

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**COMPARATIVE EVALUATION OF SUSTAINABLE SOUND ABSORPTION
MATERIALS USING TOPSIS METHOD**



M.Sc. THESIS

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Environmental Engineering Department

Environmental Science, Engineering and Management Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**SÜRDÜRÜLEBİLİR SES EMİŞİ MALZEMELERİNİN TOPSIS YÖNTEMİYLE
KARŞILAŞTIRMALI DEĞERLENDİRİLMESİ**

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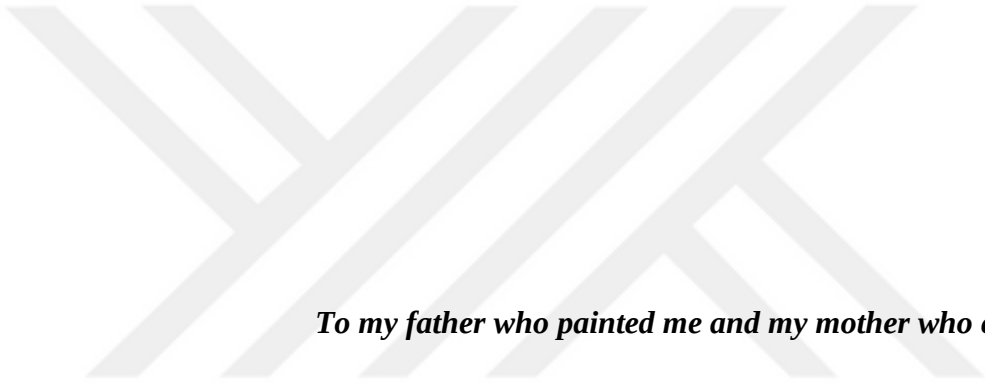
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To my father who painted me and my mother who colored me,



FOREWORD

This research work would not have been possible without the support and contribution of many people to whom I want to express my gratitude for.

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Buroog ALKRAIDI
Architect and Engineer

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ABBREVIATIONS

ACF	: Activated Carbon Fiber
AFR	: Air Flow resistivity
AHP	: Analytic Hierarchy Process
APM	: Acoustic Panel Materials
B	: Biodegradability
Bicopet	: Bicomponent Polyester Fiber
CHF	: Corn Husk Fiber
CO	: Cotton
CP	: Cost of Panel
CRM	: Cost of Raw Material
CT	: Cost of Transportation
CU	: Chemical Usage
FAO	: Food and Agriculture Organization
FG	: Fiberglass
FU	: Function Unit
GWP	: Global Warming Potential
LCA	: Life Cycle Assessment
MCDM	: Multi Criteria Decision Making
NRC	: Noise Reduction Coefficient
P	: Porosity
PES	: Polyester
PM	: Particle Matters
SAC	: Sound Absorption Coefficient
SAM	: Sound Absorption Materials
SAW	: Simple Additive Weighting
SEM	: Scanning Electron Microscopy
SMART	: Simple Multi Attribute Rating Technique
TC	: Thermal Conductivity
TLF	: Tea Leaf Fiber
TOPSIS	: Technique for Order of Preference by Similarity to Ideal Solution

TW : Tea Waste
VOC : Volatile Organic Compounds
W : Water Consumption
WHO : World Health Organization



SYMBOLS

<i>A-</i>	: Positive ideal solution
<i>A+</i>	: Negative ideal solution
<i>Ci</i>	: The relative closeness to the ideal solution
<i>dB</i>	: Decibels
<i>f</i>	: Frequency
<i>Hz</i>	: Hertz
<i>kg</i>	: Kilograms
<i>kw</i>	: Kilo watts
<i>L</i>	: Liter
<i>m</i>	: Meter
<i>Pa</i>	: Pascal
<i>Ri</i>	: Ranking
<i>RT</i>	: Reverberation Time
<i>W</i>	: Weight
<i>X</i>	: Decision matrix
α	: Sound absorption coefficient
ρ	: Density
λ	: Sound wave length
ν	: Velocity of sound



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COMPARATIVE EVALUATION OF SUSTAINABLE SOUND ABSORPTION MATERIALS USING TOPSIS METHOD

SUMMARY

In the last decades, the importance of treating noise pollution in indoor buildings has increased, especially after understanding the health problem that noise can cause to human health and other organisms. The commonly used ways of treating noise pollution may start with the design of the space itself, selecting the building materials and finally the use of acoustic panels. Acoustic panels are basically panels made of materials that provide good acoustic qualities such as sound absorption, which may be described by the parameter, namely sound absorption capacity (SAC). The traditional and commercially available materials widely used in acoustic panel production are for instance synthetic fibers, such as; mineral wools, fiberglass, polyethylene, etc. These materials, despite their good sound absorption efficiency, have a negative environmental impact due to high energy demand required for manufacturing, the emissions resulting from transportation of the raw materials over long distances, even between countries which plays a significant role in carbon dioxide emissions to the air, and finally the usage of toxic chemicals, i.e., as binders, etc., that can cause allergenic problems to the human beings. As a result, these materials may not be described as sustainable material alternatives for acoustic panel production and for noise pollution reduction.

On the other hand, natural sound absorbing materials are produced from renewable source, do not contain toxins and they do not cause harm to the health. Nowadays, many researchers investigated the useability of natural materials in the acoustic panel production industry such as bamboo, coconuts, luffa and kenaf fibers. From a sustainability point of view, it becomes important to use local resources as raw materials in the production of sound absorbing acoustic panels and take into account the availability of those materials in the area of production.

This study intends to determine, evaluate and compare new, local and sustainable sound absorptive materials for their possible use in indoors acoustic panel production. The materials selected for this study are recycled textile, tea waste and corn husk. Recycled textile is proposed for its high availability in Turkey since textile industry is very active in the region and tons of pre-consumer (production offcuts) and post-consumer (used clothes) textile wastes are sent to landfill every year. Using recycled textile in producing acoustic panels may not only assist with providing an alternative solution to remediating the noise pollution problem but may also contribute to reducing solid wastes. Additionally, its porous structure is a great quality for the aim of sound absorption. Tea waste and corn husk are proposed as food wastes and agricultural wastes, respectively, as raw materials for acoustic panel production. In addition to being locally available, they possess promising acoustics characteristic that make them promising candidates for the sustainable acoustic panel production industry. Additionally, there is a fourth material, namely fiberglass, that has been selected for the aim of comparison of the herein proposed new, sustainable raw material

alternatives with the commercially available conventional materials widely used in acoustic panel production.

To select the best sound absorbing material among different alternatives, it is important to use a decision-making tool for the aim of a comprehensive comparison. Such tools help with making the decision based on a number of selected criteria, which might be chosen by the users in accordance with their preference.

Within the framework of this study, TOPSIS was selected as the decision-making tool in order to choose the best sound absorbing material among the studied alternatives. With this tool, materials can be compared to each other based on criteria and weights for each criterion. The weight can be anywhere between 0-100. For this study, there are four main criteria with several sub-criteria, namely: Technical properties of raw materials including density and porosity, as well as technical properties of the acoustic panel which include air flow resistivity, thickness, sound absorption capacity (SAC), noise reduction coefficient and thermal conductivity. Then, the environmental aspects including: water consumption, chemical usage, global warming potential and biodegradability of the prepared raw material. Lastly, the cost aspect which includes cost of preparing the raw material, cost of transportation, and cost of manufacturing the panel. Using TOPSIS, all four materials, namely the herein proposed three wastes and the synthetic commercial material, were compared with each other at the same time and in accordance with the selected criteria. Different scenarios were created to evaluate the raw materials and to determine the best option for the purpose of sound absorbing among the proposed alternatives.

The TOPSIS results showed that corn husk is the best alternative when considering the technical aspects, while tea waste scored as the best option with regard to both the environmental and the cost aspects. On the other hand, the first ranking material with the highest overall scores in all inspected criteria is the recycled textile, suggesting it as the best sustainable sound absorbing material among the studied ones, for possible use in acoustic panel production as an alternative to the widely used synthetic materials. Finally, producing and testing composites of natural materials comprised of corn husk and tea wastes, might provide further insights in evaluating and optimizing their possible use as sound absorbing sustainable materials and might be recommended for future studies for sustainable acoustic panel production.

SÜRDÜRÜLEBİLİR SES EMİŞİ MALZEMELERİNİN TOPSIS YÖNTEMİ İLE KARŞILAŞTIRMALI DEĞERLENDİRİLMESİ

ÖZET

Gürültü kirliliğinin insan sağlığı ve diğer canlılar üzerindeki olumsuz etkilerinin anlaşılması ile, kapalı alanlarda, iç mekanlarda gürültü kirliliğinin önlenmesinin/azaltımının önemi artmıştır. Mekanın uygun tasarımı, yapı malzemelerinin amaca uygun seçimi ve akustik panellerin kullanımı, gürültü kirliliğini önlemek/azaltmak için yaygın olarak uygulanmakta olan yaklaşımlardır. Akustik paneller temel olarak ses emici malzemelerden yapılır. Ses emme kapasitesi (SAC) bu bağlamda önemli bir gösterge parametredir. Geleneksel ve ticarileşmiş akustik panel üretiminde mineral yünler, cam elyafı gibi sentetik elyaflar, polietilen, vb. sentetik malzemeler kullanılmaktadır. Bu malzemeler, yüksek ses emme özelliklerine karşılık, üretim için gerekli olan yüksek enerji ihtiyacı, karbon ayak-izinde önemli rol oynayan hammaddelerin uzun mesafelerde, hatta ülkeler arasında taşınmasından kaynaklanan karbondioksit emisyonları, alerjik sorunlara yol açabilecek bazı toksik kimyasalların üretimde kullanımı gibi nedenlerden ötürü olumsuz çevresel etkilere sahiptir. Sonuç olarak, bu malzemeler akustik panel üretimi ve gürültü kirliliği azaltımı için sürdürülebilir malzeme seçenekleri olarak tanımlanamazlar.

Doğal ses yutucu malzemeler ise yenilenebilir kaynaktan üretilir, toksin içermez ve sağlığa zararlı değildir. Son zamanlarda birçok araştırmacı bambu, hindistancevizi, kabak lifi (luffa) ve jüt (kenaf lifleri) gibi doğal malzemelerin akustik panel endüstrisinde kullanılabilirliğini araştırmaktadır. Sürdürülebilirlik ve döngüsel ekonomi açısından bakıldığında ses emici akustik panel üretiminde kullanılabilecek emici malzemelerin yerel kaynaklardan elde edilmesi ve bu malzemelerin üretim bölgesinde bulunabilirliği önem kazanmaktadır.

Bu çalışmada, iç-mekan akustik panel üretiminde kullanılabilecek yeni, yerel ve sürdürülebilir ses emici malzemelerin belirlenmesi, değerlendirilmesi ve karşılaştırılması amaçlanmıştır. Bu çalışma için seçilen malzemeler geri dönüştürülmüş tekstil atıkları, çay atıkları ve mısır kabuğu atıklarıdır. Türkiye’de tekstil endüstrisinin son derece aktif olmasına bağlı olarak üretim ve tüketim sonrasında yüksek miktarda tekstil atığı oluşmakta ve her yıl tonlarca son-kullanıcı-öncesi (üretim kırıntıları) ve son-kullanıcı-sonrası (kullanılmış giysiler, vb.) tekstil atığı katı atık depolama sahalarına gönderilmektedir. Bu nedenlerden ötürü, geri dönüştürülmüş tekstil atıkları çalışma kapsamında değerlendirilen malzemelerden biri olarak seçilmiştir. Bu bağlamda, geri dönüştürülmüş tekstil atıklarının akustik panel üretiminde kullanılması sadece gürültü kirliliğinin azaltımı için alternatif bir çözüm önerisi olmakla kalmayacak, aynı zamanda katı atıkların azaltılmasına da katkıda bulunacaktır. Ayrıca teknik özellikler açısından da gözenekli yapıları nedeniyle dönüştürülmüş tekstil atıklarının iyi ses emilimi özellikleri göstermeleri söz konusudur.

Çalışmada önerilen ve değerlendirilen doğal malzemeler olan çay atıkları ve mısır kabuğu ise sırasıyla gıda atıkları ve tarım atıkları olmaları ve yerel olarak bol miktarda bulunmaları nedenleriyle seçilmiştir. Bu doğal malzemeler olumlu akustik özellikler göstermekte, dolayısıyla sürdürülebilir akustik panel üretimi için ümit vadeden doğal malzeme seçenekleri olarak önerilmektedir. Bu çalışmada önerilen ve değerlendirilen yeni ve sürdürülebilir malzeme seçeneklerinin akustik panel üretim endüstrisinde yaygın kullanımı olan ticari konvansiyonel malzemeler ile karşılaştırmalı değerlendirmeleri için dördüncü malzeme olarak camyünü (fiberglas) çalışmaya dahil edilmiştir.

Bu çalışmada seçilen malzemelerin karşılaştırmalı değerlendirmesi için belirlenmiş kriterlere ve günlük yaşamda yaygın olan sorunlara göre en uygun çözümü belirleme süreci anlamına gelen Çok Kriterli Karar Verme (MCDM) yaklaşımı benimsenmiştir. En iyi alternatifi seçmek için tek tek veya kombinasyon halinde kullanılabilecek pek çok araç bulunmaktadır. MCDM, değerlendirilmekte olan alternatifler arasında seçim veya sıralama yapmak için birden fazla kriter (veya hedef) birlikte düşünüldüğünde en iyi kararı vermeyi olanaklı kılmaktadır.

Bu çalışma çerçevesinde, belirlenen alternatifler arasından en iyi ses emici malzemeyi seçmek için karar verme aracı olarak MCDM problemlerini çözmek için kullanılan popüler bir yöntem olan TOPSIS seçilmiştir. Kullanımı pratik olan bu yöntemin farklı alanlarda yaygın kullanımını sağlayan çeşitli avantajları vardır. Bir tür “sıralı tartım” yöntemi olan TOPSIS in-siliko derecelendirme, ideal çözüm ve negatif-ideal çözüm yapılandırmasına dayanmakta olup her bir alternatifin ideal çözüme ve negatif-ideal çözüme olan uzaklığını tanımlamayı amaçlar. Bu araç ile malzemeler her bir ana-kriter için alt-kriterler ve ağırlıklar belirlenerek ve her bir kriter için toplam 100 puanlık bir ağırlık ile kriterler ve ağırlıklar bazında birbirleriyle karşılaştırılabilir. Ağırlıklar %0 ila %100 arasında değişebilir. Çevresel etkinin değerlendirilmesi öncelik taşımakta ise, önerilen malzemenin çevresel davranışı hakkında daha iyi bir fikir vermesi için tüm kategoriler arasında en yüksek ağırlık bu kategoriye atanabilir. Benzer şekilde, bu kategori içindeki öncelikli parametrenin küresel ısınma potansiyeli (GWP) olması durumunda bu alt-kriter en yüksek ağırlığa sahip olabilir.

Bu çalışma kapsamında dört ana-kriter ve bunların altında çeşitli alt-kriterler belirlenmiş ve kullanılmıştır. Bunlar şu şekilde sıralanabilir: (i) hammaddenin teknik özellikleri (yoğunluk ve gözeneklilik), (ii) akustik panelin teknik özellikleri (hava akışı direnci, panel kalınlığı, ses emme kapasitesi (SAC), gürültü azaltma katsayısı ve termal iletkenlik), (iii) çevresel boyut (su tüketimi, kimyasal kullanımı, küresel ısınma potansiyeli ve biyobozunurluk), (iv) maliyet (hammadde hazırlama maliyeti, hammadde nakliye maliyeti ve panel üretim maliyeti). Çalışmada, malzemenin ticari olarak mevcut olanlarla karşılaştırılabilir teknik özelliklere sahip olması önem taşıdığından, teknik özellikler kategorisi 45 puanla ile ağırlıklandırılmıştır. Çalışmanın ana odağı sentetik elyafların yerini alacak sürdürülebilir malzemelerin belirlenmesi olduğundan, çevresel etki kategorisi de benzer bir ağırlıkla ve 40 puan ile ağırlıklandırılmıştır. Son olarak, bu çalışmada odak noktalarından biri olmamakla birlikte, maliyet yönü de dikkate alınmış ve toplam 15 puanla ağırlıklandırılmıştır.

Çalışmada önerilen üç atık malzeme ve piyasada kullanılmakta olan sentetik ticari malzemeden oluşan dört malzemenin tamamı TOPSIS kullanılarak aynı anda ve belirlenen kriterler doğrultusunda karşılaştırmalı olarak değerlendirilmiştir. Bu amaçla çeşitli senaryolar oluşturulmuş ve önerilen malzeme seçenekleri arasından en iyi ses emici malzemenin belirlenmesi için kullanılmıştır. Her senaryo, hammaddelerin belirli bir yerden toplanmasıyla başlar. Geri dönüştürülmüş tekstil için, taşımadan kaynaklanabilecek karbondioksit emisyonlarını en aza indirmek için tekstil atıklarının akustik panel üretim firmasına yakın bir fabrikadan toplandığı varsayılmıştır. Çay atıkları için hammaddenin (çay atıkları) İstanbul'daki kafe ve restoranlardan toplandığı kabulü yapılmıştır. Mısır kabuğu atıklarının ise İstanbul yakınlarındaki bir köydeki mısır tarlasından toplandığı varsayılmıştır. Tüm bu lokasyonlar özenle seçilmiş ve buna göre hesaplamalar yapılmıştır. Alternatifler, diğer bir deyişle seçilen ses yutucu malzemeler (SAM) arasında karşılaştırma yapılabilmesi için TOPSIS'e girdi olarak verilmesi gereken verilerin bir kısmı literatürde mevcut olan ve çeşitli araştırmacılar tarafından daha önce yapılmış çalışmalardan derlenmiş, bir kısmı ise bu çalışma kapsamındaki uygulamalar ve hesaplamalarla oluşturulmuştur. Literatürden elde edilen bilgiler ile bu çalışmada üretilen verilerin entegre edilerek TOPSIS-MCDM yönteminde kullanılması ile güvenilir bir "bilgiye dayalı karar verme" modeli ortaya konduğu düşünülmüştür. MCDM-TOPSIS uygulamalarına ek olarak, bu çalışmada incelenen SAM alternatiflerinin karşılaştırmalı değerlendirilmesi için basit/temel bir LCA (yaşam döngüsü analizi) çalışması da yapılmıştır. LCA sürecini ve hesaplamalarını basit tutmak için, "beşikten-kapıya" yaklaşımı benimsenmiştir. Bu yaklaşımda hammaddenin üretilmesi "beşik", nihai ürün olan akustik panellerin üretim sahasından ayrılması ise "kapı" olarak tanımlanmıştır. Dolayısıyla, üretilen akustik panellerin perakendecilere, ardından son kullanıcılara dağıtımı, tüketici kullanımı, kullanım sonrası bertarafı vb. gibi "kapı"dan sonraki aşamalar/süreçler bu çalışmanın kapsamı dışında bırakılmıştır.

TOPSIS sonuçlarına göre, teknik özellikler açısından mısır kabuğu en iyisi ses emici malzeme seçeneği olarak ortaya çıkmaktadır. Hem çevresel etkiler hem de maliyet açısından ise çay atıkları en iyi sonuçları vermekle birlikte, bu malzemenin teknik performansı göreceli düşük bulunmuştur. Değerlendirilen kriterlerin tamamı göz önüne alındığında ise en yüksek toplam puana sahip malzemenin geri dönüştürülmüş tekstil atıkları olduğu belirlenmiştir. Buradan yola çıkarak, akustik panel üretiminde kullanılabilecek sürdürülebilir yeni malzeme alternatifi olarak bu çalışmada incelenenler arasından en iyi seçeneğin geri dönüştürülmüş tekstil atıkları olduğu ve bunların akustik panel üretiminde yaygın olarak kullanılmakta olan sentetik materyallere sürdürülebilir bir alternatif olabileceği sonucuna varılmıştır.

Son olarak, sürdürülebilir akustik panel üretimi için gelecekte gerçekleştirilecek yeni çalışmalar bağlamında, örneğin mısır kabuğu ve çay atıklarından oluşan doğal malzeme kompozitlerinin üretilmesi ve test edilmesi, bunların ses emici sürdürülebilir malzemeler olarak muhtemel kullanımlarının değerlendirilmesi ve optimize edilmesi önerilebilir. Bunun yanı sıra, bu çalışmada sunulan ve elde edilen veriler, AHP ve SAW gibi farklı MCDM araçları kullanılarak da analiz edilebilir. Gelecekte yapılacak çalışmalarda, hurma ağacı, jüt, kahve atıkları, pirinç kabuğu, çotanak ve fındık kabuğu, vb. doğal malzemelerin ve/veya atıkların akustik özellikler, çevresel etkiler ve maliyet unsurları açısından değerlendirmeleri yapılabilir ve bunların sürdürülebilir akustik panel üretimi için olası kullanımları araştırılabilir.



1. INTRODUCTION

Pollution was part of human's life ever since groups of people first gathered and settled in any one place. In reality, ancient human settlements are frequently recognized by the waste they left in their location. At that time pollution was not considered as a serious problem; as long as there was enough resources and space available for each individual or group. By the development of settlements and the increasing number of people, pollution became a problem and it has stayed one ever since. Pollution of all types can have harmful effects on the environment and wildlife and often affects human health and well-being. It is the results of introduction of contaminants to the natural environment, which cause adverse changes. Contaminants might be naturally occurring or man-made substances. Pollution might take different forms such as a chemical substances or energy, like noise, light or heat. The major kinds of pollution, usually classified by the environment, are air pollution, water pollution, and land pollution.

On the other hand, modern society is also concerned about specific types of pollutants, these are other kind of pollution that started to get the global attention recently, for example; light pollution, thermal pollution, visual pollution, electric pollution and noise pollution and the latter the focus of this thesis study

Noise pollution can be simply defined as unwanted sound (Fink, 2019). To provide a comfortable environment, unwanted sounds must be reduced. One of the ways to reduce noise is by using acoustic panels. When the sound hits a wall, it can either be transmitted to the other side of the room, or reflected to the room again or absorbed by the wall itself. The aim of having acoustic panels in any built environment is to absorb the sound and preventing it from travelling further. This can be done with any material that possess this absorbing capacity. The commonly used materials are made from synthetic fiber which might have a negative impact for both of the environment and human health.

This thesis study will investigate and evaluate the sustainable alternatives absorbing materials and compare them using a multi criteria decision tool named TOPSIS. This

tool will allow the comparison to be made using mathematical equations and evaluate the material based on different criteria at the same time and in the end, give the result of the best sound absorbing material. Three materials were considered for this thesis study namely; recycled textile, tea waste and corn husk.

1.1 Purpose of Thesis

The purpose of this thesis is to develop a comparison between 3 sustainable sound absorptive materials made of natural and recycled fibers, from local sources and are energy efficient, harmless to health and aesthetically preferred. Within the framework of this study, TOPSIS, which is a popular method being utilized for solving Multi-Criteria Decision-Making (MCDM) problems, was selected as the decision-making tool in order to choose the best sound absorbing material among the studied alternatives.

1.2 Objectives of Thesis

The objectives of the thesis are;

- To study the technical properties of the materials and explore their acoustic and non-acoustic (physical) characteristics,
- understand their environmental impact and global warming potential using Life Cycle Assessment tool.
- Conduct a cost analysis study for producing acoustic panels from the proposed materials covering the cost of; raw material preparation, transportation and manufacturing.
- Make a comparison using one of the multi criteria decisions tools and selecting the best sustainable sound absorption material according to the selected technical, environmental and economic aspects.

2. LITERATURE REVIEW

2.1 Noise Pollution

Noise is any unwanted sound that disburse to human beings and other livings. Sound is measured in decibels (dB). Sounds in environment vary in matter of their level, from swishing of leaves (20-30 dB) to a police serin (120 decibels) to the jet engine (120-140 dB). Sounds in the level of 85 decibels or higher are considered as noise and can harm a person's ears. Figure 2.1 shows different levels of sounds in the environment (Hansen, 2009).



Figure 2.1 : Sound levels produced by different sources (Hansen, 2009).

To provide a comfortable environment, unwanted sounds must be avoided. It can be reduced either from the main resource, in the path or at the receiver. When the noise source has a high reverberation time (RT) and echoes, sound absorptive materials are applied. **Reverberation** is the resoluteness of sound in a defined space after the original sound is generated. **Echo** is the repetition of the original sound caused by distinct reflections of long delay. Sound absorption treatment is an effective noise control solution for echo and reverberation in spaces (Long, 2006). Environmental noise can be mostly described by several simple measures. All measures consider; frequency content of the sounds, overall sound pressure levels and variation of these levels with time.

2.1.1 Noise effect on human health

We use sounds in our everyday life for communication, to enjoy music, to pay attention for warnings... etc., on the other hand, noise has several of problems for human health. Some examples are summarized below (Bhave and Sayed, 2015):

1. **Hearing Problems:** There are certain ranges of sound that our ears can take in without being harmed (Figure 2.1). Any unwanted sound that human's ears are not made to filter is considered problematic to the body. Constant exposure to loud noises may result in damaging the eardrums and even losing the sense of hearing.
2. **Health Issues:** Being exposed to noise pollution continuously while working in construction sites, offices or home can cause psychological issues such as stress, nausea, anxiety, headache and instability.
3. **Sleeping Disturbance:** When sleeping in places near to loud noise sources such as near an airport, highways, construction sites... etc. The sleeping pattern might be affected, this will lead to uncomfortable or irritation sleeping conditions that affect the general performance of a person in both home and office.
4. **Cardiovascular and Physiological Effects:** Acute noise exposures result in temporary changes such as increasing blood pressure, increasing heart rate and vasoconstriction because it activates the autonomic and hormonal systems.

