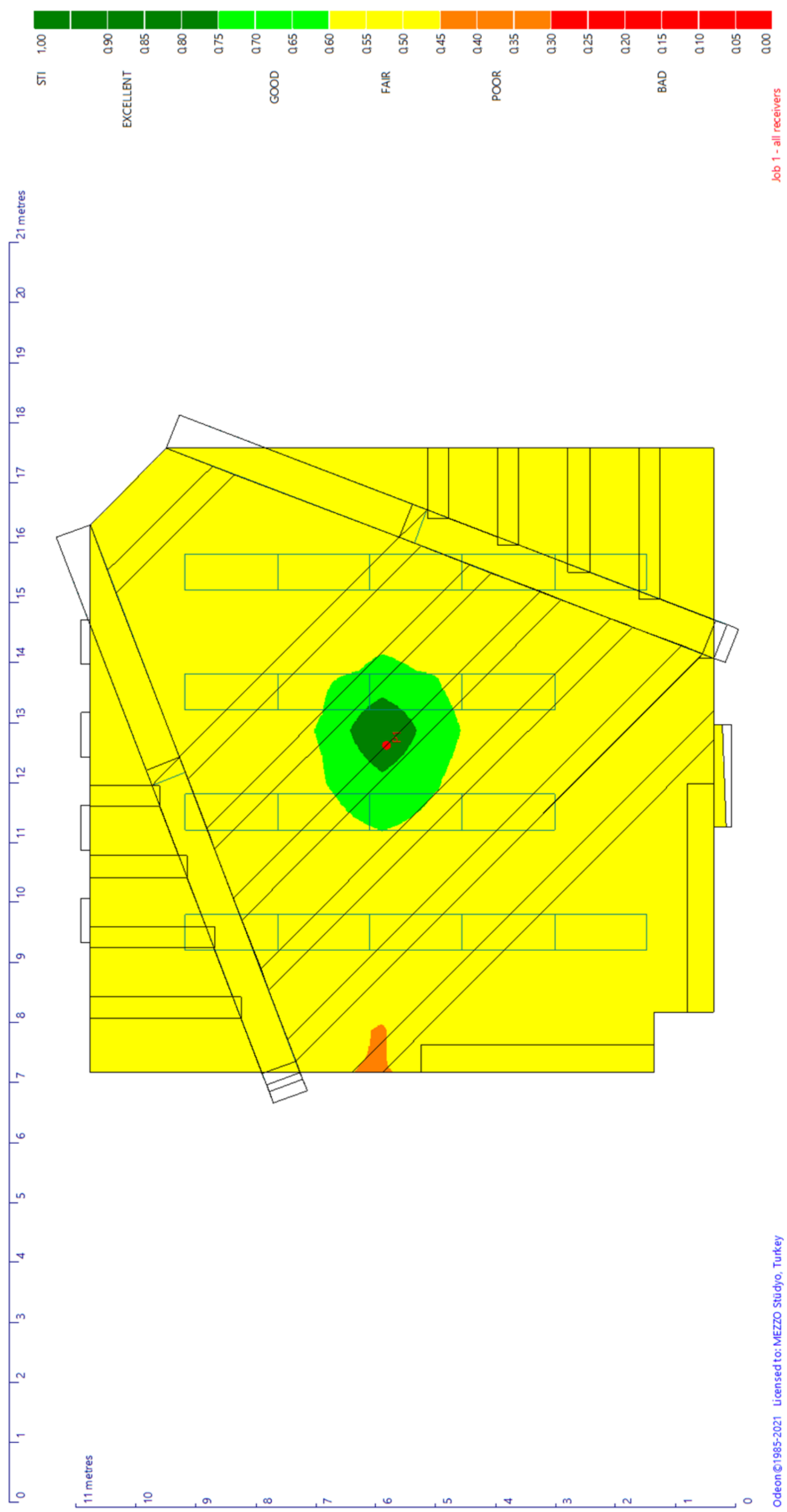


Figure 40. STI distribution maps of FB-06 design studio, acoustical design proposal