Figure 2.2 shows the noise effect on human health in relation to the number of people affected.

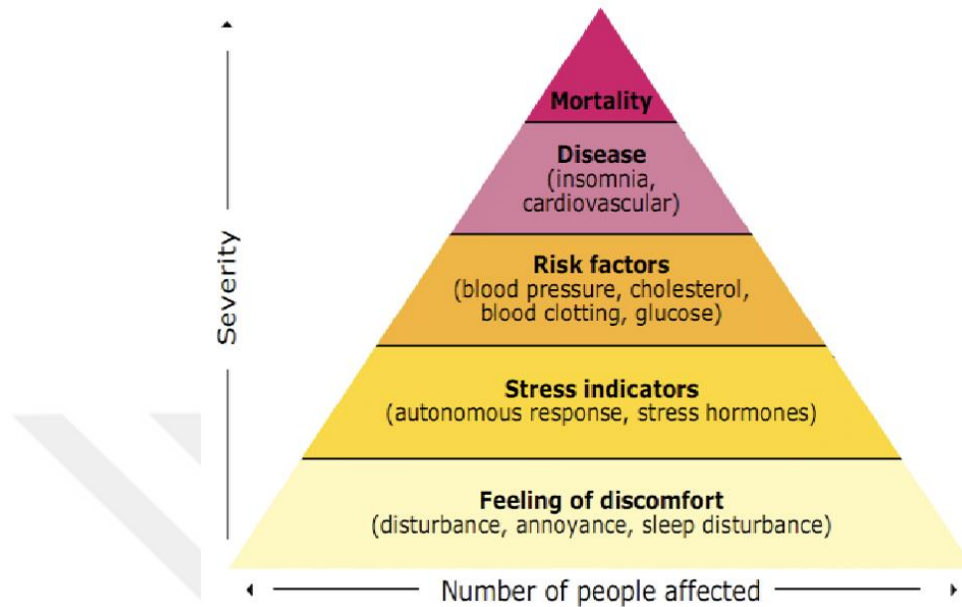


Figure 2.2 : Noise effect on human health (Milford et al., 2012).

2.2 Type of Noise

There are two types of noises according to their sources: external noise and internal noise;

a. External/Outdoor Noise

When the source of the noise is outside the space and external to the receiver, then it is called external noise and includes atmospheric noise and man-made or industrial noise. Some examples are; noise from aircrafts, car-traffic, construction sites, industrial production sites, etc.

b. Indoor Noise

The term is for the sounds generated in the inner space by any of the active or passive devices found in receivers. The sources are everything with sound levels above the comfort hearing (85 dB and higher) level in indoor spaces (Hansen, 2009).

There are many steps to consider when reducing the noise pollution; design of the space itself, the efficiency of the used building materials and their sound absorption capacity and also the use of finishing with acoustic characteristics.

2.3 Acoustic Concept

Two main parameters to be considered when working with acoustics are frequency (f) and wavelength (λ). The **frequency** of the sound is defined as the pressure variation per second. The unit of frequency is Hertz corresponding to 1 cycle per second and abbreviated as (Hz). The pressure variations should occur at least 20 times per second for the sound to be heard. The human ear can detect sounds ranged from approximately 20 Hz to 20 kHz. However, the higher limit tends to decrease with aging. The sound waves need a medium to travel through and normally this medium is air. The speed of sound at room temperature is 344 m/s. Another characteristic of sound is the **wavelength**, which is defined as the distance from one peak to the next in case of a sinusoidal sound pressure variation. The wavelength (λ) can be calculated from the speed (v) and frequency (f) of the sound as given below in equation (2.1):

$$\lambda = v/f \quad (2.1)$$

Where λ = wavelength (m)

v = velocity (m/s)

f = frequency (Hz)

This equation shows that there is a reverse relation between wavelength and frequency: as the frequency increases the wavelength decreases, for example, the wavelength at 10 kHz is as small as 3.44 cm (Katalin, 2018).

2.3.1 Reflection, Transmission and Absorption of Sound

When a sound wave faces a medium, the energy of the wave is absorbed within the material, reflected and transmitted through the material (Long, 2006). The mechanism of transmission and reflection of sound is affected by the angle of the incident sound wave and the boundary conditions. Figure 2.3 illustrates the interaction of the sound wave with a wall, and equation (2.2) shows the relation between the reflected, transmitted and absorbed sound energy.

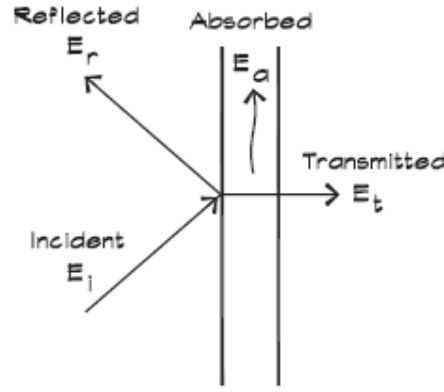


Figure 2.3 : Sound wave hitting a surface (Long, 2006).

$$E_i = E_a + E_t + E_r \quad (2.2)$$

The way that sound absorbers work is by transforming the sound energy into different types of energy like mechanical, thermal or deformation energy. The acoustic absorption thus, is an energy dissipation phenomenon.

The acoustic (or sound) absorption coefficient; α (SAC); of a surface is defined, as given in equation (2.3) and (2.4), as the relation between the acoustic energy that can absorb (E_a) and the incident energy that affects it (E_i), and it is dimensionless:

$$\alpha = \frac{E_a}{E_i} \quad (2.3)$$

$$E_a = \alpha E_i \quad (2.4)$$

When the material is stiff such as wood or metal, then it is described as “reflective surface”, and when it is porous like glass, wool or cotton, then it absorbs the sound. There are some factors affecting the absorption, transmission and the reflection on material surface, such as the **density, thickness, porosity and air flow resistivity**.

Density: Density is an important parameter for performance of acoustic panels; the higher the density of a panel, the better the sound absorption performance at middle and high frequencies, while absorption is shifted to lower frequencies with more porous and less dense structures (Nandanwar et al., 2017).

Thickness: Increasing the thickness of an acoustic panel is effective for better absorption at low frequencies, while it does not have a significant impact at high

frequencies, however thinner acoustic panels are aesthetically preferred and also, they are easier to install. (Hua and Enhui, 2017).

Porosity: it can be defined as the ratio of the voids' volume in a porous material to its total volume. Sound absorption capacity is directly proportional to porosity; increasing the porosity leads to a higher sound absorption (Umnova et al., 2005)

Air Flow Resistance: the resistance of the material to the air entering its inner structure, thus, it is named as airflow resistance. It has a proportional relation to the sound absorption capacity. (Seddeq, 2009).

2.3.2 Sound absorbing materials

Sound absorbers are materials which absorb the sound and convert it to a different sort of energy, mostly thermal energy. To measure the sound absorption of a material, there are 2 important factors to consider;

1. Sound absorption coefficient (SAC) and it is ranked from 0 to 1. Figure 2.4 shows that all materials have sound absorbing properties at some level, according to international standards, i.e., BS EN ISO 11654, class A range (0.9-1) has the best sound absorption capacity, while class E (0.15-0.25) has the lowest sound absorption potential. However, those with lower absorption capacity are described as reflective materials rather than absorptive. (Paroc, 2013)

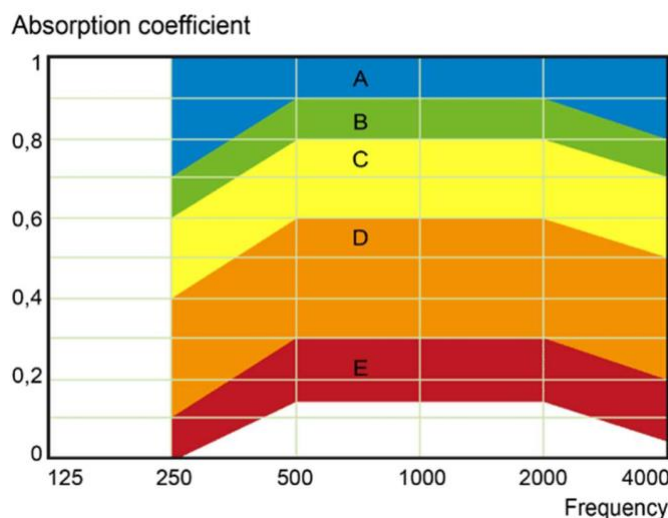


Figure 2.4 : Sound absorption classes ranging from class E (the lowest) until class A (the highest) according to BS EN ISO 11654 (Paroc, 2013).

When the sound absorption coefficient is higher than 0.2, then the material is called sound absorbing material (Rindel et al., 2016).

2. The second factor is the frequency. frequencies can be classified in 3 ranges; low, mid and high. Low ranges are >250 Hz, mid ranges are (250-2000) Hz and high ranges are <2000 Hz.

For the purpose of indoor sound absorbing, the ranges of interest are mid-high frequencies (Paroc, 2013).

Sound absorptive materials can be classified in four categories; porous/fibrous materials, membrane (resonant) absorbers, Helmholtz resonators (absorbers), and perforated absorbers. The focus of this thesis study will be on the first type (porous materials) thus, it will be further explained in the upcoming section.

2.3.2.1 Porous or fibrous sound absorbers:

Porous materials are elastic and they have fine channels in their structure that interconnect with each other and absorb the acoustic energy by two mechanisms: (i) in the soft materials, absorption happens by energy deformation when the sound wave hits the acoustic panels, while (ii) in the porous materials, the sound energy gets lost because of the friction that occurs on the edges, hence those absorb sound due to vibration of air present within the pores of the material.

The smaller the length of the sound wave in relation to the dimensions of the irregular edges of the absorber's surfaces, the better the performance will be. Therefore, the performance improves with increasing frequency, and generally it is considered good at most conversational frequencies; i.e., at 250-2000 Hz.

For the porous materials to perform efficiently, air channels must not be clogged, otherwise absorption capacity decreases. When acoustic panels made of porous materials are installed in a noise-polluted environment, their efficiency may degrade if the pores get saturated with debris. In order to protect them, sometimes they are covered with fabric or grid, even though this might affect the overall performances of the panels and the active surface is wasted. Therefore, it is important not to cover them with rigid materials which hide the surface entirely, otherwise the porous/fibrous surface will not be available for sound absorption.

For efficiency, thickness of an absorbing structure is very important: the higher the thickness, the greater the potential for the incident wave to lose energy. As the thickness of a panel increases, the panel's optimum performance shifts to lower frequencies. That is because wavelengths at low frequencies are extremely long and thus thickness of the panel becomes comparable with the wavelength (Everest and Pohlmann, 2009).

Currently, the most commonly used fibrous materials for acoustic panel production are those with synthetic fibers, such as rock wool and glass wool (Figure 2.5). Those are considered as excellent absorbers; however, their fibers are produced from synthetic polymers and minerals and their production require high energy. Also, they have a significant carbon footprint (Quintana-Gallardo et al., 2020). This altogether, hamper their use as sustainable materials in noise pollution reduction. Additionally, they contain petrochemicals which cause damage to the ecosystem and human health. On the contrary, absorptive materials comprised of natural fibers like cotton, cellulose, reed or flax, do not contain hazardous chemicals in their raw materials' structure. Therefore, do not pose hazard to the indoor air quality. In addition, some of those materials are more economical since they are natural products and their treatment requires less cost and less energy demand. However, they might be at risk of fungal attracts and dampness damage (Desarnaulds, 2005). Other examples of natural absorptive materials include kenaf, hemp and jute (Figure 2.6).

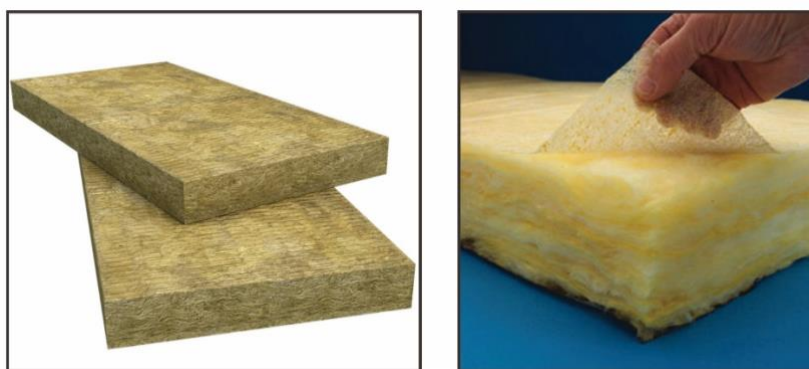


Figure 2.5 : Examples of porous absorbing materials made from synthetic fibers: rock wool (left image) and glass wool(right image)



Figure 2.6 : Examples of porous absorbing materials made from natural fibers: hemp (left image) and kenaf (right image).

2.3.3 Acoustic measurement methods

The main methods to measure the absorption coefficient of sound absorbing materials are (i) “Impedance Tube Measurement Method” (ISO-10534-1:2001), and (ii) “Reverberant chamber/room method (ISO-354-2003)”.

The impedance tube method is used for testing small samples, whereas the reverberant chamber method is used for testing large samples.

2.3.3.1 Impedence tube measurement methods

Impedance tube method is a widely used sound absorption measurement method. It depends on the frequency absorption properties of the tested material. In this technique, the sample is inserted in the tube and a loud speaker at the other end of the tube produces a quantified sound. The sound travels along the rigid tube until it reaches the tested material. The material absorbs part of the sound and reflects the rest of the sound energy. There are 2 microphones in the tube facing the sample, these microphones collect the sound’s minimum and maximum pressure. Change in the sound pressure indicates the sound absorption of the material. Illustration of an impedance tube is shown in Figure 2.7.

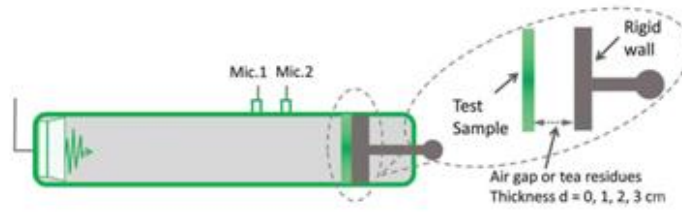


Figure 2.7 : Illustration of the impedance tube (Tang et al., 2020).

The advantage of the Impedance tube method is that the test setup is more practical due to its small dimensions. The disadvantages are that only sound at normal incidence is measured and there are uncertainties when measuring heterogeneous materials like samples taken from different regions of a large sample (Oldham et al., 2011).

2.3.3.2 Reverberation chamber method

Reverberation chamber is a special acoustic testing room used to measure the sound absorption coefficient of a material in a way similar to its behavior in reality. Waves with different frequencies, are directed towards the material surface from several directions with the same prospect. The SAC is measured by the change of reverberation time. According to ISO 354-2003, there are specification for the reverberation room dimensions, temperature and humidity. The volume of the chamber must be between 150- 500 m³. The temperature at least 15 °C, while the humidity in the range of 30%-90%. For the sample, it should be between 10 m² and 12 m².

This method has the advantage of being more realistic than the impedance tube and also providing the possibility of measuring the SAC for any material. However, it has disadvantages of the necessity to use a large sample and the inaccurate results that happen due to the edge diffraction (Kuttruff, 2009). Reverberation room picture is given in Figure 2.8



Figure 2.8 : The reverberation room used for measuring the sound absorption of a sample using sound source, the reflectors and microphones (Kuttruff, 2009).

2.4 Sounds in Buildings

Building acoustics is one of the important criterium to design comfortable and healthy living environment. There are two types of sound in buildings; (i) sounds generated outside, travel through air into the boundaries of the room. and (ii) sounds generated inside the building originating from loud speeches, instruments, and machines.

When a room has poor acoustic qualities such as low sound absorption, indoor sound pressure might gradually increase. To avoid this issue, acoustic panels are used. Acoustic panels are employed in two main ways; as **sound proofing** structures to reduce outdoor noise, and as **sound absorbing** structures to decrease noise that is generated inside. They can be installed as part of ceilings, walls, or sometimes floors (Askun et al., 2018). These structures are important installations for reducing noise pollution so it will not disturb the inner environment and does not travel further.

2.4.1 Traditional sound absorbing materials

Materials produced from synthetic fibers, such as glass wool and minerals are widely implemented for sound absorption purposes, because of their efficiency and affordability.

The European building insulation market is estimated to be consist of (Schmidt et Al., 2016)

- mineral wool (glass): 27%
- mineral wool (stone): 30%
- foam plastics: 40%
- other materials: 3%.

These materials, can have a harmful effect on human health if their fibers are inhaled, they can cause allergies and skin irritation. Therefore, these materials shall be adequately over laid if directly exposed to the air. Additionally, they have a negative impact on the environment due to toxic chemical usage, high energy demand and virgin resources depletion. (Asdrubali, F. 2015)

In the recent decades, natural materials start to be more frequently used as a valid alternative to the traditional synthetic fibers because they have a lower negative impact on the environment (Del Rey et al., 2017). There are many direct and indirect benefits of using natural materials contributing to their sustainability:

- they have no/low toxicity,
- they are recyclable,
- they indirectly help reduce consumption of synthetic alternatives which require additional energy in production phase (Turan, 2015).

On the other hand, disadvantage of using natural fibers is their low resistance to fire and fungal attacks when compared to conventional panels made off, e.g., mineral wool.

The production energy consumption for some of the natural and synthetic materials can be seen in Figure 2.9. The natural materials are marked in green color, while the synthetic is marked in red and blue.

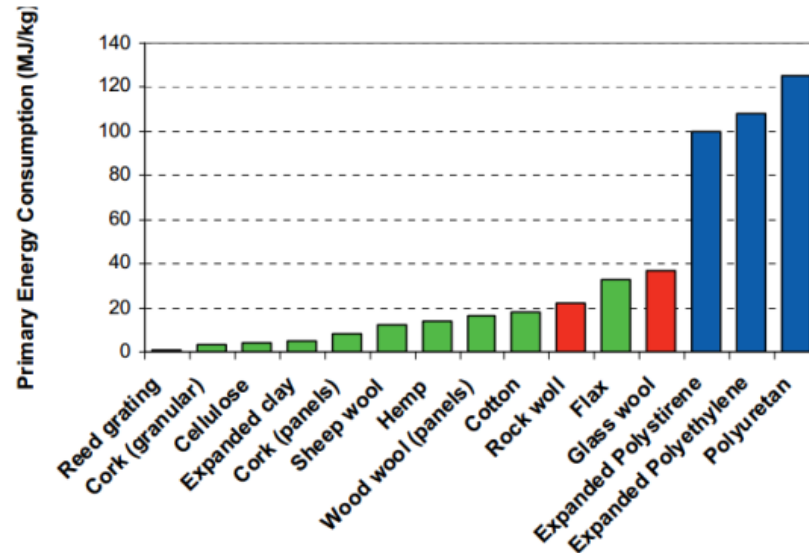


Figure 2.9 : Energy consumption chart for different natural and synthetic sound absorbing materials (Secchi, 2005).

As apparent from the figure, glass wool (synthetic material) has a lower production energy consumption compared to polystyrene, polyethylene and polyuretan. While the natural absorbers, such as reed, cellulose or hemp have much less energy consumption compared to glass wool. Therefore, a further investigation is needed to better explore the potentials of the sustainable sound absorption materials.

2.4.2 Sustainable sound absorption materials

According to the definition of sustainability, a product can be considered sustainable if its production enables the resources from which it was made to continue to be available for future generations. A sustainable product can thus be created repeatedly without generating negative environmental effects, without causing waste products or pollution, and without compromising the wellbeing of workers or communities. Sustainable materials for noise pollution control can be divided into three major categories; recycled materials, natural materials and mixed and/or composited materials (Asdrubali et al., 2012).

A wide range of natural fibers are available to be used for acoustic applications, including commercially available ones and the sustainable alternatives. The commercially available natural fibers are those present in the market in the form of kenaf, coconut, hemp and wood fibers. On the other hand, the sustainable alternatives are different from the commercial ones in the following aspects:

- Sustainable natural fibers are less pre-treated/processed and that is why they are better alternatives in terms of energy savings and sustainability,
- They are often offered/present locally, hence reducing the energy and cost of transportation.

In recent years, several researchers have focused on the use of natural or recycled sustainable materials in acoustic panel production. For instance, in their study Maderuelo-Sanz et al. (2017) focused on specific models to predict sound absorption properties of new sound absorbers made from recycled tire wastes to solve the problem of accumulating waste coming from disposed tires and to reuse those wastes as raw material for acoustic panel production instead of depleting the virgin resources. Koruk and Genc (2015) assessed the acoustic properties of luffa fiber and found that a sample of 12mm thickness has a sound absorption coefficient of 0.76. While Putra et al. (2018) studied the pineapple leaf fiber and concluded that it has a sound absorption coefficient in the range of 0.9-1 which is comparable with mineral wool and polyurethane foam. Raj et al. (2020) studied the fiber on Nettle plant and found that 56 mm thickness of nonwoven nettle fiber showed an optimum sound absorption value of 1. Another recent study by Samaei et al. (2020) stated that using 6% concentration of NaOH improved the sound absorption of kenaf fiber, compared to that of untreated kenaf. The list can go on with many other sustainable acoustic panels which were studied in the recent years.

Since the local materials have an advantage of reducing the carbon footprint that comes from shipping and transportation of the raw material, the focus of this thesis study was on locally available natural materials with promising acoustic characteristics. These Three materials are;

1. Recycled textile; Turkey is one of the largest textiles and clothing producing countries in the world. It ranks as the 3rd largest supplier to the EU and 6th most significant supplier in the world (Ersoz et al., 2021). Textile consumption has a massive growth worldwide, which makes it a large industry producing massive amounts of solid waste. The textile consumption is following the system of take-make-waste. In 2014, almost 80% of textile waste is going to landfill or incineration while only 20% is recycled. Different materials are used for the global production of textile; 60% synthetic fibers, 33% cotton and 7%

others (Wendin, 2016). Thus, the first material to be investigated for the purpose of sound absorbing will be recycled cotton from the textile industry.

2. Tea waste; Turkey, has a significant place in the global tea production agro-industry with a share of 3% and is among the world's largest producer countries. After China, India, Kenya, Sri Lanka and Vietnam, Turkey ranks at the 6th place in the world for tea production, according to the Food and Agriculture Organization (FAO, 2019). This makes tea waste an interesting, local and natural sound absorbing material to be investigated.
3. And lastly, corn husk waste; In Turkey, the annual production of corn is around 5.9 million tons in the recent years (Bolatova and Engindeniz, 2018). Demand for corn is growing due to the low cost of production, the high consumption and the possibility of processing it to various industries; oil, sweetener, glue and biofuels as ethanol. In the matter of global production, corn is the third important food crop after rice and wheat (Bolatova and Engindeniz, 2018). All this demand for corn products leave behind a lot of waste generated from the planting and harvesting the corn crope. Accordingly, corn husk waste is chosen as the third and last material for the case of this thesis study.

2.5 Studies on Sustainable Materials and their use and performance as sound absorbing acoustic panels

The following sub-sections summarize some of the studies available in the literature regarding the properties, use and performance of the three previously mentioned materials, forming the focal points of this thesis.

The intend was to screen previous work done by other researchers so to provide scientific information on the sound absorption capacity of those materials at focus. Also, to gather information on the methods for manufacturing and obtaining those materials with the main target of comparative assessment and evaluation of those materials to be used in production of sound absorbing acoustic panels, with regard to three main aspects, being performance, sustainability, and cost analysis.

2.5.1 Studies on the recycled textile as a sound absorption material

Recycled textile is found to have a great potential to be used in acoustic treatment: the porous fibrous structure can play a significant role in sound absorption, enabling use of recycled textile for producing acoustic panels. Cotton fiber has similar sound absorption properties as of some of the conventional alternatives, namely glass fiber and rock wool (Oldham et al., 2011). Moreover, a composite material comprised of cotton and polyester mixture was found to have a promising sound absorption capacity at mid and high frequencies (Kucuk and Korkmaz 2012). And this itself, will give an additional value to the textile waste.

In their study, Del Rey et al. (2015) focused on the sound absorption capacity of recycled cotton from a textile industry and they investigated the impact of

- (i) adding 2 different types of binders (polyester and phenolic), and
- (ii) mixing 2 different non-cotton fibers (polyester-PES- or bicomponent polyester-Bicopet-) with a fixed amount of recycled cotton fibers (75% of total fibers), on absorption performance of the final mixture.

Figure 2.10 shows a photograph of the studied recycled materials and a SEM (scanning electron microscopy) image showing the inner structure for one of the samples. The samples were addressed by these researchers as eco-materials because of their minimal environmental impact during the manufacturing phase and also due to their high recyclability potentials.

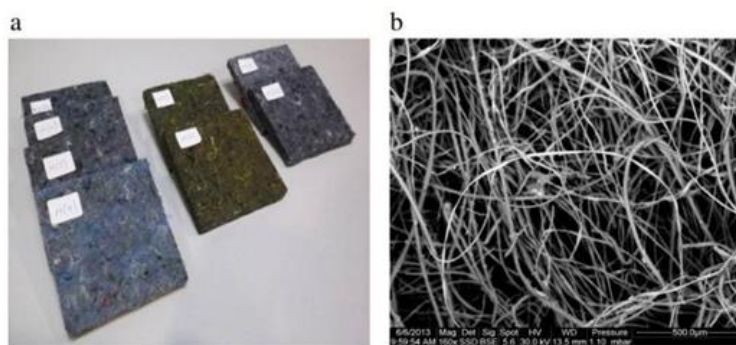


Figure 2.10 : (a) shows the recycled textile samples and (b) shows the SEM image with the internal structure (Del Rey et al., 2015).

Eight different samples were manufactured and tested for their SAC. All samples comprised of 80% of multiple fiber mixtures and 20% of binder of interest. In all samples, and aside from the binder, majority of the multi-fiber structures were recycled cotton and the remaining fibers were either PES or Bicopet. Material composition and some properties of the final samples are summarized in Table 2.1 The impedance tube method was used to determine the acoustic performance of the materials. SAC measurement results reported by the researchers are given in Figure 2.11.

Table 2.1 : Sample composition and properties produced from recycled cotton/textile wastes and binders (Del Rey et. al. 2015).

Sample	Components of Multi-Fibers*	Type of Binder	Fibers: Binder ratio	Density (kg/m ³)	Thickness (mm)
M1	75% CO–25% PES	Polyester	80%:20%	71	15
M2	75% CO–25% PES	Polyester	80%:20%	102	15
M3	75% CO–25% PES	Polyester	80%:20%	116	17
M4	75% CO–25% PES	Polyester	74%:26%	127	16
M5	75% CO–25% PES	Phenolic	74%:26%	71	14
M6	75% CO–25% PES	Phenolic	74%:26%	136	15
M10	75% CO–25% Bicopet	Polyester	80%:20%	57	15
M13	75% CO–25% Bicopet	Polyester	80%:20%	67	10

*CO: Cotton, PES: Polyester, Bicopet: Bicomponent Polyester Fiber

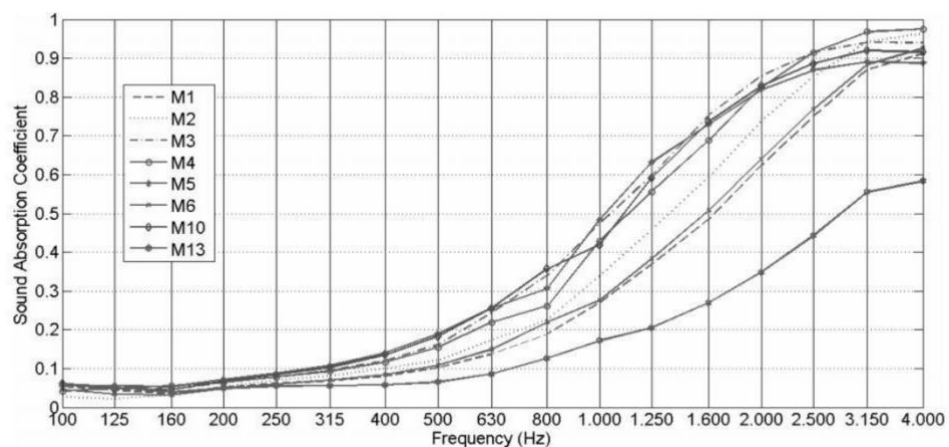


Figure 2.11 : Sound absorption coefficient (SAC) of recycled textile samples (Del Rey et al., 2015).

Del Rey et al., pointed out that materials M10, M3 and M5 had the highest values of the normal-incidence sound absorption coefficient with (0.97, 0.92 and 0.9) respectively as a function of frequency. In general, all of the prototype's results were found to function well in comparing to the available traditional materials with SAC values of (0.9-1) which are made from conventional non recycled sound absorption fibers. Lastly, the researchers stated that the tested sound absorbing materials manufactured from recycled cotton fibers can be a promising alternative that might replace the traditional materials in the acoustic panels industry.

Another research conducted by Sakthivel et al. (2020) reports on the sound absorption made of recycled cotton/polyester. The samples are; recycled cotton (white and colored), polyester (white and colored) and composite of cotton-polyester blend (colored and white) were tested for sound absorption while bonding them with PET fibers. The SAC was measured using an impedance tube method according to ASTM E 1050. The measurements covered the following frequency bands: 125, 250, 500, 1000, 2000, and 4000 Hz.

The result showed that samples prepared from recycled polyester-cotton waste have confirmed an adequate sound absorption capacity equal to 0.58 at 3000Hz and 0.72 at 4000Hz which is considered as a great absorption for the high range frequencies as can be seen in Figure 2.12.

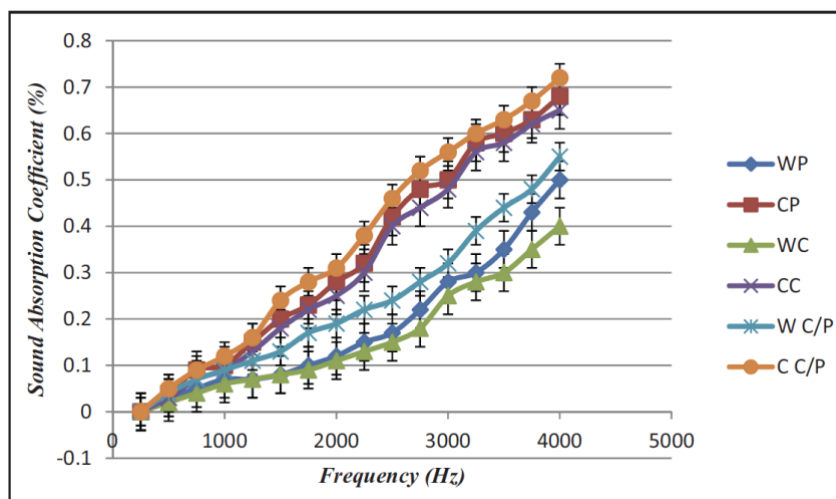


Figure 2.12 : Sound absorption coefficient for the textile waste sample (Sakthivel et al., 2020).

In another study conducted by Jiang et al. (2009), three samples were selected to analyze the acoustic properties of cotton. Each sample consisted of a base and a surface. The base was the unwoven cotton for all samples and the surface layers were; bleached cotton nonwoven, glass fiber nonwoven and activated carbon fiber nonwoven. Activated carbon is made from carbonaceous materials by carbonization and activation. The sound absorption coefficient (SAC) measurements were conducted using an impedance tube (type 4206T) for sound frequencies of 100-6400 Hz.

Results reported by those researchers are given in Figure 2.13. It shows that base and activated carbon fiber (ACF) cotton had the optimal sound absorption capacity of 1 at 4000Hz which is excellent for high frequency. The reason behind this result is that the surface structure of the ACF cotton nonwoven is highly porous.

The cotton base-cotton nonwoven surface sample had a higher absorption compared to that with glass fiber nonwoven, the latter being commonly used as an absorbent material.

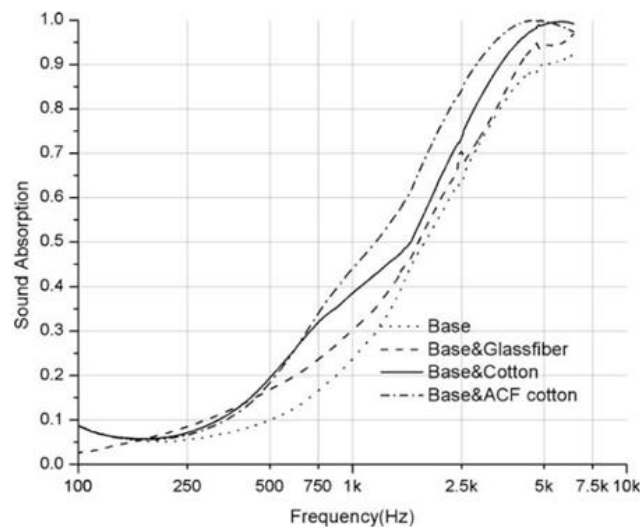


Figure 2.13 : Sound absorption coefficient (SAC) for acoustic panels from different nonwoven cotton (Jiang et al., 2009).

Taking in account the previous studies, it can be concluded that cotton/re-cycled cotton materials showed promising acoustic characteristics in regard to the sound absorption capacity for mid and high ranges.

2.5.2 Studies on the tea waste as a sound absorption material

Tang et al. (2020) investigated the possibility of using waste tea residues as a natural sound absorption material. Two cases were considered by those researchers; using

- (i) tea residues with mesh and
- (ii) tea residues with woven fabric,

Where both of the mesh and fabric were used as facing layers. Preparation process of tea residues is shown in Figure 2.14. After consumption of the tea, residual tea leaves were dried and used in making two different sound absorber samples (Figure 2.15):

- 1- tea leaf residues covered with wire mesh, where the latter was used as a protection surface layer,
- 2- tea leaf residues covered with woven fabric as a protection surface layer



Figure 2.14 : Illustration of flow chart showing the steps to obtaining tea waste (Tang et al., 2020).

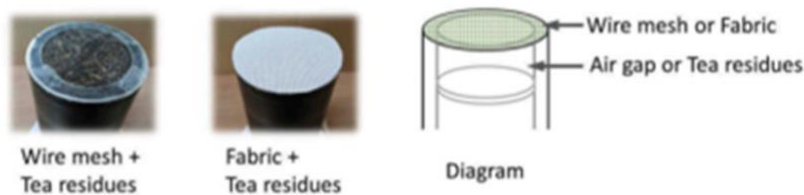


Figure 2.15 : Sound absorbers samples made from tea waste and either wire mesh or woven fabric (Tang et al., 2020).

The measurements of SAC were made using the impedance tube method in accordance with ISO 10534–2 w for frequencies in the range of 100 to 6300 Hz.

Results of SAC measurements for the first case, where tea waste was covered with wire mesh are shown in Figure 2.16. The researchers noted that the SAC of the wire mesh itself is generally lower than 0.1, thus their contribution to measured SAC values was neglected. Results indicated that SAC values were improved when the thickness of the tea residues was higher. For instance, 3 cm thickness moved the absorption peak to lower audible frequency. On the other hand, the absorption coefficients were generally lower than 0.5, and that was evaluated by the researchers as a result of having relatively thin samples in comparison to those of commercial porous materials.

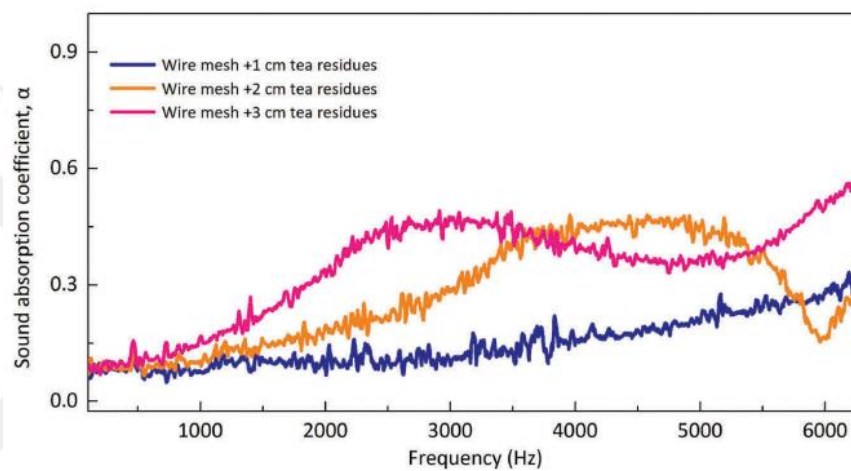


Figure 2.16 : Sound absorption coefficients (SAC) of tea waste covered with wire mesh at different thicknesses (Tang et al., 2020).

Results of SAC measurements for the second case, where tea residues were covered with woven fabric, the latter being one of the most common materials used as facing layers for the coverage and decoration of porous materials, are given in Figure 2.17. SAC measurements showed that 3 cm of tea residues covered with fabric functioned better than 3 cm of air cavity covered with the same fabric. An absorption concavity was formed about at 4500 Hz and the minimum SAC was around 0.4, which was higher than that of woven fabric with a backing air cavity (Tang et al., 2020).

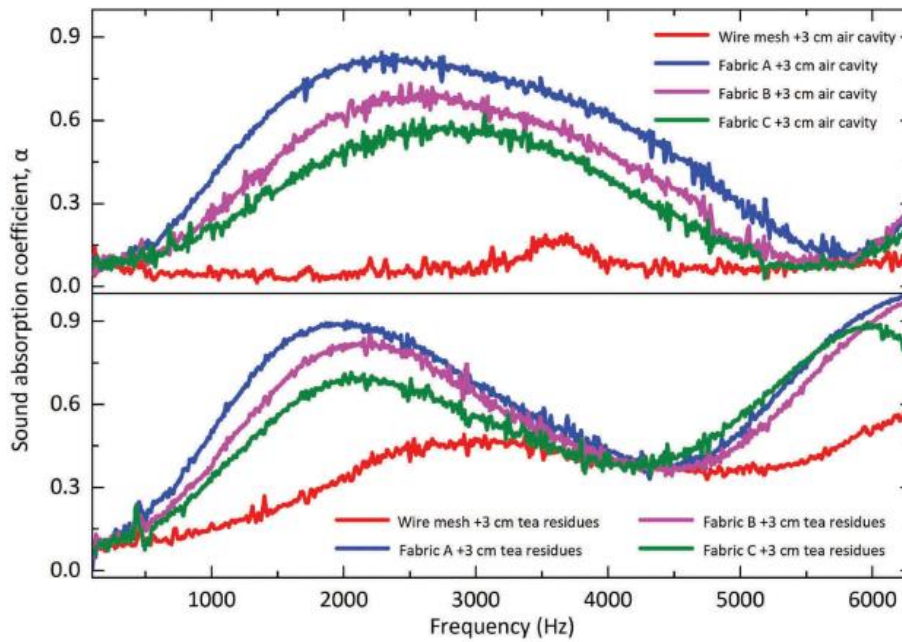


Figure 2.17 : Sound absorption coefficients (SAC) of samples: 3 cm tea waste or air cavity covered with wire mesh or fabrics with different properties (Tang et al., 2020).

Tang et al., 2020 summarized the results of their study by stating that tea waste meets the requirement of common acoustic treatment and it is recommended for the practical applications of sound absorption, and 1 cm of tea residues can improve the sound absorption of woven fabric for frequencies 100 to 6300 Hz.

Another study to test the sound absorption properties of tea leaf fiber (TLF) was carried out by Ersoy and Küçük (2009). Three samples were used: 10, 20, and 30 mm in thickness and with weight of 0.67, 1.34 and 2.18 g, respectively. The sound absorption coefficient was measured using an impedance tube with transfer-function method according to ISO 10534-2 for the frequencies (500–6300 Hz). 10 mm thick TLF sample showed a maximum absorption of 0.26 for the frequency range 4000-6300 Hz (Fig 2.18). Doubling the thickness of the sample resulted in almost a linear enhancement in sound absorption coefficient with a peak value of 0.60 at 6300 Hz.

For the last sample of 30 mm thickness, SAC was measured as 0.7, with a peak starting at 5600 Hz and continuing steadily until 6300 Hz. The sound absorption coefficient of TLF without backing was satisfying for a layer thickness at and above 20 mm.

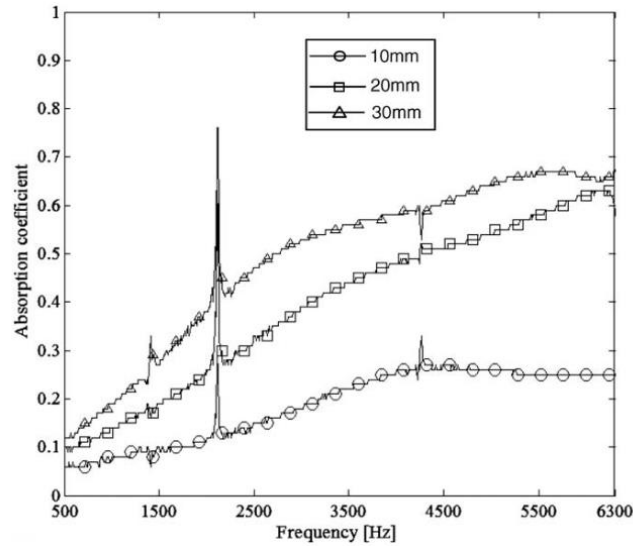


Figure 2.18 : Sound absorption coefficients (SAC) of tea leaf fibers (TLF) conducted at varied thicknesses (Ersoy and Küçük, 2009).

Ersoy and Küçük (2009) conducted another SAC measurement with samples where one layer of cotton fabric was used together with the TLF. They recorded approximately a 3x improvement in sound absorption performance of the 10 mm thick sample covered with cotton fabric (Figure 2.19).

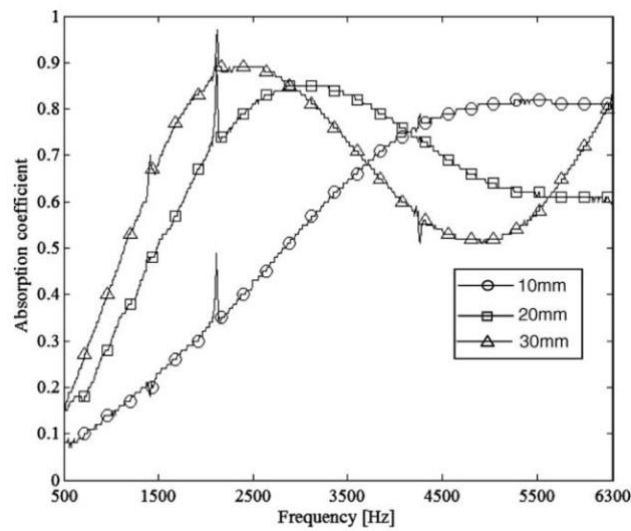


Figure 2.19 : Sound absorption coefficients (SAC) of tea leaf fibers (TLF) tested at varied thicknesses with cotton backing (Ersoy and Küçük, 2009).

For the sample with 20 mm thickness, backing with a single layer of cotton fabric increased the sound absorption by as much as 100% in the frequencies at 1000-3500 Hz. A similar 100% improvement was also recorded for the 30 mm thick TLF sample with cotton fabric backing, at low frequencies of 1000-2500 Hz.

After analyzing their results, Ersoy and Küçük (2009) concluded that the tea leaf fibers (TLF) alone exhibited good sound absorption properties for sample thickness above 20 mm. Additionally, using a single layer of cotton fabric as a backing significantly improved the performance of those natural materials as sound absorbing elements. Therefore, it can be stated that tea leaf fibers, being a natural material, meets the performance requirements for being used in acoustic panel production.

When screening the relevant literature on the use of tea leaf fibers, the aim was to collect sound and scientific data from the previous studies regarding the properties and performance of that natural material as an effective sound absorbing material, and also compile that data to be used in assessing sustainability and understanding the environmental impacts of using a natural material such as tea leaves in the industry of sound absorption. As summarized above, results of the studies conducted by Ersoy and Küçük (2009) and Tang et al. (2020) showed that TLF uphold good acoustic characteristics and can be used in production of efficient acoustic panels. Additionally, the sound absorption performance of tea leaf fibers/wastes was enhanced when supported by a layer of fabric. Accordingly, when considering tea wastes for acoustic panels production, using fabrics as support materials is required to be investigated.

2.5.3 Studies on the corn husk as a sound absorption material

Several researcher investigated and reported the acoustics properties of corn husk fibers and evaluated the possibility of using it as a sound absorbing material. What meant by corn husk here is the leafy part that surrounds the corn corpe and covers it as it can be seen in Figure 2.20



Figure 2.20 : Raw corn husk material for sound absorption performance tests (Tang et al., 2018).

Sari et al. (2016) studied the performance of acoustic panels made from corn husk fibers treated with 1%-8% of an alkali solution (NaOH). Five samples were produced in the form of panels and were tested using two-microphone impedance tube transfer-function method, according to ISO 10534-2/ASTM E-1050-98 standards for the frequencies 100-6400 Hz.

First step for preparing the samples was cleaning and drying. For that, the corn husk fibers (CHF) were soaked in water for 16 days to facilitate bacterial degradation. Then, the CHF were combed using a plastic brush to clean the fibers from any residues and to align the fibers equally. Then, CHF were left to air dry. Five panels were prepared in circular shape with a diameter of 29 mm and thickness of 20 mm (Figure 2.27). The second step was alkaline treatment to improve the fibers quality, four of the CHF panels were soaked in 1-8% of NaOH for two hours, then rinsed 5 times with mineral water to remove any residual of NaOH from the surface, and left under sunlight for drying (Figure 2.21).



Figure 2.21 : Images of the sample: (a) raw CHF panel; and panels treated with addition of NaOH solutions at percentages of (b) 1%; (c) 2%; (d) 5%; (e) 8% (Sari et al., 2016).

Physical properties of all five samples are given in Table 2.2. As apparent from the table, alkali treatment affected both the airflow resistivity and the porosity of the

panels. Porosity of the sample without alkali treatment (raw CHF) was higher than those of treated CHF panels, while airflow resistivity of former was lower than those of the treated samples. (Table 2.2)

Table 2.2 : Physical properties of the tested CHF samples (Sari et al., 2016)

Material (CHFs)	Thickness (mm)	Density (Kg.m ⁻³)	Porosity (%)	Airflow resistivity (Pa.s.m ⁻²)
Raw	20	344	0.88 ± 0.02	1375 ± 332
Treated (1% NaOH)	20	438	0.87 ± 0.01	1885 ± 93
Treated (2% NaOH)	20	566	0.86 ± 0.00	2540 ± 44
Treated (5% NaOH)	20	584	0.82 ± 0.01	5572 ± 157
Treated (8% NaOH)	20	615	0.77 ± 0.01	11.118 ± 462

Results of the SAC measurements reported by Sari et al., (2016) are given in Figure 2.22. Based on those, the researchers concluded that all tested samples were effective in absorbing sound, whereas the treated fibers performed better than the raw fibers. They also suggested that alkaline treatment affected the physical form of the panels by decreasing the diameter of the fibers, which resulted in improvement in the acoustic properties of the CHF panels. Additionally, they noted that NaOH treatment had an additional benefit in preserving the form of the panels and protected the fibers from damage.

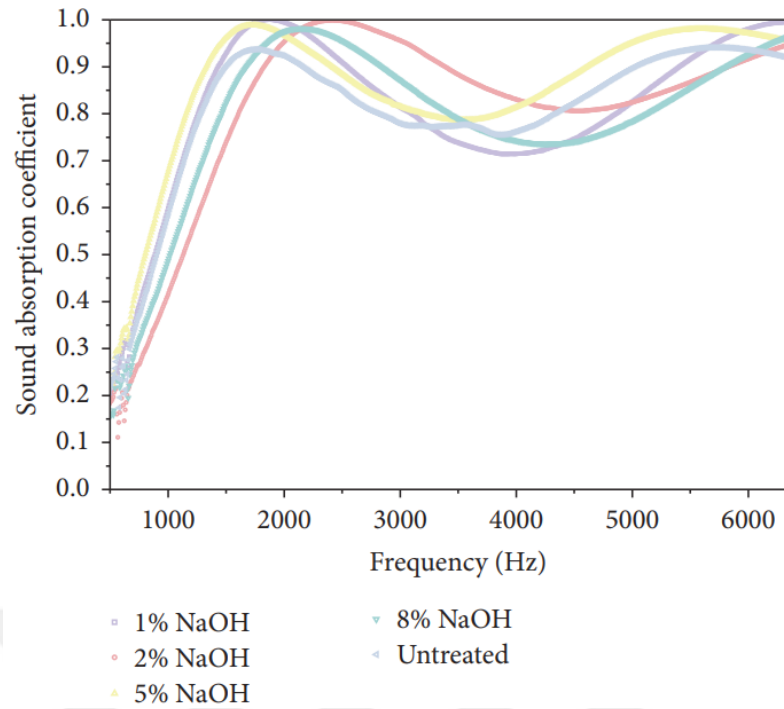


Figure 2.22 : SAC of corn husk fiber panels with different percentage of NaOH (Sari et al., 2016).

Another study by Sari et al. was conducted one year later (2017) to measure the SAC of CHF with polyester binder. Six samples were prepared with different CHF: polyester ratios as it can be seen in Table 2.3. The preparation process was similar to the previous study and the treatment was made with 5% NaOH after its positive impact was proven in the 2016 study. All the samples were molded with a thickness of 20 mm and a diameter of 29mm.

Table 2.3 : The composition of the CHF and polyester samples (Sari et al., 2017).

Sample	CHF (%)	Polyester resin (%)
PF-E 20 80	PF-E 20 80	PF-E 20 80
PF-G 40 60	PF-G 40 60	PF-G 40 60
PF-H 50 50	PF-H 50 50	PF-H 50 50
PF-I 60 40	PF-I 60 40	PF-I 60 40
PF-K 70 30	PF-K 70 30	PF-K 70 30

The sound properties of the studied samples were measured with two-microphones transfer-function method, in accordance with ASTM E-1050-98/ISO 10534-2 standards. Both acoustical and non-acoustical (physical properties) of the samples were studied. Table 2.4 shows the physical characteristics of the samples. While Figure 2.23 shows the acoustical properties.

Table 2.4 : Physical properties of the CHF and polyester binder composite (Sari et al., 2017).