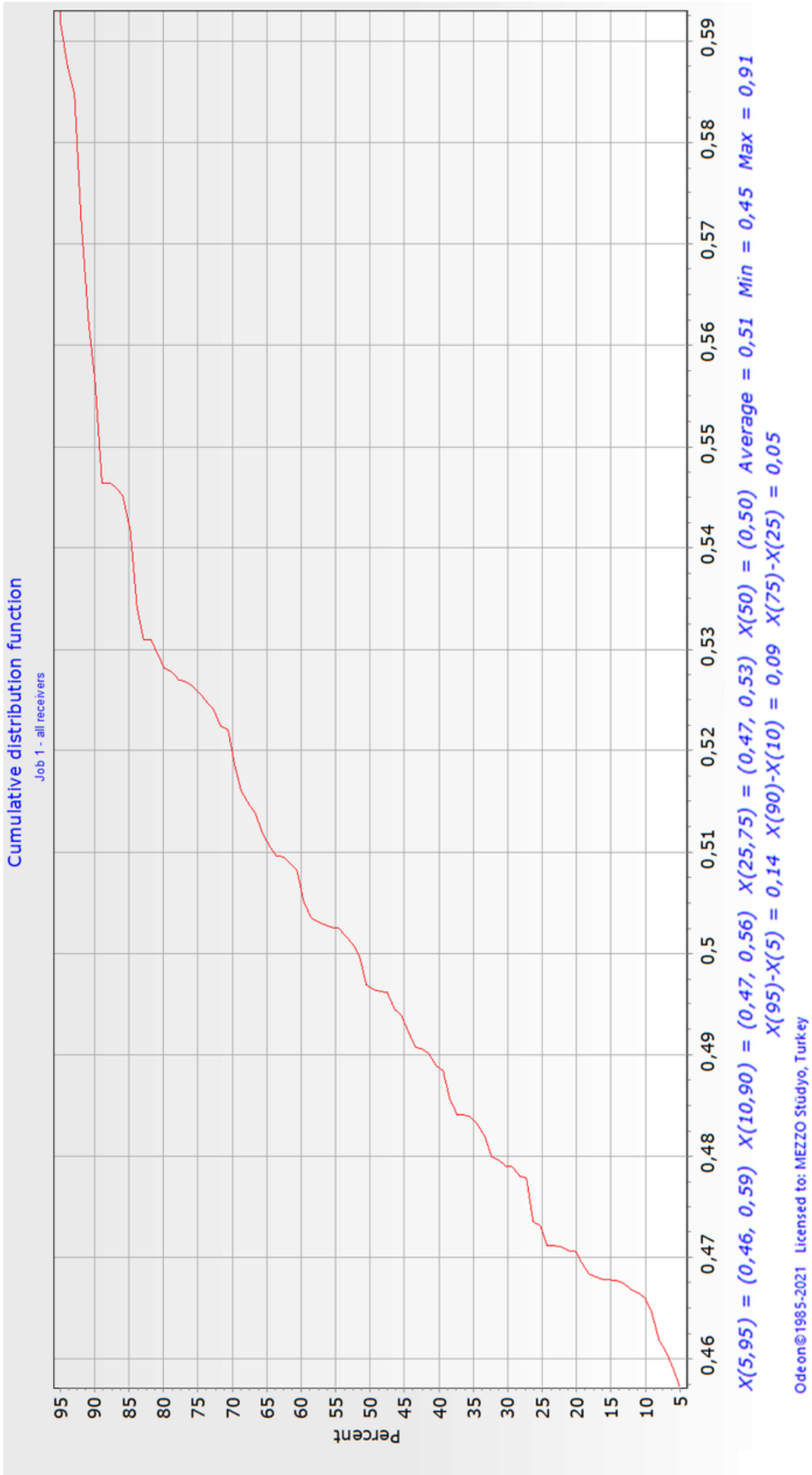


Figure 41. STI cumulative distribution graphs of FB-06 design studio, acoustical design proposal

At this point it is important to criticize the results obtained from the simulations. The selected material Sample A, as one of the highly performing materials in overall samples at speech frequencies, still necessitates an improvement in mid-low frequency range. One solution is increasing the airgap behind the panel in its application on wall surfaces. Another solution can be increasing the thickness of material sample, which eventually necessitates usage of more fruit seed wastes. In future studies mixing more types of seeds (different sized) or using alternative panels of different samples developed in this study may aid improving the effective frequency range. Using different airgaps in the application of panels can also provide a better distribution of sound absorption over octave bands, which as well can be used to create a pattern and rhythm in interior surfaces. Eventually this will improve the artistic value of designed surfaces.

CHAPTER 5

CONCLUSION

The utilization of environmentally detrimental products within the construction and building industry surpasses the threshold of sustainability. Consequently, substantial research has been conducted on the development of eco-friendly sound insulation materials. Fruit seeds have been investigated as bio-based sound absorbing materials in various studies documented in the literature. Previous studies mostly focus on one type of seed. This study focuses on available fruit waste seeds in Turkey and searches for alternative combinations of those to increase the potential of sound absorption performance when they are mixed. One notable distinction of this research, in comparison to existing literature, is in the combination of three distinct fruit seeds, using varying proportions and adhesives to create nine unique combinations. The accompanying analysis involves a comparison of the sound absorption coefficients across these combinations. This research aims to examine the sound absorption coefficients of materials by changing the fruit types and proportions that constitute them, while maintaining a constant thickness of 20 mm.

Furthermore, the literature does not provide any information on the fire resistance of the materials under investigation using fruit seeds. In the present investigation, a coating of spray paint is applied to sample I, resulting in a notable alteration of the effective frequency range. In brief, towards higher octaves the alpha values of the sample are decreased. For this reason, alternative methods for fire proofing of natural seed-based panels, with minimum negative effect on sound absorption performance should be further studied.