Sample	Thickness (mm)	Density (Kg.m ⁻³)	Porosity (%)	Airflow resistivity (Pa.s.m ⁻²)
PF-E	20	640.5	0.6474	44,980
PF-G	20	383.4	0.7053	29,353
PF-H	20	304.1	0.7247	25,424
PF-I	20	244.1	0.7457	21,576
PF-K	20	198.0	0.7582	19,568
PF-M	20	158.3	0.7954	14,435

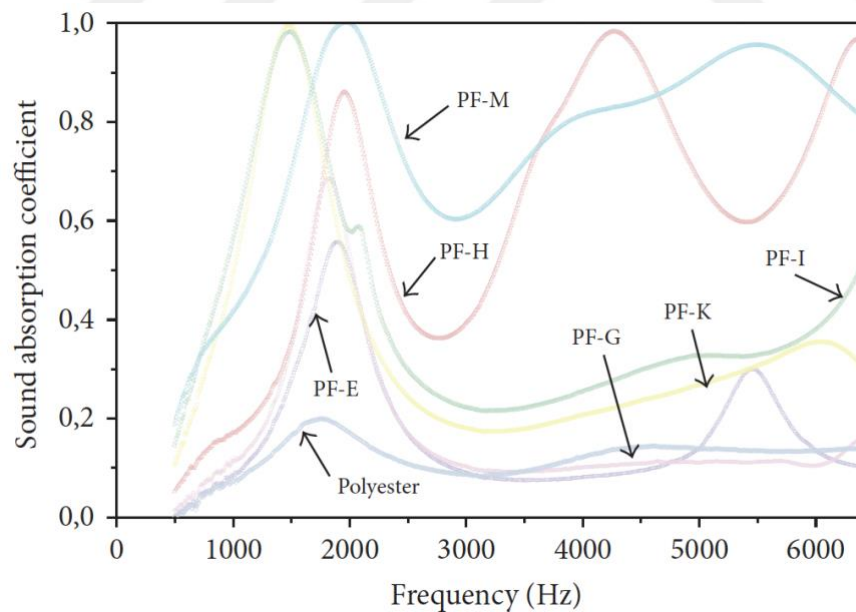


Figure 2.23 : SAC of CHF composite samples and polyester binder (Sari et al., 2017).

Sari et al. reported that all samples demonstrated an increase in SAC values in the range of 1 kHz–2.5 kHz. While at the frequencies above 2 kHz, the sound absorption capability of PF-E, PF-G, PF-I, and PF-K samples decreases. The decrease is caused by the fiber arrangement that cause the higher value of the flow resistivity of the sample making the movements of the sound difficult to pass through the samples. It was also noticed that increasing the resin resulted in lowering the friction between the fibers and subsequently reducing the sound absorption coefficient.

At the end Sari et al. (2017) concluded that all the samples have the potential to be used as acoustic panels. These results indicate that CHF material can be a high-performance sound absorbing material alternative and this will participate in solving the environmental problems and help with decreasing the noise pollution.

In his research, Sasikumar et al. (2020) studied five different types of agricultural wastes and one of them is corn waste. Corn waste was sundried for drying, chopped to shorter sections and then entered into the grinder to make the particles finer. The coming fibers are sieved in the sieves to obtain a uniform size of 0.5 to 0.9 mm. The sample is then molded while adding a urea formaldehyde resin. Then, the samples were compressed by applying pressure over a period of time. The impedance tube was used for measuring the sound absorption coefficient study in accordance with ASTM E1050-98. Figure 2.24 and Figure 2.25 shows the SAC of corn waste material for different ranges of thickness and frequencies.

Sasikumar et al. (2020) concluded that the corn waste material possesses a good sound absorption capacity. The sample with thickness 20mm performed the best with a peak of 0.5 at 1500 Hz for mid frequency ranges and a peak of 0.76 at 4000 Hz for high ranges.

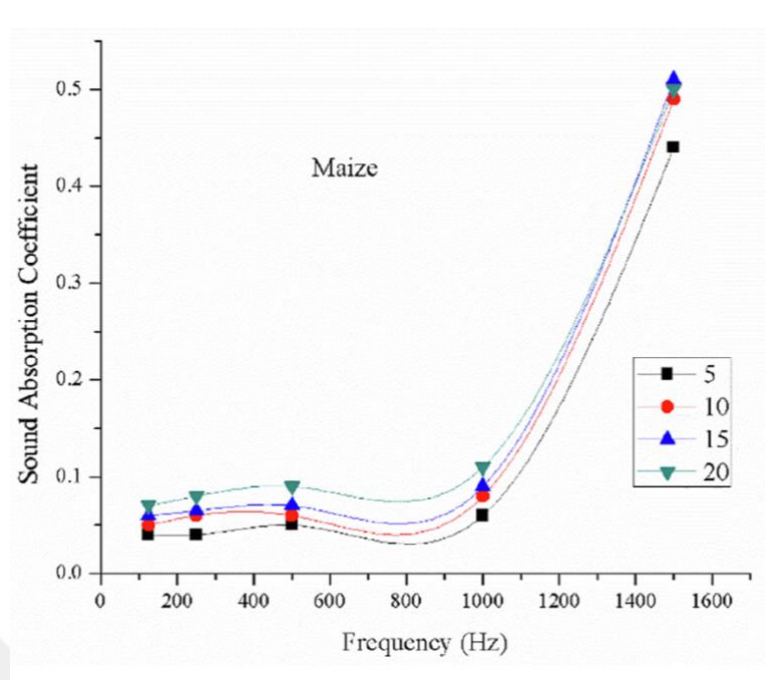


Figure 2.24 : SAC of corn husk samples with different thickness for low frequency ranges (Sasikumar et al., 2020).

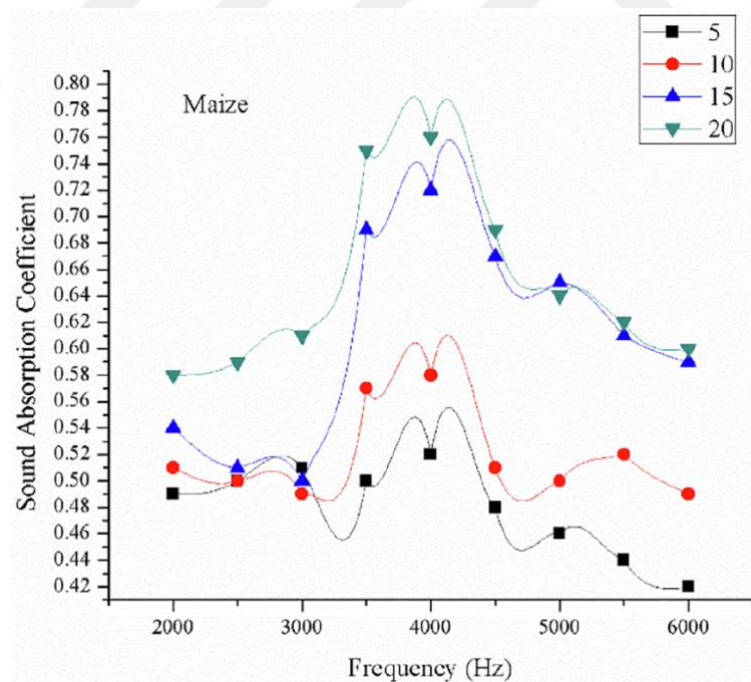


Figure 2.25 : SAC of corn samples with different thickness for high frequency (Sasikumar et al., 2020).

From reviewing the previous studies for the selected materials (recycled textile, tea waste and corn husk) it can be concluded that these materials make good candidates for producing acoustic panels. Their technical, environmental and economic aspects will be further investigated in chapter 3.

As of now, it is important to understand how to compare between the materials and to be able of evaluating them, this can be done using a methodology known as Multi-Criteria Decision (MCD)

2.6 Multi-Criteria Decision (MCD)

Multi Selecting the most suitable materials for multiple engineering applications is often recognized as multi-criteria decision-making (MCDM). Issues for which the applicable decision matrix needs to be constructed, consisting of a defined set of practical alternatives and a preset number of criteria (Jahan et al., 2010).

2.6.1 MCDA methods

There are many critical and conflicting decision involved in the process of selecting a specific material. To choose the most suitable option for the intended application in varied field, the use of MCDM is important to assess. There are several tools that have been reported in literature. These tools can be utilized either individually or in combination with one another to solve the problem of selecting the best alternative. (Emovon & Oghenenyerovwho, 2020).

Multi-Criteria Decision-Making (MCDM) is about methods to make the best decision when multiple criteria (or objectives) are considered together, in order to select or rank between the alternatives being evaluated. There are many MCDA methods but only four are considered in the study; methods using aggregation like Analytic Hierarchy Process (AHP) (Saaty, 1990), methods with weighted summation such as The Simple Multi Attribute Rating Technique (SMART) (Edwards, 1971) and Simple Additive Weighting (SAW) (Churchman and Ackoff, 1954) and method using ideal point which is Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Hwang and Yoon, 1981).

2.6.1.1 The analytic hierarchy process (AHP)

The analytic hierarchy process is used in various fields as a multi-attribute decision analysis tool with multiple criteria and alternatives. For every decision-making process, a logical and systematic approach is used to reach the solution. To weight a criterion, AHP relies on matrix and 'pair-wise comparisons and the decision is determined from the derived weights of the evaluative criteria (Saaty, 1980). The evaluation is made based on a 1-9 scale with each number carries an interpretation. The downside of using AHP is the lack of accuracy and subjectiveness in the pair-wise comparison process. Which is why, the method was improved to the Fuzzy AHP method where instead of using imprecision value, fuzzy AHP uses a range of value to combine the decision maker's uncertainty (Demirel et al., 2008) When there is uncertainty in the multi-criteria decision analysis, the fuzzy set theory method is used. A wide range of researches used AHP whether on its own or combined with different MCDM methods.

2.3.3.1 The Simple Multi Attribute Rating Technique (SMART)

SMART is one of the MCDA methods that works based on giving weight values for each criterion depending on the importance of these criteria comparing to the other ones.

The SMART method supports decision according to a linear additive model based on the available parameters. These parameters have a range of values and weights. The overall value for a specific criterion is calculated by the total sum of the performance score for each attribute multiplied by the weight of that criterion. (Rahim, 2016).

The weighting of SMART is made using a scale between 0 and 1, therefore, simplifying the comparison and decision making for each alternative (Arh and Blažič, 2007)

2.6.1.3 Simple Additive Weighting (SAW)

Simple Additive Weighting (SAW) is weighted sum method that considered one of the most applicable and easy MCDA method. Churchman and Ackoff (1954) are first known implementers of the SAW method.

Firstly, the weights of each alternative must be defined. Then the importance factor is multiplied by the alternative, the score of the alternative is calculated and the alternative with the highest score is selected.

2.6.1.4 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method

TOPSIS is a very common method of multi-criteria decision making (MCDM) and it is the method that will be used for this study. The main reasons for using this method are;

- The criteria are weighted in order of importance and these weight ratios are calculated for each scenario.
- It includes simple understandable calculations.
- And it is applicable for the case of materials comparison and commonly used for that purpose.

TOPSIS method is based on creating a synthetic rating, ideal solution and negative-ideal solution. It aims at defining the distance of each alternative from the ideal solution and negative-ideal solution.

The ideal solution is defined based on the best available value within the set in the frame of each criterion (Hwang, Yoon, 1981). On the other hand, a negative-ideal solution is defined based on the worst available values. Criteria can be a set of benefits (set C benefits) and costs criteria (set C costs). As a result, depending on the character of the criterion while defining an ideal solution there is a maximum value chosen in the case of benefits criteria and a minimum value in the case of costs criteria. The TOPSIS method is applicable and considered in many studies (Behzadian et al., 2012), it has several steps to follow in order to make the final decision. Figure 2.26 illustrate those steps.

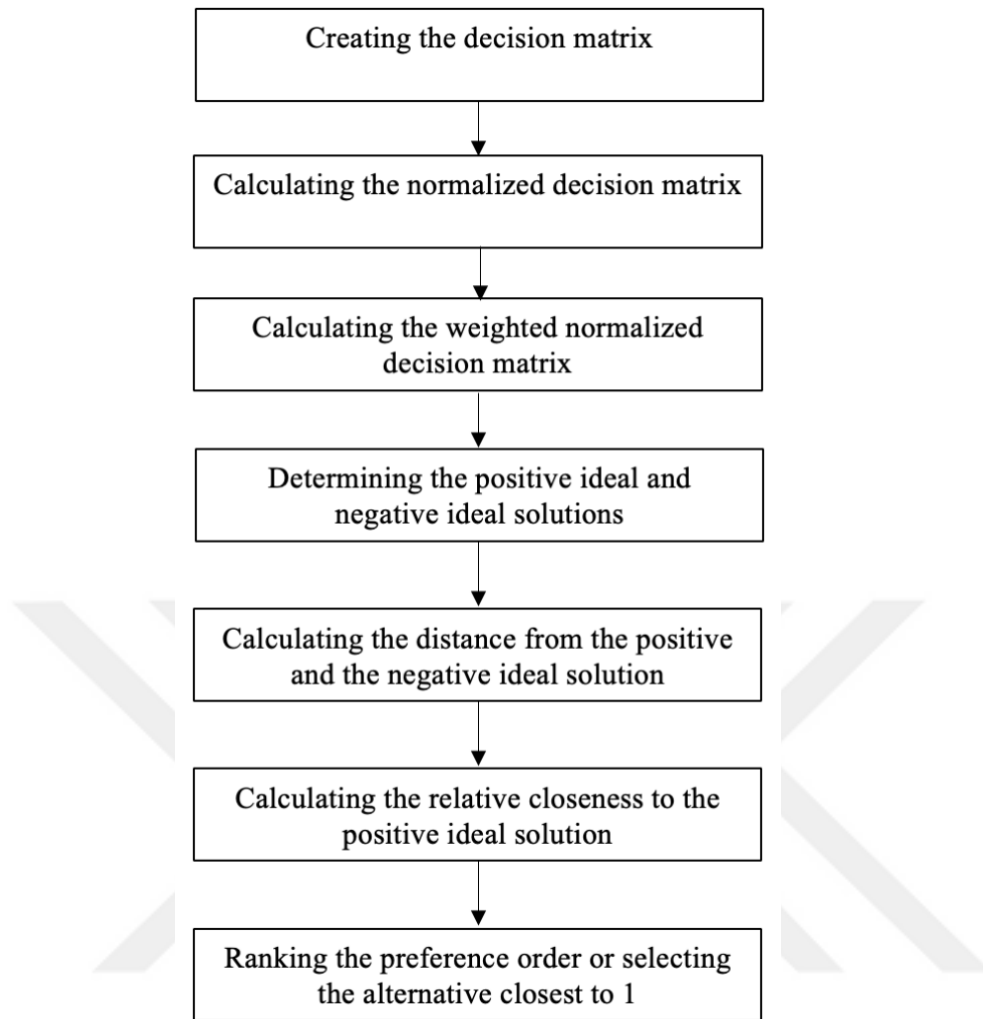


Figure 2.26 : The processes flow of applying the TOPSIS method (Adapted from Roszkowska, E., 2009).

The algorithm of this method has seven steps, these steps and the formulas they contain are as follows (Roszkowska, E., 2009);

Step 1. Creating the decision matrix and deciding the weight of each criterion.

Let $X = (x_{ij})$ be a decision matrix and $W = [w_1, w_2, \dots, w_n]$ be a weight vector, where $w_1 + w_2 + \dots + w_n = 1$ or 100

Criteria can be either benefit function (the bigger the better) or cost function (less is better) (Roszkowska, E., 2009)

Step 2. Calculating the normalized decision matrix.

This step makes all the attribute comparable. Since each criterion can be measured in a different unit, then the scores in the evaluation matrix X shall be normalized. The normalization of values can be carried out by one of the several known standardized formulas. Calculating the normalized value n_{ij} in a matrix can be done using equation (2.5) and equation (2.6) as it can be seen below (Roszkowska, E., 2009);

$$n_{ij}(x) = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad \text{for } i = 1, \dots, m ; j = 1, \dots, n. \quad (2.5)$$

$$n_{ij} = \frac{x_{ij}}{\max x_{ij}} \quad (2.6)$$

When the criteria are benefit (positive), then equation (2.7) can be used;

$$n_{ij} = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (2.7)$$

And when the criteria are cost (negative), then equation (2.8) is used;

$$n_{ij} = \frac{\max x_{ij} - x_{ij}}{\max x_{ij} - \min x_{ij}} \quad (2.8)$$

Step 3. Calculating the weighted normalized decision matrix.

The weighted normalized value v_{ij} can be calculated using equation (2.9);

$v_{ij} = w_j n_{ij}$ for $i = 1, \dots, m; j = 1, \dots, n$.

where w_j is the weight of the j -th criterion,

$$\sum_{j=1}^n w_j = 1 \quad (2.9)$$

Step 4. Determining the positive ideal and negative ideal solutions.

The ideal positive solution is the ideal that maximizes the positive/benefit criteria and minimizes the cost/negative criteria whereas the negative ideal solution maximizes the cost/negative criteria and minimizes the benefit/positive criteria.

Positive ideal solution A^+ has the form of:

$$A^+ = (v_1^+, v_2^+, \dots, v_n^+)$$

$$v_j^+ = \{(\max v_{ij} | j \in I), (\min v_{ij} | j \in J) \}$$

Whereas, negative ideal solution A^- has the form of:

$$A^- = (v_1^-, v_2^-, \dots, v_n^-)$$

$$v_j^- = \{(\min v_{ij} | j \in I), (\max v_{ij} | j \in J) \}$$

where I is associated with benefit criteria and J with the cost criteria,

$i=1, \dots, m; j=1, \dots, n$.

Step 5. Calculating relative closeness degree.

TOPSIS method ranks each alternative based on the relative closeness degree to the positive ideal and distance from the negative ideal. Therefore, in this step, the calculation of the distances between each alternative and the positive and negative ideal solutions is obtained by equations (2.10) and (2.11) (Roszkowska, E., 2009);

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad , \quad i = 1, 2, \dots, m \quad (2.10)$$

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad , \quad i = 1, 2, \dots, m \quad (2.11)$$

Step 6. Calculating the relative closeness to the positive ideal solution.

The relative closeness to the ideal solution (C_i) is calculated for each alternative with equation (2.12) as follows;

$$C_i = \frac{d_i^-}{(d_i^+ + d_i^-)} \quad , \quad i = 1, \dots, m \quad (2.12)$$

where $0 \leq C_i \leq 1$, $i = 1, 2, \dots, m$.

Step 7. Ranking the preference order or selecting the alternative closest to 1.

The alternative with the largest C_i value is considered to be the best solution.



3. METHODOLOGY

3.1 Model construction

Within the scope of this thesis, TOPSIS; one of the multi-criteria decision-making (MCDM) methods was utilized to comparatively evaluate three materials, in fact wastes, to be used as the main material in acoustic panel production, and to determine the most suitable, feasible, and sustainable alternative as a candidate to be used for sound absorption in built environments.

TOPSIS is a popular method being utilized for solving MCDM problems. This method is practical in use and has several advantages that make it widely implemented in different domains and applications. It is a “rank order weighing” method and is based on structuring an in-silico rating, ideal solution and negative-ideal solution. It aims at defining the distance of each alternative from the ideal solution and negative-ideal solution (Hwang and Yoon, 1981).

A flow chart for the research methodology in this work is shown in Figure 3.1. All the calculations were conducted using Excel spread-sheets. Criteria and sub-criteria have been carefully proposed to assist with the decision of selecting the best sound absorbing material.

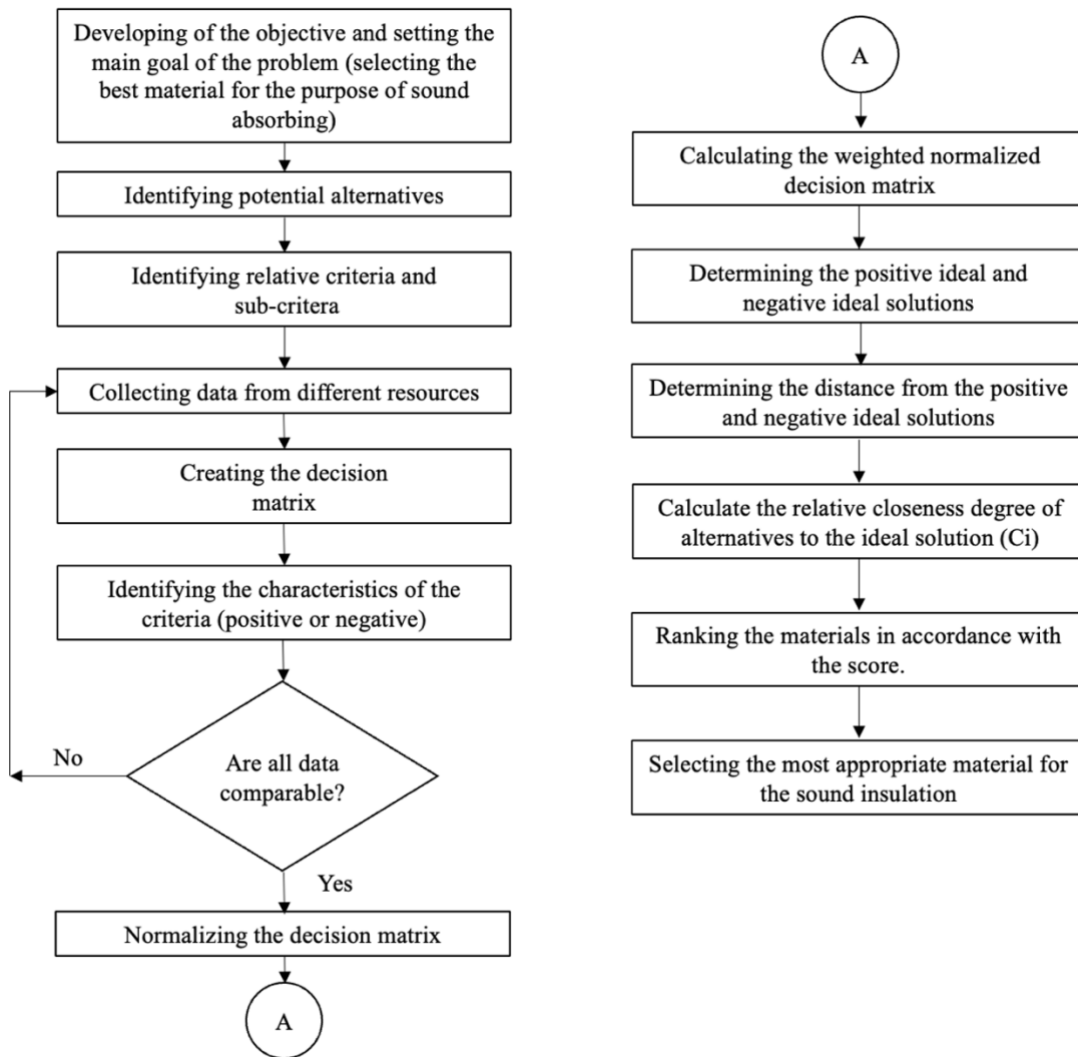


Figure 3.1 : Flow diagram of the TOPSIS methodology.

3.2 Material alternatives, comparison criteria, hierarchy of proposed model, and simple LCA approach

In this study 4 materials were considered as acoustic panel materials (APM): namely,

1. Recycled Textile Waste (pre-customer production left-overs),
2. Tea Waste (post-consumer wastes),
3. Corn Husk (agro-production left-overs),
4. Fiberglass (in use in commercial acoustic panel market).

Fiberglass is made from synthetic fibers, widely used as a sound absorption material, and has been in the acoustic panel market for decades. It is selected in this study to represent the commercially available sound absorbing materials and providing the base-line for comparison. The other 3 alternatives, namely recycled textile waste, tea waste, and corn husk, were at the core of the study, and were selected carefully and particularly as wastes generated by industries/business with significant market shares in Turkey. Those alternatives are claimed to be emerging sustainable materials derived from wastes, hence contributing to circular economy.

Excel spreadsheets were utilized to carry out the comparisons based on properties of materials and/or acoustic panels, and at the following four main categories/criteria:

1. Technical properties/performance of the raw material,
2. Technical properties/performance of the acoustic panel,
3. Environmental aspect,
4. Cost.

The hierarchy structure of the model used in this study is demonstrated in Figure 3.2. Similar hierarchy structure can be found in (AL-Oqla et al., 2015). Data required to the fed to TOPSIS as input so to enable comparison between the alternatives, in other words the selected sound absorption materials (SAM), were both compiled from previous works carried out and reported by several researcher in the relevant literature, and also generated by running calculations in this study. Integration of the information

from the literature and the data generated in this study and utilization of those in the TOPSIS-MCDM method is suggested to lead to a reliable information-based decision-making model.

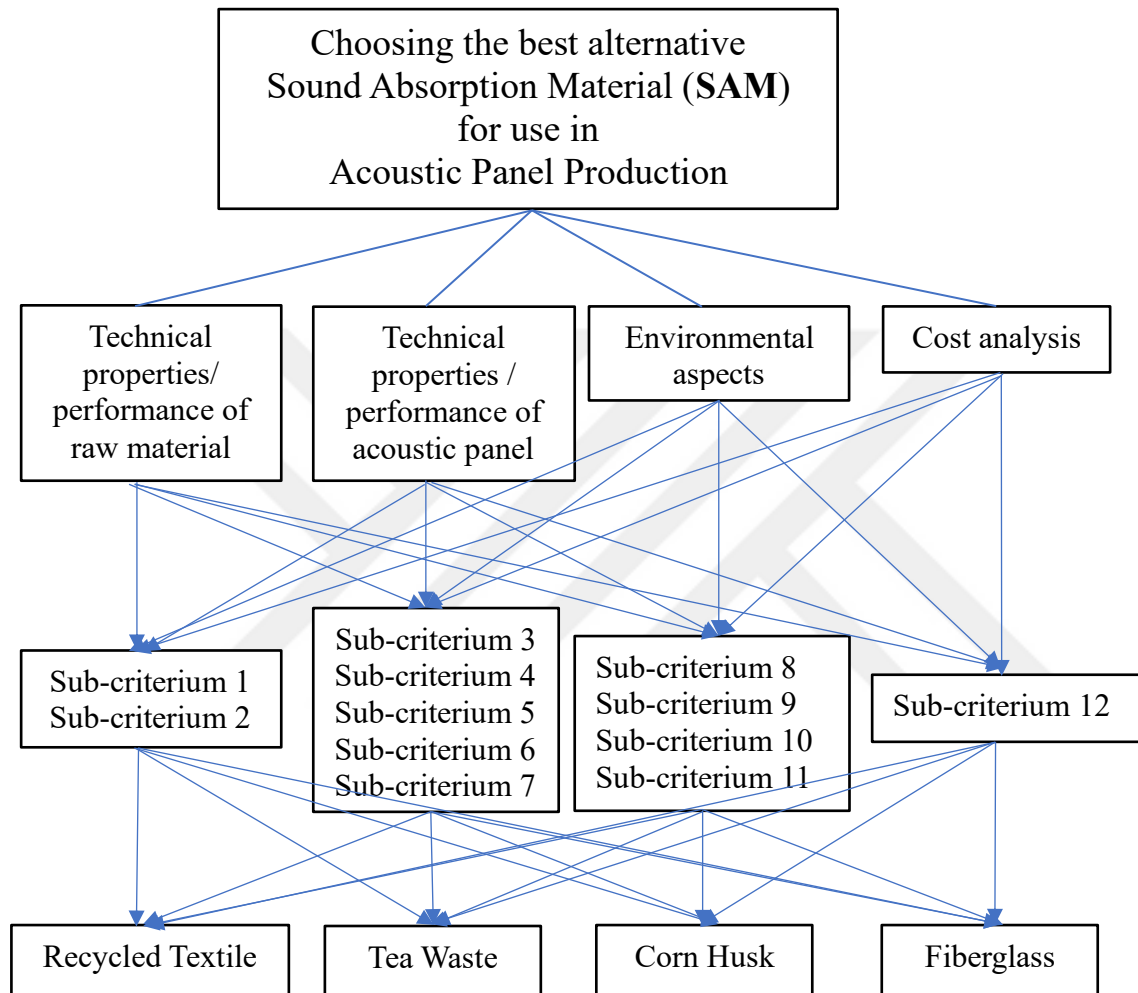


Figure 3.2 : The hierarchy structure of the proposed model.

Simple LCA approach

In addition to the MCDM-TOPSIS applications, a simple/basic LCA (Life cycle assessment) study was also conducted for assessment and comparative evaluation of the SAM alternatives investigated in this study. For that, the fundamental LCA approach seen in Figure 3.3 was adopted (ISO 14040). Moreover, to keep the LCA process and calculations simple, the “*cradle-to-gate*” approach was selected and

implemented, which resulted in defining the overall system boundaries of the basic LCA as given in Figure 3.4. Accordingly, the basic LCA included *the “cradle”*; generation of the raw material, followed by production/manufacturing of the final product leaving the production site; *the “gate”*. Therefore, phases/processes after the “gate”, such as distribution of the product to retailers, then to end-users, consumer use, disposal, etc. were left out of the scope of this study.

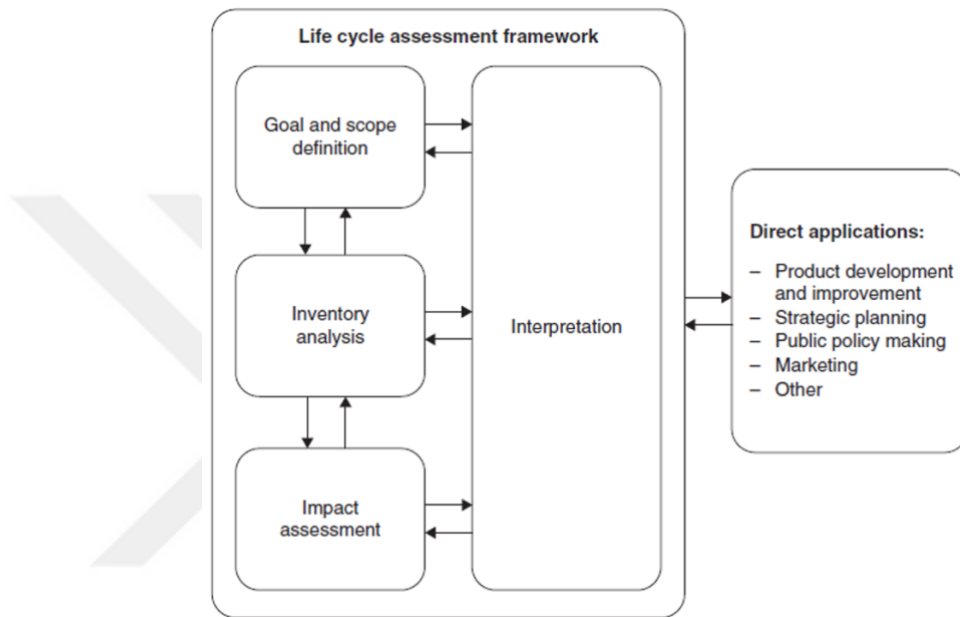


Figure 3.3 : The general methodological framework for LCA (ISO 14040) adopted in this study.

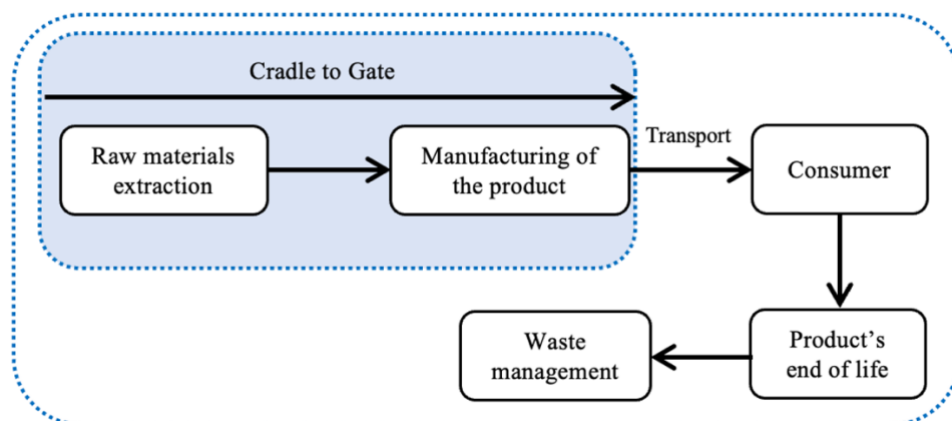


Figure 3.4 : Cradle to Gate approach and overall system boundaries (blue-shaded area) adopted both in LCA and TOPSIS-MCDM works executed in this study.

The upcoming sections of this chapter will focus on the cradle to gate phase of the 3 selected materials. Based on the information provided in the literatures, a flow chart will be designed for all materials individually to show each input and output in the preparation, transportation and manufacturing phases.

There are few assumptions that needs to be set before moving forward and they are:

- All the materials will be manufactured in the same factory and it is located in the industrial zone in Umranyie/ Istanbul.
- Packaging materials, machines maintenance was excluded from the calculations of the environmental impact and cost estimation.
- The final product is a sound absorption panel that can be released to markets but the assembling parts (adding frames, fabrics... etc.) are not covered because it is outside the system boundaries of cradle to gate.
- Transportation-related matters are different for each scenario depending on the location of the raw materials.
- The function unit (FU) must be determined, the main purpose of a functional unit is to provide a reference to which the input and output data are normalized. e.g., number of products produced, kg of raw material used, m² floor area, ... etc. For the case of this study, the function unit is producing 1 acoustic panels in the following dimensions; height= 1m, width= 1m and thickness is dependent on the material itself.

Each material has its own scenario that will be described carefully in the next sections.

3.2.1 Scenario for recycled textile material

Conversion of textile waste into acoustic panel materials is not a straight forward process. As the type of textile waste is different including industrial or post-consumer, synthetic and natural, therefore the conversion process is also varied. For the case of this study the post-industrial textiles (also known as pre-consumer) scraps will be taken in account because it is a textile waste that cannot be re-used for the industry. Also,

they are generated at a single point-source, thus; eliminating the need for collecting textile waste from various sources as in the case of post-consumer textile wastes.

The assumption is to use the waste coming from a textile factory in the industrial zone in Umranyie, this decision will assist in lowering the carbon footprint by eliminating the transportation phase that usually participate in the carbon dioxide emissions.

3.2.1.1 Recycled textile material process flow:

According to (Del Rey *et al.*, 2015), the best performance of a recycled textile sample occurred at a thickness of 17mm and density of 57 Kg/m³. Using those panel thickness and density values, volume and weight of a 1x1 m² acoustic panel might be calculated as 0.017 m³ and 0.969 kg, respectively. Thus, the quantitative relation between the initial input and the final output for this case-study is set as follow: each 0,97 kg of recycled textile produces 1 acoustic panel.

The composite consists of: 75% Cotton and 25% polyester which will adds up to be 80% of the total weight size while the rest 20% is binder.

The textile scraps are previously categorized according to their fiber type and color. manually cut into small pieces, shredded using a shredding machine and manually opened back into fibers without breaking the length of the fibers. The recycled fiber is then converted into a web structure by using a mechanical carding process in a carding machine to form an air-laid web, and the binder used here is polyester. Bonding is done by spraying the binder into the textile structure by means of sprayer arranged above the moving web. The binder saturates on the surface layers and does not penetrate far in the structure which is normally quite thick. The adhesive add on percentage is taken care of to maintain at 20% which is equivalent to 0.24 kg of polyester solution. The yarn leaving the carding machine is a sound absorption material that can be used for the purpose of sound absorption as shown in Figure 3.5. After this step, the product is finished and ready to be used. However, additional step – assembling- is considered in all scenarios to show one of the potential utilizations of the material; where wooden frames and fabrics are added for the facing and backing of the absorbing material. This last step is not included in the system boundaries

because it is not within the cradle-to-gate approach that has been followed. The purpose of having it, is to show one way of assembling the acoustic panel (Figure 3.5).

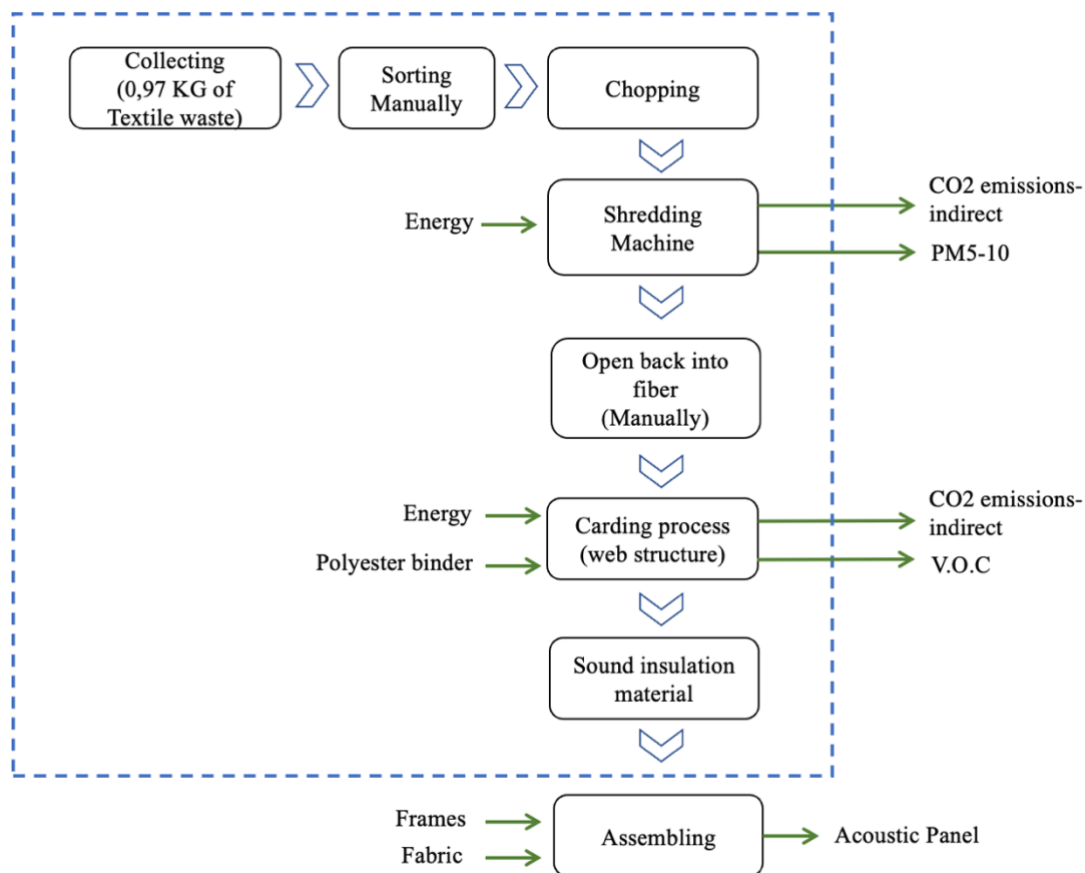


Figure 3.5 : The process flow chart of manufacturing acoustic panels from recycled textile.

As a result of the previously mentioned processes an output will be released. The shredding machine (HR35, vecoplan) consumes 0.038 kw/FU unit electrical energy. Thus, an indirect carbon dioxide emission will be released, in addition to some particulate matters 5-10 μm that will be emitted to the indoor environment and it can be neglected due to its small amount. The carding machine (L-9060, TFON Leveltech®) consumes 0,152kw\FU and it will also participate in the indirect carbon dioxide emissions and form volatile organic compounds (VOCs) in very small quantities which also can be neglected (Wendin, 2016). Table 3.1 shows the flow chart of producing 1 acoustic panel from the recycled textile.

Table 3.1 : Input data for manufacturing acoustic panels from recycled textile.

Process	Input	Amount	Unit	Reference
-	Recycled textile	0,97	kg/FU	This study
Shredding	Electricity	0,038	kw/FU	HR35, vecoplan
Carding	Electricity	0,144	kw/FU	L-9060, TFON Leveltech®
Binding	Polyester Binder	0.194	kg/FU	Adapted from Del Rey et al., (2015)

3.2.2 Scenario for tea waste material

The material is basically the tea waste that is left after drinking tea. It is collected from different locations (such as cafes and restaurants) using a truck that travels around Istanbul to collect tea waste and bringing it to the acoustic panels factory where it will be used for manufacturing the panels. The transportation here is assumed to be 100 km in total. The material composition consists of: 95% tea waste and 5% binder.

3.2.2.1 Tea waste process flow

According to Tang et al., (2020), the best performance of a tea sample occurred at a thickness of 30 mm and density of 91.5 Kg/m³. Using the dimensions of 1x1m acoustic panel lead to the weight of 2.745 Kg of tea waste.

The first step after the tea waste arrives to the factory is drying because it is initially disposed in damp condition. The material is recommended to be dried for 24 h at 80 °C (Taban et al., 2021)

The energy consumption of the drying oven is calculated as 0,62 kw/FU. (Hafer M., 2017). Drying the tea wastes will results in decreasing its weight to up to 5% because of its water absorbing capacity (Taban et al., 2021)

Later on, the tea is placed in molding templates where the binder is added. For the case of this material, 0,137 kg/FU. of natural latex rubber binder is used.

Wong et al., 2017 mentioned that the rubber has almost no effect on the sound absorption capacity values. However, it has a great binding quality for material like tea leaves. The final step is pressing the composite for 15 minutes at temperature of 140 °C, this process will consume 0.14 kw/FU (Wong et al., 2017) and this will cause

indirect CO2 emissions to the air. At this point, the sound absorption panel is finished and ready to be transported to the market. Figure 3.6 shows the process flow chart while Table 3.2 shows the numeric input value.

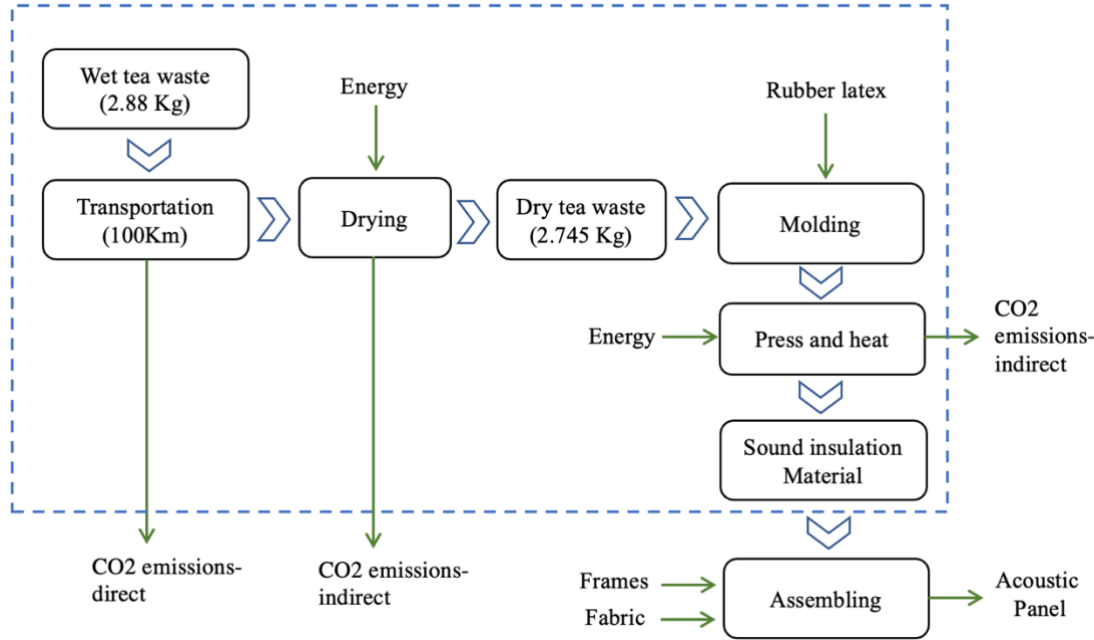


Figure 3.6 : The process flow chart of manufacturing acoustic panels from tea waste.

Table 3.2 : Input data for manufacturing acoustic panels from tea waste.

Process	Input	Amount	Unit	Reference
-	Tea residues (wet)	2.88	kg/FU	Adapted from Uthai et al., (2019)
Transportation (100Km)	Truck	0,288	(t*km)/FU	This study
Drying	Electricity	0.62	kw/FU	Adapted from Hafer M., (2017)
Molding (press and heat)	Electricity	0.14	kw/FU	Adapted from Wong et al., (2017)
Binding	Rubber latex	0,137	kg/FU	Adapted from Wong et al., (2017)

The commonly used unit to understand the environmental impact of transportation is tonne-kilometre, which is a measurement unit corresponding to the transport of one ton over a distance of one kilometer. For this case, the weight is 2.88×10^{-3} ton/FU, multiplying it by the distance (100 km) results in 0,288 (t*km)/FU.

3.2.3 Scenario for corn husk material

Corn husks are the outside green leaves on a cob of corn, which are usually peel off and discard. The corn husk fields are widely available around Turkey. To keep the carbon footprint low, a corn field in agva-Istanbul is considered. The distance between the corn field and the acoustic panel factory (in the industrial zone of Umraniye) is calculated as 98 km using Google maps. Corn husk wastes are collected from the corn field after de-husking the corn. Then it is washed, treated with 5% NaOH solution and rinsed with water. The raw material is sundried for removing moisture that may be present in the materials. After that, it is transported to the manufacturing facility. Corn waste had a preparation phase which haven't occur for the other two raw materials. The composition consists of: 80% corn husk and 20% binder.

3.2.3.1 Corn husk fiber process flow

The best performance of a corn husk fiber treated with 5% NaOH occurred at a thickness of 20 mm and density of 158 kg/m³ (Sari et al., 2017). For a 1x1 m acoustic panel the required weight of the raw material is 3,16 kg. Accordingly; each 3,16 kg of corn waste produces 1 acoustic panel. The corn husk is chopped to shorter pieces and then fed into the grinder to make it finer. The obtained particles are then sieved in the sieves set to obtain uniform size of 0.5 to 0.9 mm. Afterwards, the whole mass is molded with resin. According to Sari et al., 2017 polyester solution makes a suitable binder for corn husk when used in the following ratio: 20% polyester binder, 80% corn husk. Later on, the mixture is compressed in a mold by applying pressure over 15 minutes at temperature of 140 °C. The final product is cooled down and then transported to the market. Figure 3.7 summarize the steps.

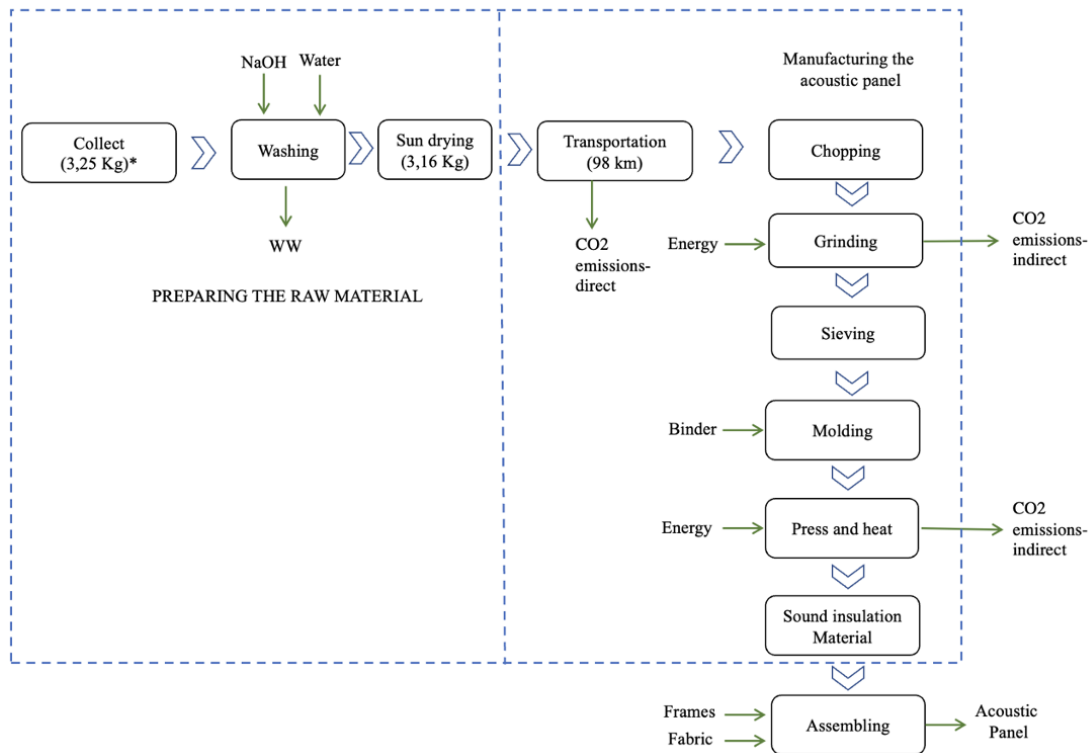


Figure 3.7 : The process flow chart of manufacturing acoustic panels from CHF

*The total mass of the corn husk collected from the field before drying is 3% more due to the water content.

The amount of water required in the washing process was calculated manually. Using a pot with the following dimensions: 12 cm radius and 12 cm height. 1 kg of corn husk was washed using 5 L. Thus, 15,8 L of water is required per function unit.

Additionally, 0,3 L of water is needed in the preparation phase to dilute the sodium hydroxide used for treating of the corn husk waste. Thus, 16,1 L is required in total. Just like with tea waste, the unit of transportation is changed to tonne-kilometre.

Table 3.3 shows the input for each process included in producing 1 acoustic panel from corn husk waste.

Table 3.3 : Input data for manufacturing acoustic panel from corn husk waste.