In this study, the first choice for the adhesive material is natural tree resin, which exhibited the maximum sound absorption performance among the samples. However, wood glue is subsequently used as an alternative due to the challenges associated with the production of the products utilizing natural resin. According to the findings, it can be inferred that the utilization of tree resin as the primary constituent in the production of all products will lead to enhanced sound absorption capabilities.

The sound absorption capabilities of the samples are enhanced when there is variation in seed types and seed sizes. Moreover, increase in pore sizes (as visually observed) in the examined materials has a positive relationship with the size of the seeds. When the seed size of the sample is increased, as well as the pores, the sound absorption capacity of the sample is improved.

The use of discarded fruit seeds, such as cherry, olive, and watermelon, in the design and manufacturing process of sound-absorbing acoustic panels indicates a considerable potential. The simulation results indicate an improvement in sound absorption area within the design studio but limited to mid to high frequencies. For improving the effective range in overall frequency spectrum most reasonable solution is the application of panels out of waste seeds with varying airgaps behind. This will increase the sound absorption performance at mid to low frequencies, while preventing the use of more material (more seeds).

In conclusion, the developed panel systems have several potential applications in interior environments where speech intelligibility and reverberation control are critical. These include settings like open-plan workplaces, conference rooms, living rooms, as well as public establishments such as cafés and restaurants. Given that the suggested materials will serve as interior finishing elements, the application of paint may also enhance their visual appeal via the use of color and the incorporation of specific patterns, so enriching the overall design.

The sound absorption performance of proposed material combinations may be further improved by using other fruit seeds such as peach, apricot, carob seed and various adhesives. Additional investigation is required to explore a wider range of biodegradable binder types, as well as to examine the impacts of various paints on different material compositions.

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APPENDIX

APPENDIX A _IMPEDANCE TUBE MEASUREMENTS

Table A 1. Alpha(α) values over 1/3 octave bands obtained for sample A-I with a 30 mm air gap backing

Freq.	Absorption Coefficient (α)								
	A	B	C	D	E	F	G	H	I
50	0	0	0	0	0	0	0	0	0
63	0,018	0,013	0,046	0,008	0,013	0,019	0,024	0,009	0,001
80	0,047	0,037	0,057	0,007	0,023	0,021	0,038	0,002	0,014
100	0,003	0	0,045	0,001	0,016EKR	0,014	0,027	0,004	0,003
125	0	0	0,032	0,001	0,010	0,006	0,018	0,004	0,000
160	0	0	0,025	0,009	0,013	0,008	0,017	0,008	0,005
200	0	0	0,026	0,011	0,014	0,009	0,018	0,010	0,007
250	6,570	0	0,028	0,029	0,025	0,021	0,028	0,029	0,028
315	0,029	0,007	0,035	0,037	0,031	0,032	0,040	0,037	0,037
400	0,121	0,058	0,049	0,048	0,037	0,041	0,059	0,051	0,048
500	0,257	0,100	0,068	0,068	0,052	0,053	0,085	0,077	0,066
630	0,522	0,187	0,098	0,098	0,069	0,069	0,137	0,128	0,091
800	0,701	0,371	0,651	0,346	0,438	0,363	0,369	0,566	0,137
1000	0,596	0,445	0,689	0,505	0,574	0,506	0,551	0,688	0,217
1250	0,395	0,301	0,513	0,567	0,548	0,566	0,553	0,570	0,345
1600	0,248	0,189	0,338	0,445	0,407	0,454	0,393	0,369	0,414
2000	0,203	0,140	0,277	0,314	0,306	0,324	0,288	0,291	0,305
2250	0,194	0,138	0,291	0,31	0,317	0,324	0,309	0,311	0,302
3150	0,158	0,121	0,222	0,263	0,282	0,274	0,249	0,267	0,270
4000	0,150	0,130	0,282	0,302	0,371	0,321	0,273	0,335	0,213
5000	0,167	0,279	0,501	0,512	0,670	0,600	0,556	0,704	0,290

Table A 2. Alpha(α) values over 1/3 octave bands obtained for sample C-H without air gap

Freq.	Absorption Coefficient (α)					
	C	D	E	F	G	H
50	0	0	0	0	0	0
63	0,089	0,013	0,021	0,027	0,019	0,002
80	0,064	0,040	0,010	0,008	0,008	0,009
100	0,055	0,034	0,013	0,015	0,016	0,009
125	0,045	0,032	0,011	0,014	0,015	0,008
160	0,034	0,028	0,014	0,014	0,016	0,013
200	0,034	0,028	0,015	0,016	0,017	0,015
250	0,029	0,029	0,021	0,026	0,024	0,021
315	0,029	0,031	0,025	0,030	0,028	0,026
400	0,037	0,035	0,031	0,031	0,037	0,035
500	0,038	0,036	0,028	0,029	0,033	0,034
630	0,046	0,050	0,038	0,040	0,045	0,044
800	0,083	0,082	0,070	0,072	0,086	0,075