Process	Input	Amount	Unit	Reference
-	Corn waste- before sun drying	3,25 (3%)	kg/FU	This Study
-	Dry Corn waste	3,16	kg/FU	This Study
Cleaning	Water	15,8	L/FU	This Study
Treatment	NaOH (5%)	0,0158	kg/FU	Sari et al., (2017)
Treatment	Water to dilute NaOH	0,3	L/FU	Sari et al., (2017)
Grinding	Electricity	0,056	kw/FU	Buratti et al., (2016)
Molding (Press and heat)	Electricity	0,2	kw/FU	Adapted from Wong et al., (2017)
Transportation (98km)	Lorry 1 ton	0,31	(t*km) /FU	This Study
Binding	Polyester binder	0.63	kg/FU	Sari et al., (2017)

3.3 Introduction of Selected Criteria

Three main comparison categories, namely technical, environmental, and cost aspects, are considered in this study for TOPSIS application. However, regarding the technical aspects, technical properties of the raw materials before being used in AP production, and technical properties of the acoustic panels themselves are evaluated separately, since the raw materials used for producing the acoustic materials have certain qualities that changes after manufacturing the acoustic panels. Accordingly, the following 4 criteria and their sub-criteria are utilized in this study; Technical properties of raw material and it includes density (D) and porosity (P). Secondly, technical properties of the acoustic panel which includes; air flow resistivity (AFR), thickness (TH), sound absorption capacity (SAC), noise reduction coefficient (NRC) and thermal conductivity (TC). Third, the environmental aspect and it includes: water consumption (W), chemical usage (CU), global warming potential (GWP) and the biodegradability of the prepared raw material (B). Lastly, the cost aspect which includes; the cost of preparing the raw material (CRM), cost of transportation (CT) and cost of manufacturing the panel (CP) as can be seen in Table 3.4.

The technical properties of the raw materials and the acoustic panels data were collected from literature. While the environmental impact was calculated specifically in this study. Lastly the cost analysis was conducted in this study based on the preparation and manufacturing cost coming from chemical usage, electricity and water consumption, labor and other additional costs.

Each sub-criteria will be explained in details in the following sections.

Table 3.4 : Selected main criteria and sub-criteria.

Main criteria	Sub-criteria	Symbol
Technical properties of the raw material/ Fiber	Density	(D)
	Porosity	(P)
Technical properties of the acoustic panel	Air Flow resistivity	(AFR)
	Thickness	(TH)
	Sound Absorption Capacity	(SAC)
	Noise reduction coefficient	(NRC)
	Thermal conductivity	(TC)
Environmental aspect	Water Consumption	(WC)
	Chemical usage	(CU)
	Global Warming Potentials	(GWP)
	Biodegradability of the prepared raw material	(B)
Cost	Cost of preparing the raw material	(CRM)
	Cost of transportation	(CT)
	Cost of manufacturing the panel	(CP)

3.3.1 Technical properties of the raw material

3.3.1.1 Density

Density is an important quality for acoustics, when the density of a material is high, then the sound absorption improves at middle and high frequencies. However, when the structure is less dense and has more porous then, the absorption is shifted to lower frequencies (Nandanwar et al., 2017) (Sakthivel et al., 2020). Density is a unique character for each material and differ widely depending on how the raw material is prepared. For recycled textile, it was reported as 57 kg/m³ by (Del Rey et al., 2015) and 154 kg/m³ by (Sakthivel et al., 2020). While tea waste density was reported as 91.5 kg/m³ by (Tang et al., 2020) and 310 kg/m³ by (Evbuomwan and Boyle, 2020). For corn husk the density was reported as 112 kg/m³ by (Pandecha et al., 2015) and 158 kg/m³ by (Sari et al., 2017). Lastly, Fiberglass density is measured as 34 kg/m³ by Asdrubali and 48 kg/m³ by KINETICS (a fiberglass acoustic panel company that produces sound absorptions worldwide). For the case of this study, densities will be selected in 2 terms, high enough to provide acoustic absorption characteristics, but not too high where it will make the panels heavy (see Table 3.5).

3.3.1.2 Porosity

It can be defined as the ratio of the voids volume in a porous material to its total volume. Porosity has a proportional relation to the sound absorption; Increasing the porosity leads to a higher sound absorption (Umnova et al. 2005). Table 3.5 summarize the technical properties (density and porosity) values of the studied raw materials.

Table 3.5 : The technical properties values of the studied raw materials.

Material	Density (kg/m ³)	Reference	Porosity (%)	Reference
Recycled Textile	57	Del Rey et al., (2015)	90%	Sakthivel et al., (2020)
Tea Waste	91.5	Tang et al., (2020)	59%	Evbuomwan and Boyle, (2020)
Corn Husk waste	158	Sari et al., (2017)	79%	Sari et al., (2017)
Fiberglass	48	Kinetics PA., (2022)	98%	Kinetics PA., (2022)

3.3.2 Technical properties of the acoustic panel

3.3.2.1 Sound Absorption Coefficient

SAC is used to evaluate the sound absorption efficiency of materials. It is the ratio of absorbed energy to incident energy. The absorption coefficient ranges between zero and one, one meaning no sound energy is reflected and the sound is absorbed and zero means no absorption. For a material to meet the minimum limits of SAC value, it has to be 0.2 or more, keeping in mind, the higher the better. This study is interested in absorbing the sound frequencies in the mid-high ranges. Mid frequencies are 200-2,000 Hz. Anything below 200 Hz is considered low frequency and anything above 2,000 Hz is high frequency sound. Figure 3.8 shows the SAC graphs of the 4 studied materials adapted from the following references; (Del rey at al., 2016), (Tang et al., 2020), (Sari et al., 2017) and (Kinetics PA., 2022).

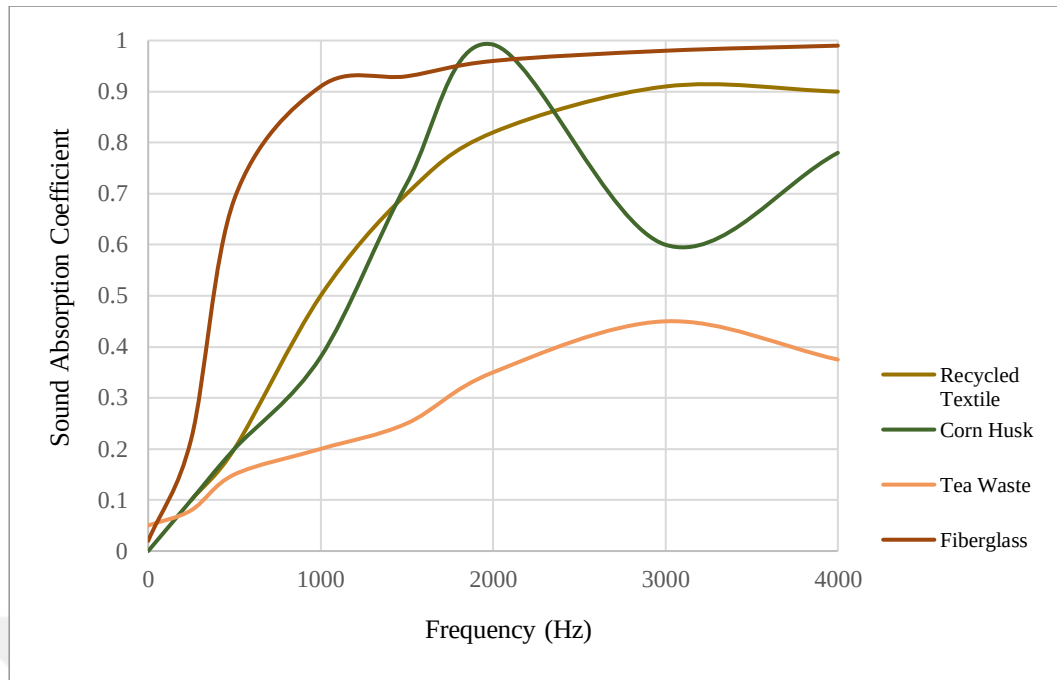


Figure 3.8 : The sound absorption coefficient values for studied materials.

For this sub-criterion, SAC value is selected at 2000 Hz to give an indication of the quality of sound absorption at mid-high ranges as it can be seen in Table 3.6.

Table 3.6 : The SAC values at 2000 Hertz.

Material	Sound absorption capacity @2000 Hz	Reference
Recycled Textile	0,82	Del Rey et al., (2015)
Tea Waste	0,35	Tang et al., (2020)
Corn Husk	1	Sari et al., (2017)
Fiberglass	0,96	Kinetics PA., (2022)

3.3.2.2 Noise reduction coefficient

NRC is a single number rating which represents the average of sound Absorption Coefficients of a material at specific mid-range frequencies (tested at 250, 500, 1,000, and 2,000 Hz octaves). The purpose of an NRC rating is to provide a simpler way to determine how well an acoustical product absorbs mid-range sound. (Acoustical Surfaces, 2020). NRC ratings are calculated by taking the arithmetic averages of a material's sound absorption coefficients at the specified frequencies and then rounding it to the nearest 0.05. NRC values were calculated using Figure 3.8 and they are as following; Recycled textile 0,37, tea waste 0,20, corn husk 0,42 and fiberglass 0,7.

3.3.2.3 Air Flow Resistivity

Air flow resistivity is defined as the resistance to air within a unit of thickness; it reflects the permeability of air through porous materials. It can be deduced that higher airflow resistance results in higher sound absorption values (Sakthivel et al., 2020). This is due to sound waves losing energy because of the surface friction increases, resulting in an increase in the material's sound absorption performance. AFR in literature, was reported as following: recycled textile; 2680 pa.s.m^{-2} (Del rey et al., 2015), tea leaf fiber; 2264 pa.s.m^{-2} (Wong et al., 2017), corn husk waste; 14435 pa.s.m^{-2} (Sari et al., 2017) and fiberglass 9000 pa.s.m^{-2} (Berardi and Ramakrishnan., 2016).

Where pa= pascal, s= second, m^{-2} = square meter

3.3.2.4 Thickness

Increasing the thickness of a material is effective for the absorption of low frequencies ranges, while it doesn't have a significant impact for the absorption in the high frequencies (Hua and Enhui, 2017). However, it is an important parameter when it comes to the aesthetic aspect of the acoustic panels. It is preferable to have a thinner panel that is easily installed and light in weight. For the studied materials, the thickness is as following; 12 mm for recycled textile, 30 mm for tea leaf fiber, 20 mm for corn husk waste and 25 mm for fiberglass. These values were selected after analyzing the SAC in literature for each material. References are available in Table 3.7.

3.3.2.5 Thermal conductivity

This parameter has no direct influence on the SAC values and the efficiency of the acoustic panel. However, it was considered as an advantage for the panel to have a thermal resistance, thus less energy consumption for heating and sequentially a lower environmental impact. Low values of the thermal conductivity imply higher resistance to conduction of the heat through the material, so the lower the value the better heat transmission resistance. Table 3.7 summarize the technical aspects of the acoustic panel including the thermal conductivity values.

Table 3.7 : The technical properties of the acoustic panels made from the proposed raw materials.

Criteria	Recycled Textile	Tea Waste	Corn Husk	Fiberglass
Sound absorption capacity @2000 Hz	0.82	0.24	1	0.96
Reference	Del Rey et al., (2015)	Tang et al., (2020)	Sari et al., (2017)	Kinetics PA., (2022)
Noise reduction coefficient	0.37	0.20	0.42	0.7
Reference	Del Rey et al., (2015)	Tang et al., (2020)	Sari et al., (2017)	Kinetics PA., (2022)
Thermal conductivity (W/mK)	0.128	0.36	0.052	0.04
Reference	Sakthivel et al., (2020)	Jayalakshmy and Philip., (2010)	Ramos et al., (2021)	Ricciardi et al., (2014)
Airflow resistivity (Pa·s·m ⁻²)	2680	2264	14435	9000
Reference	Del Rey et al., (2015)	Tang et al., (2020)	Sari et al., (2017)	Kinetics PA., (2022)
Thickness (mm)	12	30	20	25
Reference	Del Rey et al., (2015)	Tang et al., (2020)	Sari et al., (2017)	Kinetics PA., (2022)

3.3.3 Environmental properties

3.3.3.1 Water consumption

Water use is the first parameter in this study that lays under the environmental impact. It corresponds to the gross quantity of the total water volume that is withdrawn from the natural environment for all purposes required in the studied system.

The evaluation of water consumption will be based on a semi-quantitative Likert scale at the range of 1 to 5, Whereas; 1 is the lowest and 5 is the highest.

As discussed earlier in this chapter 3 (3.2.1 and 3.2.2) there was no water consumption for both the recycled textile and the tea waste materials. Whilst for the corn husk fiber, 15.8 L/FU of water is used for preparing the raw material. It includes both the washing and the alkali treatment of the corn husk.

The data of water consumption for fiberglass were adapted from a report prepared for the European Glass Fiber Producers Association commissioned (PwC, 2016). The report presents the cradle-to-gate life-cycle inventory and life-cycle impact assessment results of several glass fiber products including sound absorptions. The water required for producing 1 acoustic panel is 34.5 L/FU.

3.3.3.2 Chemical usage

This parameter gives an indication of the amount of chemicals required to prepare one acoustic panel. The aim is to have eco-friendly acoustic panels that replace the existing which are made from synthetic fibers. Therefore, this parameter is considered and it will be evaluated with the Likert scale at the range of 1 to 5, Whereas; 1 is the lowest and 5 is the highest.

For the recycled textile, the raw material is made from 80% recycled textiles; 75% of this percentage is cotton (CO) and the other 25% is polyester fiber. Since this polyester fiber is from waste textile and it participates in solving a waste issue then it will not be considered as chemical input. However, the rest of the composition (20%) corresponds to the polyester binder and this can be considered as a chemical input to the system.

For the case of tea waste, the material is a type of food waste, no chemicals were used for preparing it. The binder is natural rubber latex which comes from trees. Thus, no chemicals were used.

For the corn husk, the material is agriculture waste. For preparing it, 0,0158 kg/FU of NaOH was used to improve the properties of the natural fiber (Sari et al., 2016 and 2017) (Pandecha et al., 2015). Additionally, 0.63 kg/FU of polyester binder is used.

For fiberglass, there are many chemicals included in the manufacturing such as; calcined alumina, borax, feldspar, nepheline syenite, magnesite, and kaolin clay and others chemicals. Some of them for example borax is a toxic chemical and can quickly broke down by the body if ingested and inhaled. Scientists have linked borax exposure to organ damage and serious poisonings (Hadrup and Frederiksen, 2021).

3.3.3.3 Global warming potentials

This is one of the most important parameters that has a global impact, it gives an indication of the carbon dioxide emissions from the different processes included in producing a product. GWP is described in terms of CO₂ emission equivalence.

There is no data available in literatures about the GWP for the exact proposed process flow in this thesis. That is why, there was a need to conduct a simple Life Cycle Assessment study specifically for the scenarios structured in this study including the proposed materials and process flows. There are many common LCA tools such as, GaBi, SimaPro, Tally, Athena and OpenLCA. The results conducted by these softwares can show significant variation even when the studied cases were the same due to methodological choices and assumptions (Emami et al., 2019). For the case of this thesis study, OpenLCA software will be used. It is a free, easy to use and a professional Life Cycle Assessment (LCA) and footprint software with a broad range of features and many available databases.

The version that will be used is 1.10.3 by GreenDelta, Berlin. Database used is ecoinvent 3.7 and the impact assessment method is IPCC. The outputs are mentioned in Tables 3.8.

Table 3.8 : Output data for manufacturing acoustic panels from the 3 proposed materials.

	Output	Amount	Unit	Reference
Recycled Textile				
Shredding-Electricity	CO2 emissions indirect	0,024	kg CO2 eq/FU	This Study
Shredding-Electricity	PM5-10	Can be neglected	-	This Study
Carding-Electricity	CO2 emissions indirect	0,091	kg CO2 eq/FU	This Study
Carding	VOC	Can be neglected	-	Wendin, (2016)
Tea Waste				
Transportation	CO2 emissions-direct	0,09	kg CO2 eq/FU	This Study
Drying	CO2 emissions-Indirect	0,391	kg CO2 eq/FU	This study
Molding (press and heat)	CO2 emissions-Indirect	0,088	kg CO2 eq/FU	This study
Corn Husk				
Cleaning	Wastewater (90%)	14,22	L/FU	This study
Transportation	CO2 emissions-direct	0,09	kg CO2 eq/FU	This study
Grinding	CO2 emissions-indirect	0,035	kg CO2 eq/FU	This study
Moulding (Press and heat)	CO2 emissions-indirect	0,126	kg CO2 eq/FU	This study

It is worthy to mention that output data for the electricity were calculated using the technical sheet of the machine. In the sheet, information about the capacity and the electricity consumption are provided. After calculating how much electricity is needed per function unit (Tables 3.1, 3.2, 3.3). The kilowatts are then converted to the its equivalent of CO2 emissions using the online tool: RENsmart. This tool uses data from reliable resources such as exio base. Exio Base is a global, detailed Multi-Regional Environmentally Extended Supply-Use Table (MR-SUT) and Input-Output Table

(MR-IOT). It was developed by harmonizing and detailing supply-use tables for a large number of countries to estimate emissions.

Entering the process flow inputs and outputs in OPENLCA software resulted in calculating the GWP for each material. Some references such as Wendin, 2016 suggest adding 5% on the top of GWP results to take in account any unexpected\unplanned inputs. The results of calculating GWP using OPENLCA software are reported in Table 3.9 with and without the 5%.

Table 3.9 : The global warming potentials results of all the proposed materials using OPENLCA software.

Material	GWP (kg eq. CO ₂ \ FU)	GWP with 5% TOP	Reference
Recycled Textile	0,115	0,121	This study- OPENLCA
Tea Leaf Fiber	0,569	0,597	This study- OPENLCA
Corn Husk Waste	0,251	0,264	This study- OPENLCA
Fiber Glass	2,037	2,037	Adapted from Asdrubali et al., (2012)

3.3.3.4 Biodegradability of the prepared raw material

Biodegradable materials are materials that can safely be disposed of in the natural environment, where they decompose and breakdown completely, in the presence of microorganisms like bacteria and fungi found in soil. A truly biodegradable material breaks down completely and leaves behind no residues or traces.

This part evaluates the biodegradability of the prepared raw material before adding the binders because binders can be changed into alternatives in the future which are more eco-friendly and perhaps from natural resources.

In the case of recycled textile, the material consists of 75% cotton and 25% polyester. Frey M., 2010 studied the biodegradability of both cotton and polyester textile and she found out that 50-77% of cotton fibers biodegrade after 90 days and when the cotton is not treated with chemicals, gradually it will biodegrade completely. But this is not the case for polyester, after 90 days it was found that only 20% of its weight biodegraded. As a conclusion, it is fair to say that 75-80% of the raw material is biodegradable whilst the other 20-25% is not.

For tea leaf fiber, Ogata and Gao, 2019 investigated the possibility of using tea waste as “Tea Waste Recycling System” because its high biodegrading rate. Basically, the study proposing a way of making composites of other materials with tea to make use of the fast-biodegrading capacity of tea waste. In the matter of fact, China produces a large amount of tea waste every year, to use this waste in the development of new biodegradable tea waste products based on the “tea waste recycling system”. Based on this study, tea waste sound absorption material can be considered as 100% biodegradable material.

For corn husk waste, Pang et al., 2008 proved in his study that adding 6% of NaOH for the corn husk waste for pretreatment increase the cellulose content and accelerate the biodegradability of corn husk waste to a rate higher than of the untreated corn husk. This state that the corn husk raw material is biodegradable even with sodium hydroxide treatment.

Lastly, for the case of fiberglass it is made of synthetic fibers, therefore fiberglass does not decompose; regardless of the weather, chemicals, and other environmental factors, fiberglass cannot be broken down by microorganisms. The “fiber” in the name represents plastic, and plastic does not decompose, neither does glass. This is the last sub-criteria in the environmental aspect. Table 3.10 summarize all the data and their values. For the case of; chemical usage and biodegradation of raw materials the evaluation is done with a Likert scale, ranges from 1 to 5 where:

1= low, 2= relatively low, 3= average, 4= relatively high and 5= high

Table 3.10 : The environmental impact of the proposed acoustic panels.

Recycled Textile	Sub-criteria	Value
	Water consumption	0 L
	Chemical usage	2
	Global warming potential (kg CO ₂ equivalent/FU)	0,121
	Biodegradability of raw material	4
Tea Waste	Sub-criteria	Value
	Water consumption	0 L
	Chemical usage	1
	Global warming potential (kg CO ₂ equivalent/FU)	0,597
	Biodegradability of raw material	5
Corn Husk Waste	Sub-criteria	Value
	Water consumption	15,8 L
	Chemical usage	3
	Global warming potential (kg CO ₂ equivalent/FU)	0,264
	Biodegradability of raw material	5
Fiberglass	Sub-criteria	Value
	Water consumption	34,5 L
	Chemical usage	5
	Global warming potential (kg CO ₂ equivalent/FU)	2,037
	Biodegradability of raw material	1

3.3.4 Cost

This section investigates the cost analysis of preparing, transporting and manufacturing the acoustic panels from the proposed materials. A cost chart has been created for all input data including, raw materials, electricity, fuels, water and chemicals used. The costs per items have been selected by taking the last updated prices in the private sector and it may vary due to factors such as brand and manufacturer variability.

3.3.4.1 Cost of producing one acoustic panel from recycled textile

As mentioned earlier in this chapter, it requires 0,97 kg of waste textile to produce one acoustic panel. This waste textile has a cost and it must be considered, by interviewing textile factory owner in Istanbul (Beethoven factory, January 2022-Merter/Istanbul) it was stated that waste textile is sold for an average price of \$0,75 for 1 kg. This waste is usually sold for other textile plant owners to recycled the fabric and re-use it as a raw material.

This price of the textile waste is 15% its original price. When it costs \$5 to buy 1 kg of a new fabric then it requires \$0.75 to purchase the waste. Since the manufacturing of the sound absorption materials occurs in the industrial zone of Umraniye, which is assumed to be adjacent to the textile factory where the waste is collect then, transportation costs are considered to be negligible. For shredding and carding process, the cost of electricity is considered. For the case of Turkey and for the industrial sector the cost of 1 kwh is \$0,09 (Hacaoglu, S., 2022). For the polyester binder, the price difference between the powder and liquid forms were not large; powder polyester: 1,16 \$/kg and solution polyester: 1,75 \$/kg. Therefore, the decision was to go with the solution polyester option to minimize the water footprint coming from binding the material.

It is also necessary to take the labor cost in account. For the middle east region, the labor wages are estimated to be 35% of the total initial cost. (The Egyptian Cotton Project, 2020). Additionally, a 30% of the total is considered to cover any unplanned cost. All this result in a cost of \$2,04 for producing one acoustic panel from the recycled textile. See Table 3.11 for the further details and cost values.

Table 3.11 : The cost of producing one acoustic panel from the recycled textile.

Input	Amount	Unit	Unit Cost (\$/Unit)	Cost per Acoustic Panel (\$/FU)	Reference
Recycled textile	0,97	Kg	0,75	0,728	This study (interview with a textile company)
Electricity	0,182	Kw	0,09	0,016	Hacaoglu, S., (2022)
Polyester Binder	0,24	Kg	1,75	0,420	Mike, (2021)
Labor (35%)				0,407	The Egyptian Cotton Project, (2020)
Total				1,571	
Unplanned cost 30%				0,471	Sorrels et al., (2017)
Total				2,04	

3.3.4.2 Cost of producing one acoustic panel from tea waste

It requires 2,88 kg of waste tea to produce one acoustic panel. This waste can be collected from different coffee shops around Istanbul.

To give a detailed assumption about the tea waste cost, an interview was held with the manager of Espresso Lab, the popular coffeeshop chain, in Bomonti branch/Istanbul at January, 2022.

The manager stated that; there is no current system of collecting tea waste in his coffeeshop, but if there is a company that might be get benefits from using this waste, then they are willing to provide their tea waste free of charge. Because, in his opinion, this will help with getting rid of the waste and also, gives their coffeeshop the credit of being part of a green project. Another interview took place at the same day with the branch manager of Starbucks/ Bomonti/ Istanbul. They also expressed their willing to give the tea waste free of charge.

Accordingly, and based on the interviews above, it is fair to assume that tea waste will have no purchasing fees.

Collecting the tea waste from different coffeeshops around Istanbul will consume fuel for transportation. It is assumed that a light duty track with maximum capacity of 1,800

kg is used. This truck requires 6 L/100 km of diesel which results in 0,003 L/FU of fuel. Therefore, 0,003 \$/FU as the diesel price is \$1 in Turkey (2022).

After the raw material arrives the manufacturing location, different processes will be applied and some of them (drying and pressing) will consume electricity. Lastly, rubber latex -binder- is applied and its cost is counted. 35% labor and 30% unplanned costs are added similar to recycled textile material. Table 3.12 shows the detailed prices per each process and item and their references.

Table 3.12 : The cost of producing one acoustic panel from the tea waste.

Input	Amount	Unit	Unit Cost (\$/Unit)	Cost per Acoustic Panel (\$/FU)	Refeferenc
Tea Waste	2.88	Kg	0	0	Interview
Electricity (drying)	0,62	Kw	0,09	0,06	Hacaoglu, S., (2022)
Electricity (press and heat)	0,14	Kw	0,09	0,01	Hacaoglu, S., (2022)
Rubber Latex	0,137	Kg	1,7	0,23	Wamucii, S., 2022
Transportation (100Km)	0,003	L	1	0,0030	Turkey diesel prices, (2022)
Labor (35%)				0,11	The Egyptian Cotton Project, (2020)
Total				0,41	
Unplanned cost 30%				0,12	Sorrels et al., (2017)
Total				0,53	

Therefore, the total cost of producing one acoustic panel using the tea leaf waste is \$0.53.

3.3.4.3 Cost of producing one acoustic panel from corn husk waste

The corn husk waste is available to be purchased from many suppliers for different costs. The current use of the corn husk is stockfeed. However, it is assumed that the corn husk price is 5% of the commercially available corn.

The amount of corn husk required to produce one acoustic panel is 3.25 kg. The average corn price was found to be 0,6 \$/kg. Therefore, corn husk is assumed to cost 0,097 \$/FU.

For the preparation phase, the price of water used for washing, sodium hydroxide and the water used to dilute sodium hydroxide were counted and added to Table 3.13

For transportation the assumption is as following; 1 ton lorry was used to transport the prepared raw material from corn field exist in villages Ağva-Şile/Istanbul to the manufacturing factory in Umraniye\ Istanbul, the distance was calculated using Google maps and found to be 100 km and for that, the cost of fuel is calculated.

Lastly, in the production phase, there is electricity consumption for grinding and pressing in addition to the binder cost. Adding up the costs of preparing the raw material, transportation and manufacturing, labor and the additional unplanned cost will result in a total cost of \$2,38 to produce one acoustic panel from corn husk waste, which makes it less affordable material among the Three. Reasoning and discussions will be further explained in Chapter 4.

Table 3.13 : The cost of producing one acoustic panel from the corn husk.

Input	Amount	Unit	Unit Cost (\$/Unit)	Cost per Acoustic Panel (\$/FU)	Reference
Corn waste	3,25	Kg	0,03	0,0975	Assumption
Water	11,2	L	0,0017	0,02	www.invest.gov.tr
NaOH	0,158	Kg	0,19	0,030	Mike, (2021)
Water to dilute NaOH	0,30	L	0,0017	0,00051	www.invest.gov.tr
Electricity (Grinding)	0,056	Kw	0,084	0,005	Hacaoglu, S., (2022)
Electricity (press and heat)	0,2	Kw	0,084	0,02	Hacaoglu, S., (2022)
Polyester binder	0,63	Kg	1,75	1,10	Mike, (2021)
Transportation (98Km)	0,086	L	1	0,0860	Turkey diesel prices, 2022
Labor (35%)				0,47	The Egyptian Cotton Project, (2020)
Total				1,83	
Unplanned cost30%				0,55	Sorrels et al., (2017)
Total				2,38	

3.3.4.4 Cost of producing one acoustic panel from fiberglass

Many researchers in the last decade conducted studies to calculate the cost of insulations (thermal or acoustic) from fiberglass. Here are some of them; Pandecha et al., 2015 mentioned the cost of fiber glass insulation is 5.1 US/m². While Asdrubali et al., 2012 reported \$1.2 for the 1 kg of fiberglass. When checking the suppliers and market, it was found that the price can vary between \$1.2 to \$5.2 with the majority of prices laying in the range of \$1.2- \$2.75. Thus, an average of \$2/kg is considered for this study. Since 0,96 kg of fiberglass is needed to manufacture 1x1 m acoustic panel with a thickness of 25 mm, then the cost of producing 1 acoustic panel from fiberglass is \$1,92.

4. RESULTS

The main output of the TOPSIS within the scope of the thesis is to select the best option among the alternatives, evaluate them within the framework of the criteria, and determine the most suitable material alternative to be used in acoustic panel production. Each material was selected carefully while taking in account the availability of the material in Turkey. The data were collected from literatures for the technical aspect, while it was calculated in this thesis for both of the environmental and economic aspects. According to TOPSIS each criteria\aspect must have a weight that is determined by the user. It is possible to weight different criteria for each user depending on the aspect of interest. When evaluating the environmental impact is the priority, then this category might have the highest weight among all criteria to give a better insight on the environmental behavior of the suggested material. Likewise, within this category if global warming potential (GWP) is the parameter of interest, then this sub-criterion may have the highest weight.

In this study the technical aspect was weighted with 45 points since it is important for the materials to have technical characteristics comparable to the commercially available ones. Comparable to that, the environmental aspect was weighted with 40 points as the main focus here is to have sustainable materials to replace the synthetic fibers. Lastly, although cost effectiveness was not the primary focus in this study, the cost aspect was also taken into account with a total of 15 points. In the end the total weight for all criteria combined must be 100. Calculations were made for a total of twelve sub-criteria for the technical (raw material and acoustic panel) environmental and cost aspects and each criteria have its own sub-criteria to give an insight of the material's overall characteristics. Figure 4.1 shows a graph of the decision matrix to choose the best alternative sound absorbing materials (SAM) for use in acoustic panel production.

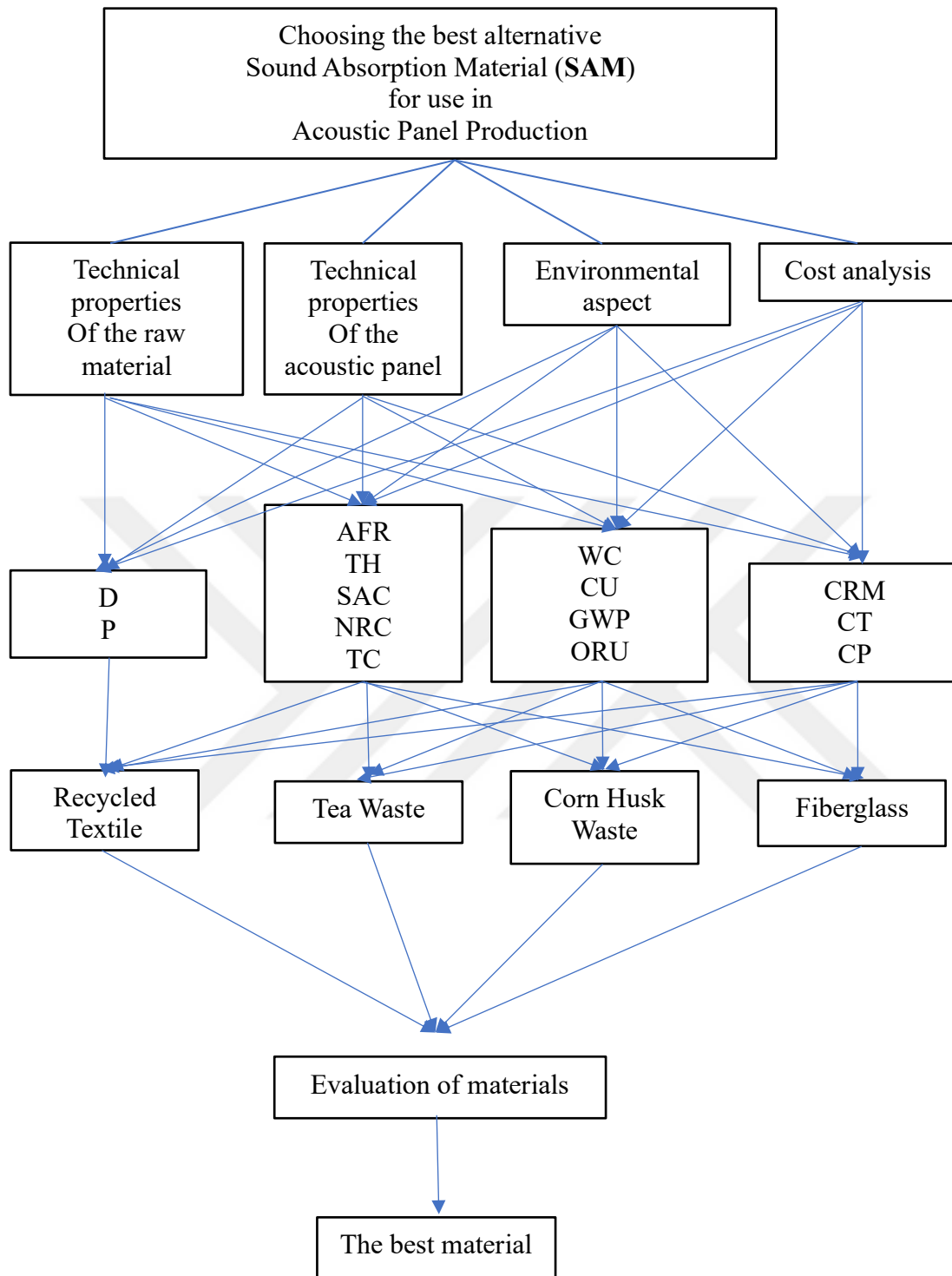


Figure 4.1 : Decision matrix of criteria and sub-criteria of sound absorbing materials.

4.1 Evaluation of Technical, Environmental and Economic Aspects

4.1.1 Evaluation of technical aspects

The most important technical qualities of the acoustic panel are:

- sound absorption capacity, since it is one of the primary indicators of technical performance in terms of sound absorbing.
- and noise reduction coefficient (NRC), it is also a measure of sound absorption performance but it covers wider ranges of frequencies, which makes it more accurate in understanding the sound absorbing behavior of a material. Figure 4.2 shows the SAC of the materials at 2000 Hz

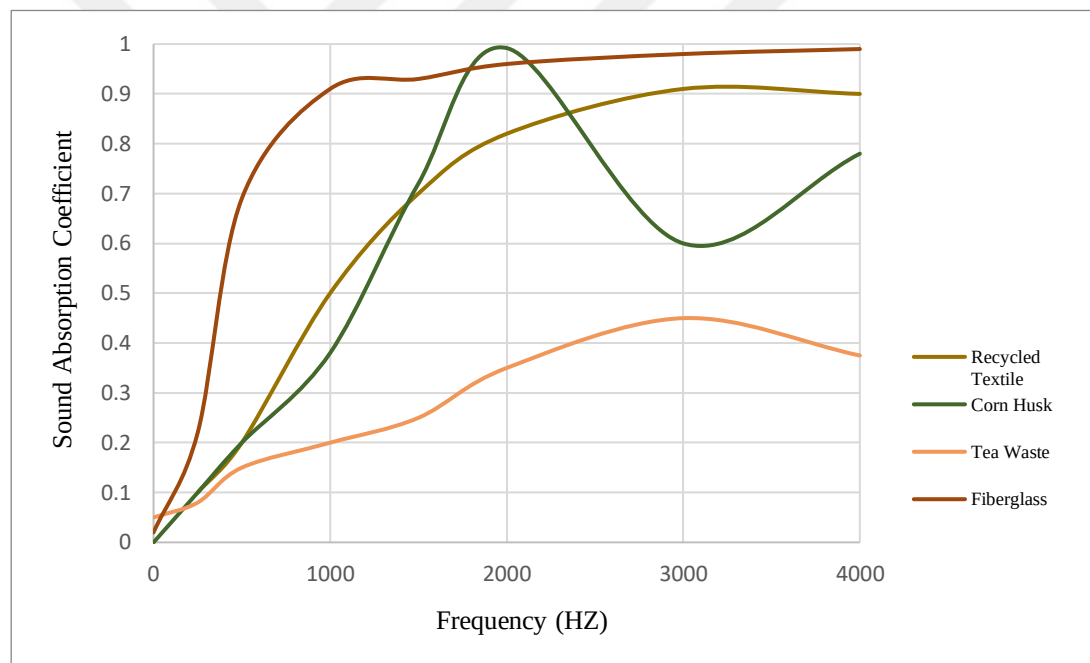


Figure 4.2 : SAC of the studied materials at 2000 Hz.

From the first observation of Figure 4.2 it can be seen that Fiberglass shows a steady behavior of the SAC considering it is a commercial material optimized for this purpose. Followed by recycled textile which shows a similar behavior to FG in matter of having a steady raise and promising results. On the other hand, corn Husk material has a peek at 2000 Hz which equals to 1 and it is optimal for this study (mid to high ranges). However, when looking at the overall performance of the CH material it can be stated that it is not stable like FG and RT.

For tea waste, although it has the lowest SAC value among the other alternatives but the sound absorption performance is found to be satisfactory for high ranges (2000 Hz-4000 Hz). Additionally, it has an advantage of being a steady material and this indicates promising possibilities if combined with other materials.

To have a better idea of the material's acoustic characteristics, NRC is studied (Figure 4.3)

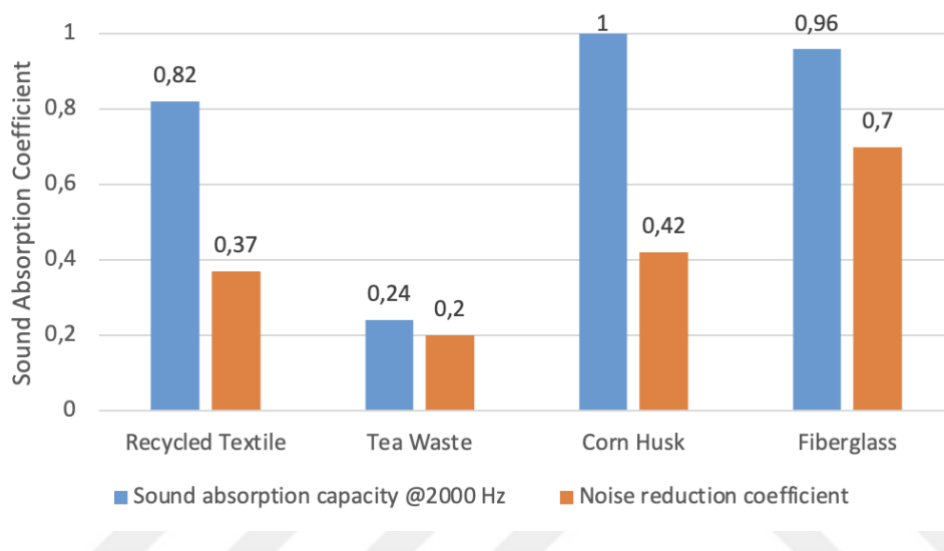


Figure 4.3 : Sound absorption capacity and noise reduction coefficient of the 4 materials.

The other technical parameters have an impact on the SAC/NRC values, either direct or indirect. The majority of them (density, porosity, airflow resistance and thickness) relate proportionally to the sound absorption coefficient. While the thermal conductivity does not have an impact on the SAC (Nurzyński et al., 2015) but it is an additive advantage for the material to have low thermal conductivity. It is important to determine which parameter has a positive impact on the acoustic panel and which one does not. Table 4.1 shows the technical properties of each material and the type of the impact (positive or negative); where positive means the higher the better, and negative means the lower the better.

Table 4.1 : The technical properties of each material and their impact on the acoustic panel.

Criteria	Impact	Recycled Textile	Tea Waste	Corn Husk	Fiberglass
Sound absorption capacity @2000 Hz	+	0,82	0,24	1	0,96
Noise reduction coefficient (NRC)	+	0,37	0,20	0,42	0,7
Thermal conductivity (W/mK)	-	0,128	0,36	0,052	0,04
Airflow resistivity (Pa. s. m ⁻²)	+	2680	2264	14435	9000
Thickness (mm)	+	15	30	20	25
Density (kg/m ³)	+	57	91,5	158	48
Porosity (%)	+	90	59	79	98

4.1.2 Evaluation of the environmental aspect

Within the scope of the TOPSIS method, the environmental criteria of the emerging sound absorption materials were evaluated and compared with each other. The parameters of water consumption, chemical usage, global warming potentials and biodegradability were selected.

By using the data collected from literature and OPENLCA software, the environmental parameters were evaluated. In Figure 4.4 the impact of each criterion is given.

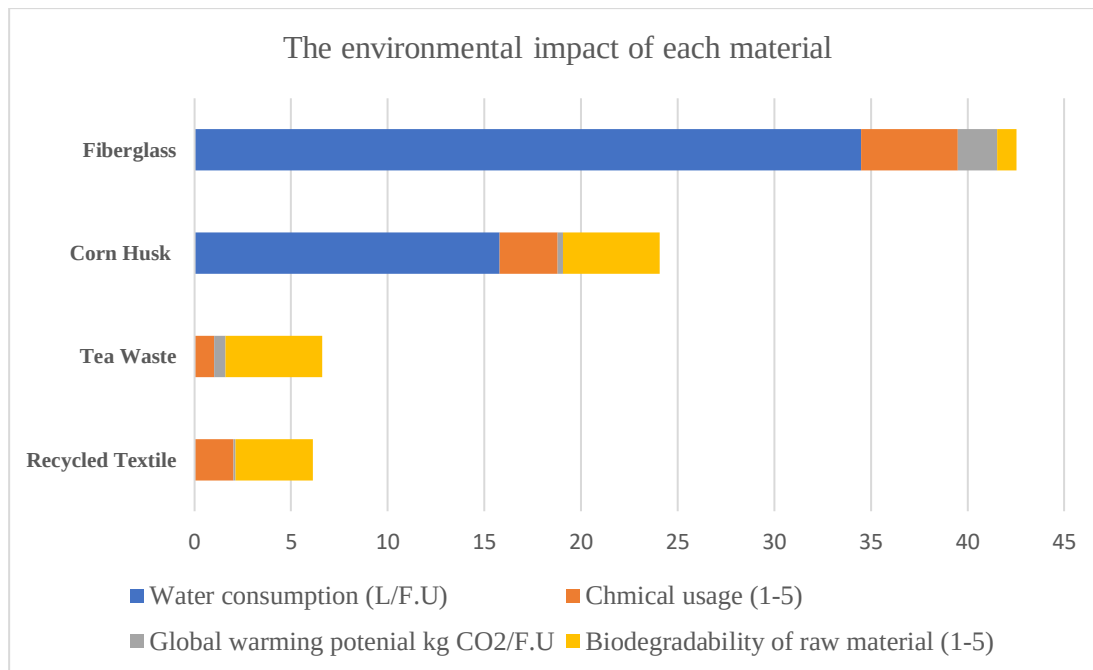


Figure 4.4 : The evaluation of the environmental aspect. Biodegradability is the only positive parameter among the four, where more is better.

It can be seen in the Figure 4.4 that water consumption is the highest in fiberglass, followed by corn where water is used for both washing the corn and diluting the treatment agent. In tea waste, no water is needed for washing the waste, the first step for preparing the material is drying in the oven. This process lasts for 24 hours and results in disinfection of the raw material and drying it out so it is ready to be manufactured into an acoustic panel. Also, no water is needed for the recycled textile material, the waste is collected from post-industrial/ pre-consumer where the fabrics are clean and new.

In the chemical usage parameter, fiberglass also ranks the highest because a different mix of chemicals is used and some of them like borax compounds has a toxic effect of human's health (Hadrup and Frederiksen, 2021). This is followed by recycled textile where polyester is part of the material's composition and also a binder. While for corn husk and tea waste low- no chemicals were used.

The third parameter is the biodegradability of the raw material before adding binders. And this is a positive criterion. Tea waste and corn husk are the best in this matter because they are natural fibers made of food wastes and agricultural wastes, respectively.

Lastly, the evaluation of the global warming potential (GWP). This is an important criterion and it will be study in details. Figure 4.5 shows the GWP of each material.

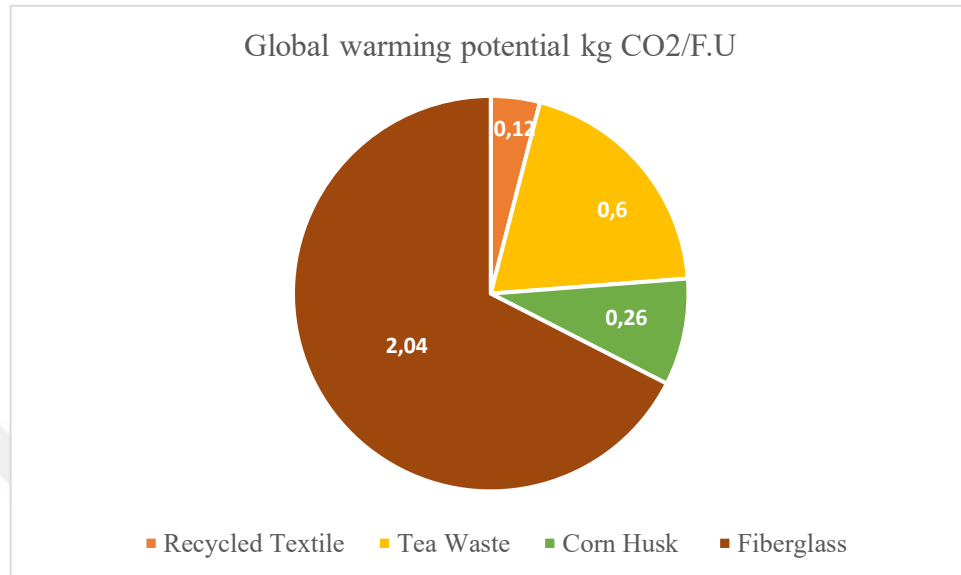


Figure 4.5 : The global warming potential of each material.

Fiberglass has the highest GWP value. The breakdown of the contributors is (50 %) for the galss production stage (energy consumption from fossil fuels and decarbonation of raw materials), 22 % of emissions are due to the production of raw materials, 17% to electricity production and 11% to fossil fuel production. (European Glass Fiber Producers Association commissioned PwC, 2016).

Figure 4.6 shows the breakdown of GWP for tea waste material, it is calculated as 0.6 kg CO2/FU and the main contributor to this value is the drying process, it is responsible for 0,414 kg CO2/FU of indirect CO2 emissions that comes from electricity usage.

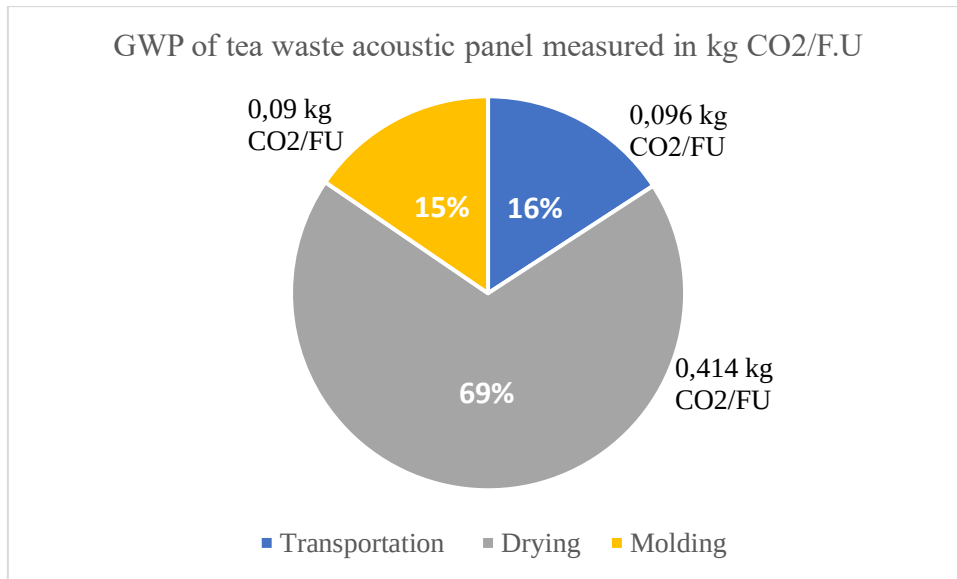


Figure 4.6 : The global warming potential of tea waste acoustic panel.

For corn husk acoustic panel, GWP is calculated as 0,26 kg CO₂/FU and it is a low value when compared to the first 2 materials. It is around 3 times less than the GWP of tea waste and 10 times less than Fiberglass panel. Figure 4.7 shows each production process contribution to the GWP of corn husk acoustic panel.

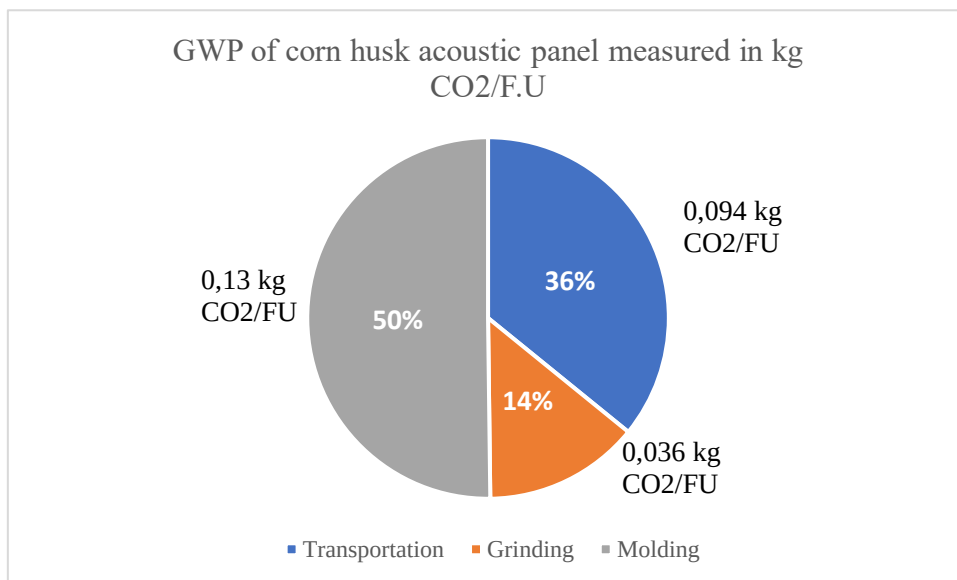


Figure 4.7 : The global warming potential of corn husk acoustic panel.

Lastly, and with the lowest GWP comes the recycled textile material, it has 0,12 kg CO₂/FU. The reason behind it is, there is no transportation phase for shipping the raw material and the indirect CO₂ emissions from electricity are low as it can be seen in Figure 4.8.

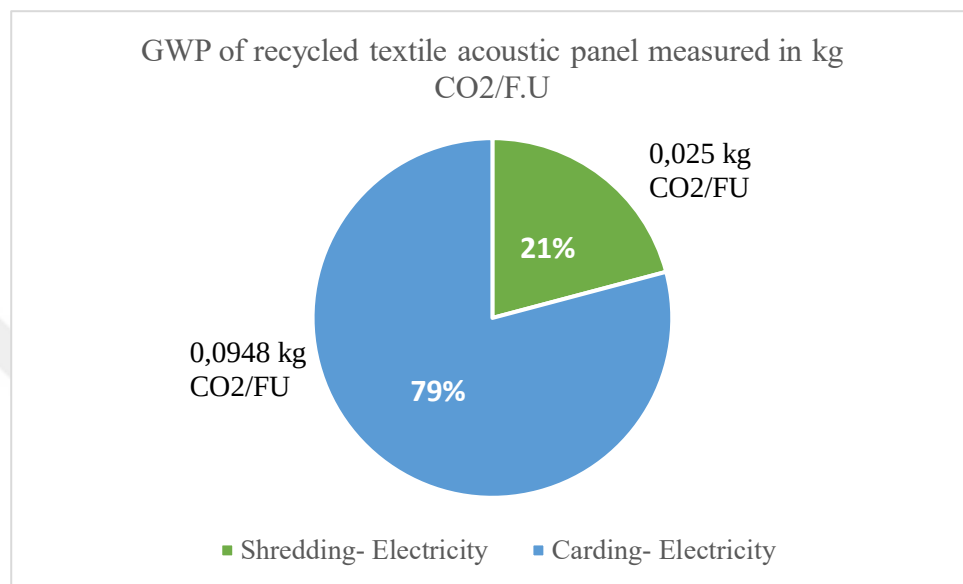


Figure 4.8 : The global warming potential of recycled textile acoustic panel.

4.1.3 Evaluation of the economical aspect

In terms of cost, a chart has been created for all materials, taking into account the cost of electricity, water consumption, chemicals used and the fuel needed for transportation. Costs were calculated by taking the last updated prices in the private sector (as of the first quarter of the year 2022). Costs may vary due to different factors such as brand and manufacturer variability. Figure 4.9 shows the production cost of each material in US dollar.

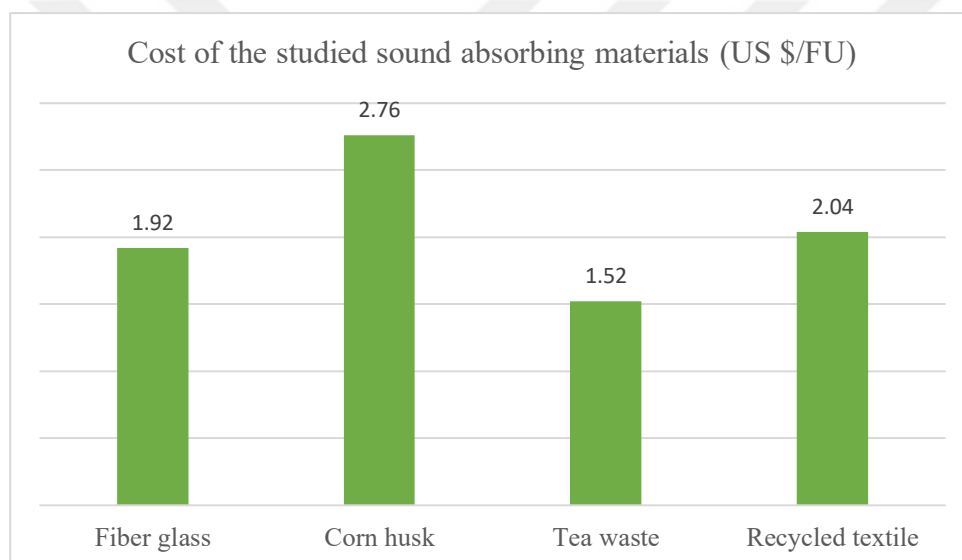


Figure 4.9 : The production cost of each acoustic panel in US dollar.

It can be seen that the production cost is the highest for the corn husk acoustic panel with 2,76 US \$/FU. Followed by RT with a total cost of 2,04 US \$/FU. When comparing these two values with the price of Fiberglass acoustic panel, the difference is reasonable especially for the RT material.

Tea waste acoustic panels had the lowest cost, namely 1,52 US \$/FU which is even lower than the cost of the commercially available material.

If the cost is studied separately for each material, then the influence will be better understood. Figure 4.10 shows the price breakdown for the corn husk acoustic panel.

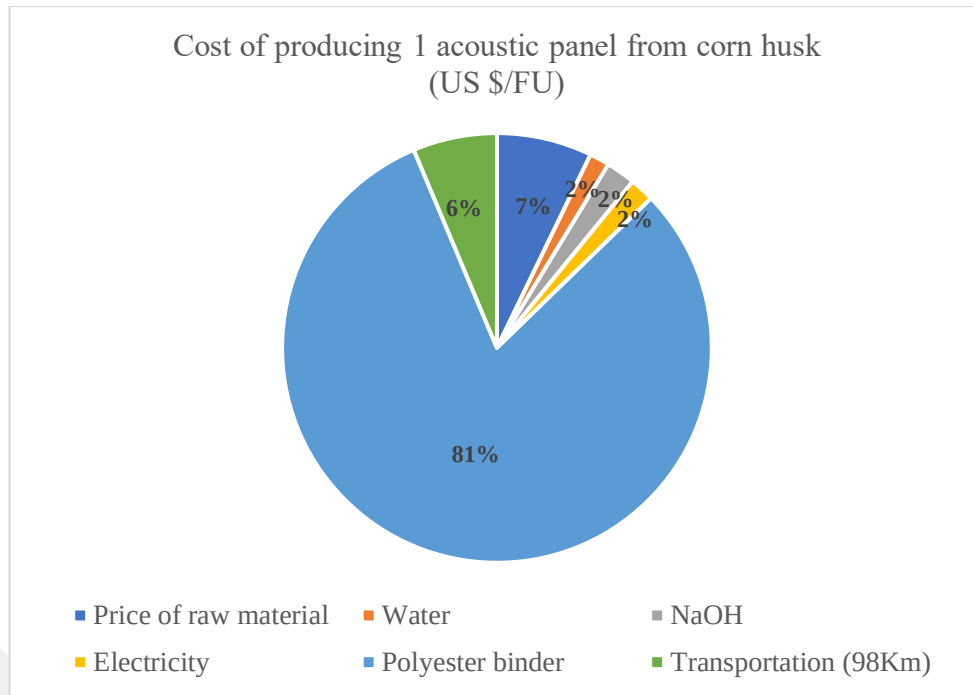


Figure 4.10 : Contribution of each process to the total cost of the corn husk acoustic panel.

There are many processes which contributed to this raise in cost. the highest contribution to the overall cost comes from the binder, In addition to the manufacturing cost, corn husk raw material had a preparation phase in which water and NaOH has been consumed, this contributes to around 5% of the total cost of the CH acoustic panel.

Figure 4.11 shows the cost in US dollar for each process, in addition to the labor and unplanned cost required to produce 1 acoustic panel from CH material.

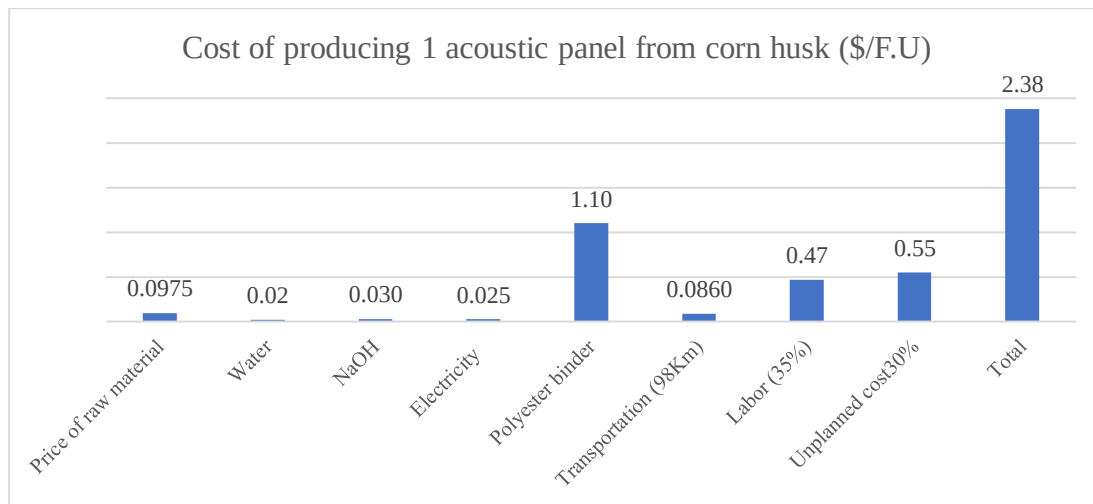


Figure 4.11 : Cost breakdown for producing 1 acoustic panel from corn husk material.

Corn husk is followed by recycled textile acoustic panel in the cost of production. Figure 4.12 shows the contribution of each input on the total cost of the RT panel. Mainly, there are 3 contributors; the price of raw material, electricity and polyester binder. The highest cost comes from the raw material which is the postindustrial textile waste.

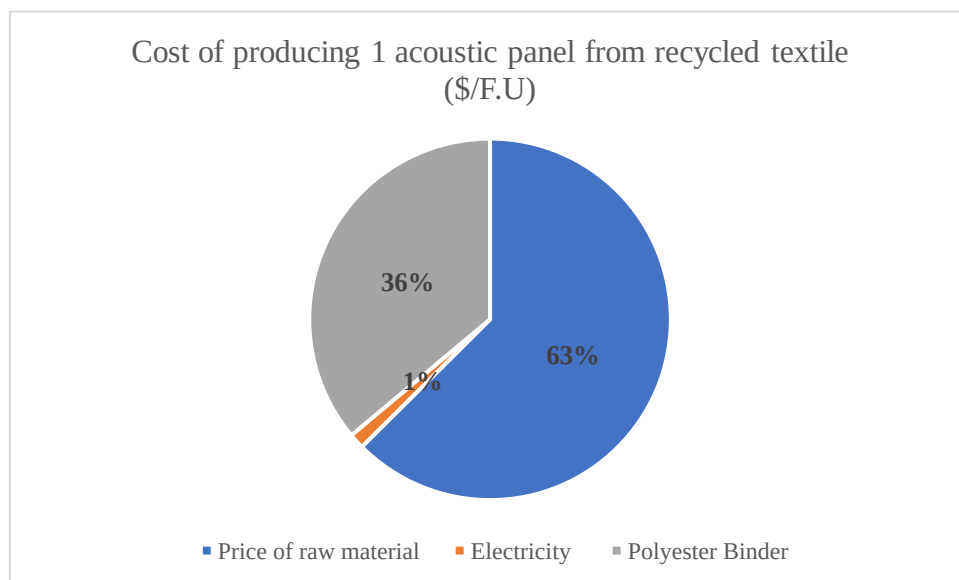


Figure 4.12 : Contribution of each process to the total cost of the recycled textile acoustic panel.

Figure 4.13 display the cost in US dollar for each process besides the labor and unplanned cost required to produce 1 acoustic panel from RT material.

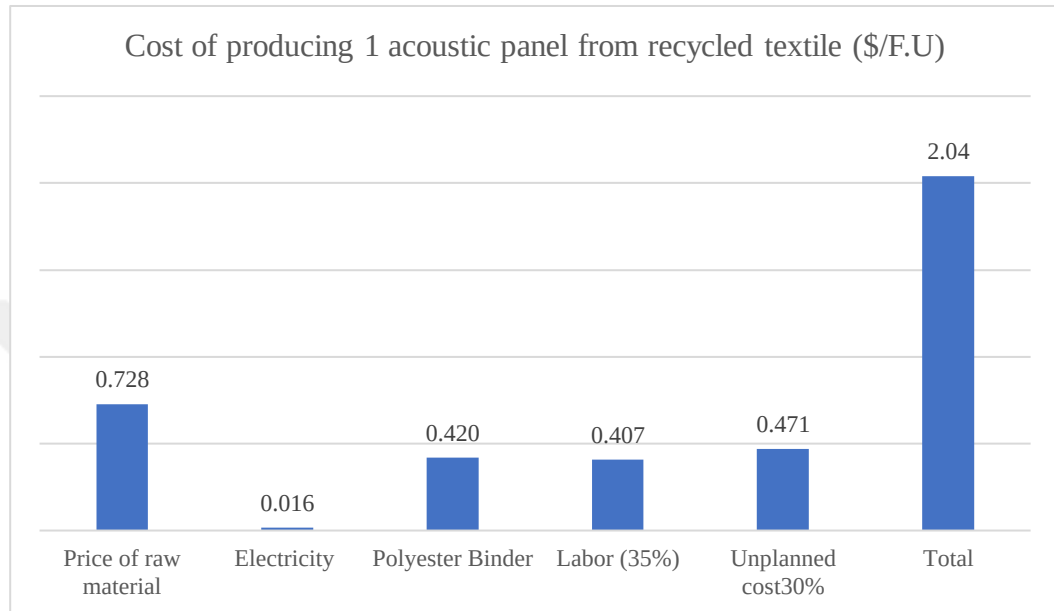


Figure 4.13 : Cost breakdown for producing 1 acoustic panel from recycled textile material.

Lastly and the most economical panel is the tea waste acoustic panel. It has 3 contributors; electricity, rubber latex binder and transportation. As it can be seen form Figure 4.14 there is no raw material price, based on the survey explained in chapter 3, the local cafes and restaurants were willing to give the tea waste for free in exchange to having their waste taken care of by the acoustic panel facility.

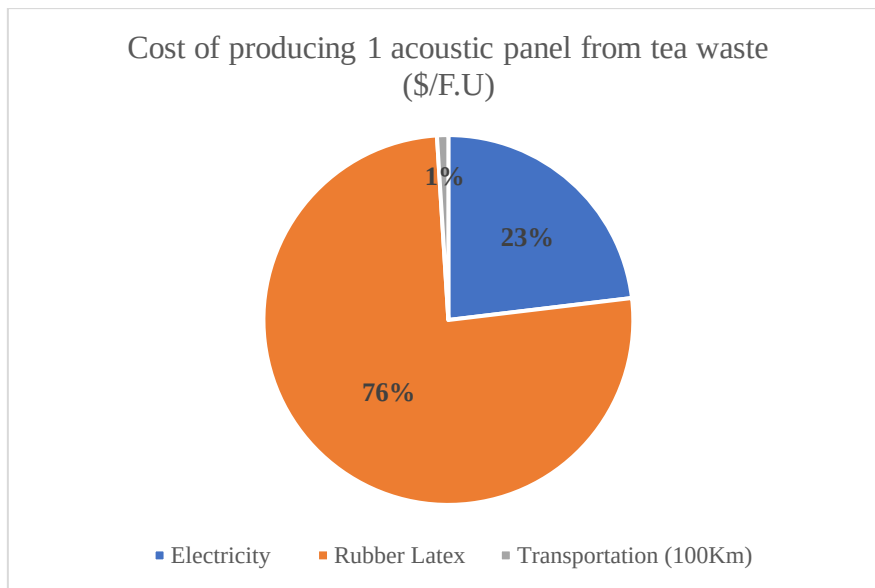


Figure 4.14 : Contribution of each process to the total cost of the tea waste acoustic panel.

Figure 4.15 illustrate the cost in US dollar for each process besides the labor and unplanned cost required to produce 1 acoustic panel from tea waste material.

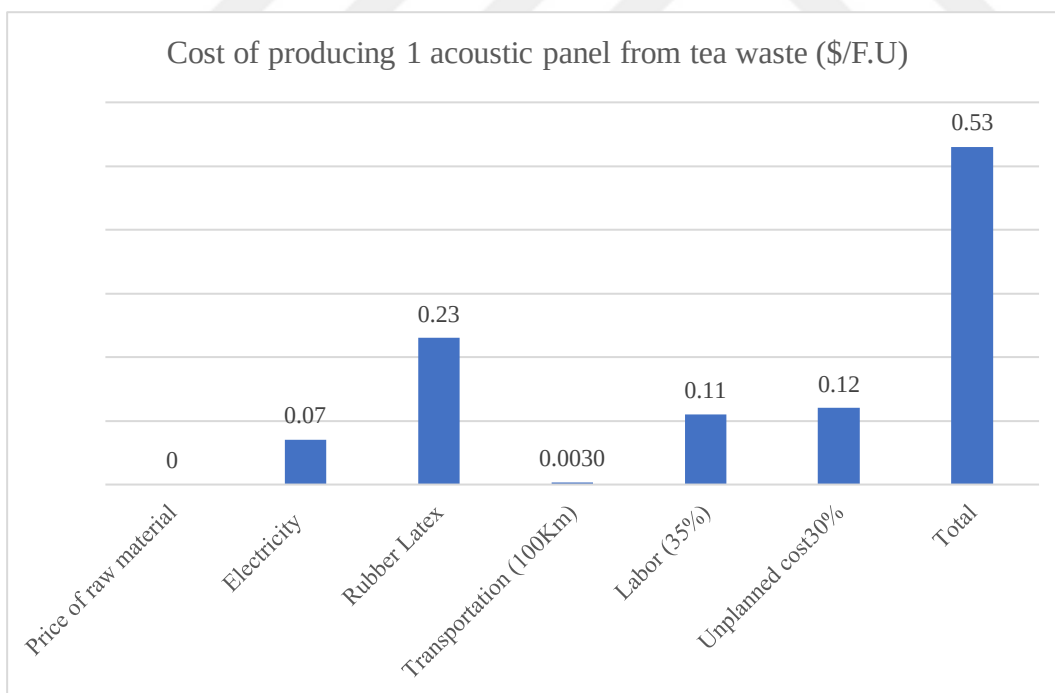


Figure 4.15 : Cost breakdown for producing 1 acoustic panel from tea waste material.

It can be concluded that the 3 studied material showed promising results, comparable to the commercially available acoustic panels in both of the technical and economic aspects. However, the tea waste material needs an additional layer of support to enhance its performance. All the material showed an excellent environmental impact that went above the expectations.

4.2 Technical, environmental and economical evaluation of the studied material using TOPSIS method.

In the evaluation of the acoustic panel materials, the three main criteria and their sub criteria were selected carefully. Each criterion has its own weight that can be determined in accordance with the researcher's preference in a way that total weight of all should be 100. Table 4.2 shows the weight for each criterion and its sub-criteria. Technical and environmental aspects are assigned almost equal weights of 45 and 40, respectively, since the main focus of this study is environmentally friendly sound absorbing materials with a good performance. The remaining 15 points was assigned to the cost aspect. It is important to normalize the numbers with their suggested weight in order to select the best material in each of the 3 main aspects. For example, when it is required to select the best material according to the environmental impact, a weight will be giving for each sub criteria (Water consumption, GWP..., etc.) and a normalized matrix will be formed. Using the TOPSIS formulas and equations provided in the EXCEL sheet will give instant results of the best material in the environmental aspect.

Each part will be discussed separately in the upcoming sections using the weights proposed in Table 4.2

Table 4.2 : Weight points of each criterion and sub-criteria.

Criteria	Sub-criteria	Type of criteria	Weights
Technical properties of raw material	Density (Kg/m ³)	positive	5
	Porosity (%)	positive	5
	SAC @2000	positive	10
	NRC (250-2000) Hz	positive	10
Technical properties of acoustic panel	Thermal conductivity (W/mK)	negative	5
	Airflow resistivity (Pa·s·m ⁻²)	positive	5
	Thickness (mm)	positive	5
	Total criteria score		45
Environmental Aspect	Water Consumption (L\FU)	negative	10
	Chemical usage	negative	10
	Global warming potentials (Kg CO ₂ eq\FU)	negative	10
	Biodegradability	positive	10
	Total criteria score		40
Cost	Cost of preparing the raw material (\$)	negative	-
	Cost of transportation (\$)	negative	-
	Cost of manufacturing the panel (\$)	negative	-
	Total criteria score	negative	15
Total Weight			100

Cost is divided into 3 parts; cost of preparing the raw material, cost of transportation and cost of manufacturing the panel. But since RT and TW materials do not have a preparation phase and RT does not have a transportation cost, the 15 points will be taken for the total cost regardless of the sub-criteria.

4.2.1 Selecting the best material in regard to the technical aspect

When applying the TOPSIS formulas, the final score will be between 0-1, the material with the score closest to 1 is considered to be the best material. To obtain the results for the technical aspect only, all the other main criteria were set to zero and only the technical properties of the raw material and the acoustic panel and their sub-criteria were left with their selected weights. Table 4.3 shows the TOPSIS decision matrix for the technical aspect and Figure 4.16 illustrate the TOPSIS results for all four materials in regard to technical aspects.

Table 4.3 : TOPSIS decision matrix for the technical aspect.

Criteria		Sub-Criteria	Recycled Textile	Tea Waste	Corn Husk	Fiberglass
Raw Material Properties		Density (Kg/m3)	57	91,50	158,0	48
		Porosity (%)	0,90	0,59	0,79	0,98
Acoustic Panel Properties		SAC @2000 Hz	0,82	0,35	1,00	0,96
		NRC (500- 2000) Hz	0,37	0,20	0,42	0,70
		Thermal conductivity (W/mK)	0,13	0,36	0,05	0,04
		Airflow resistivity (Pa·s·m ⁻²)	2680	2264	14435	9000
		Thickness (mm)	17	30	20	25

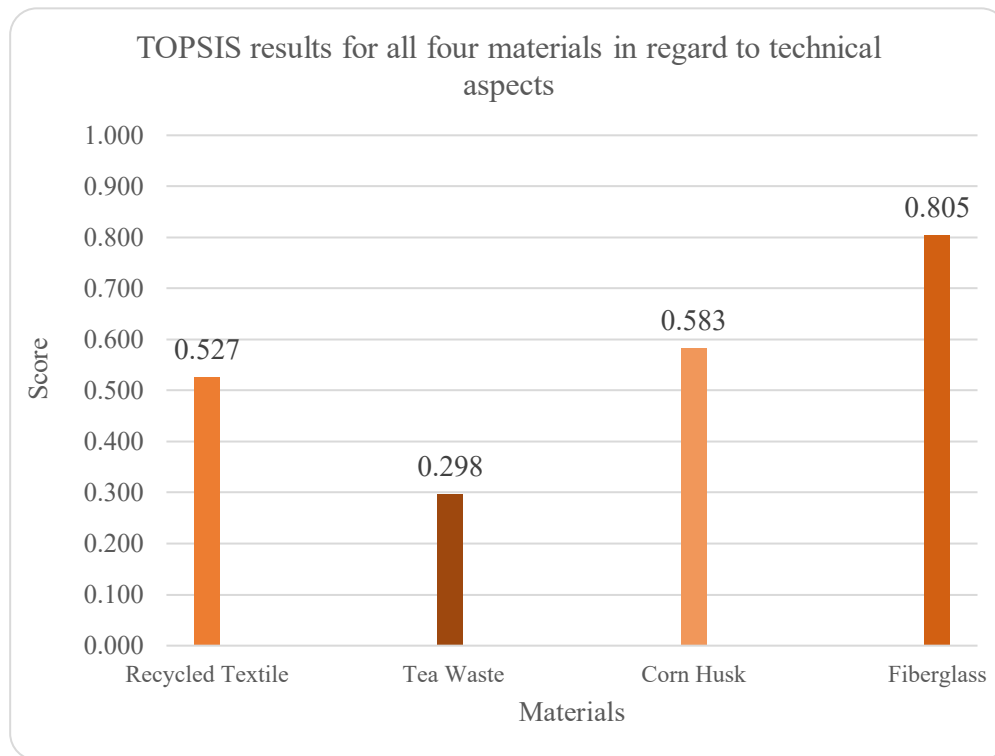


Figure 4.16 : TOPSIS results for all four materials in technical aspects.

As it was expected, fiberglass material ranked the highest with the value of 0,8. Thus, it is considered to have the best technical characteristics. This material has been synthetically optimized to work as a sound absorbing material and this explains the reason behind the results in Figure 4.16. For the studied materials, corn waste performed the best followed by and with a small difference the recycled textile, which indicates a promising application of these materials in market. Lastly comes the tea waste acoustic panel, this material can be part of a composite sandwich panel to enhance the performance and make use of widely available, biodegradable, and free-of-charge material.

4.2.2 Selecting the best material in regard to the environmental aspect

The environmental aspect is very important because it determine the sustainability of the studied materials and this is one of the objectives of the study. To obtain the results for the environmental aspect only, all the other main criteria were set to zero and only the environmental criteria and their sub-criteria were left with their selected weights.

For this aspect, comparison and selection rely on 4 sub-criteria, which are; water consumption, chemical usage, GWP and biodegradability. All except for biodegradability have a negative impact. The weight of these criteria can be changed in accordance with preference of the researcher. If the GWP is the point of interest then it can get the most points. However, in this study all the criteria have an equal impact of 10 points for each. Table 4.4 shows the TOPSIS decision matrix for the environmental aspect and Figure 4.17 illustrate the TOPSIS results for all four materials in regard to environmental aspects.

Table 4.4 : TOPSIS decision matrix for the environmental aspect.

Criteria	Sub-Criteria	Recycled Textile	Tea Waste	Corn Husk	Fiberglass
Environmental Aspect	Water Consumption (L\FU)	0	0	15,8	34,5
	Chemical usage	2	1	3	5
	Global warming potentials (Kg CO2 eq\FU)	0,121	0,597	0,264	2,037
	Biodegradability	4	5	5	1

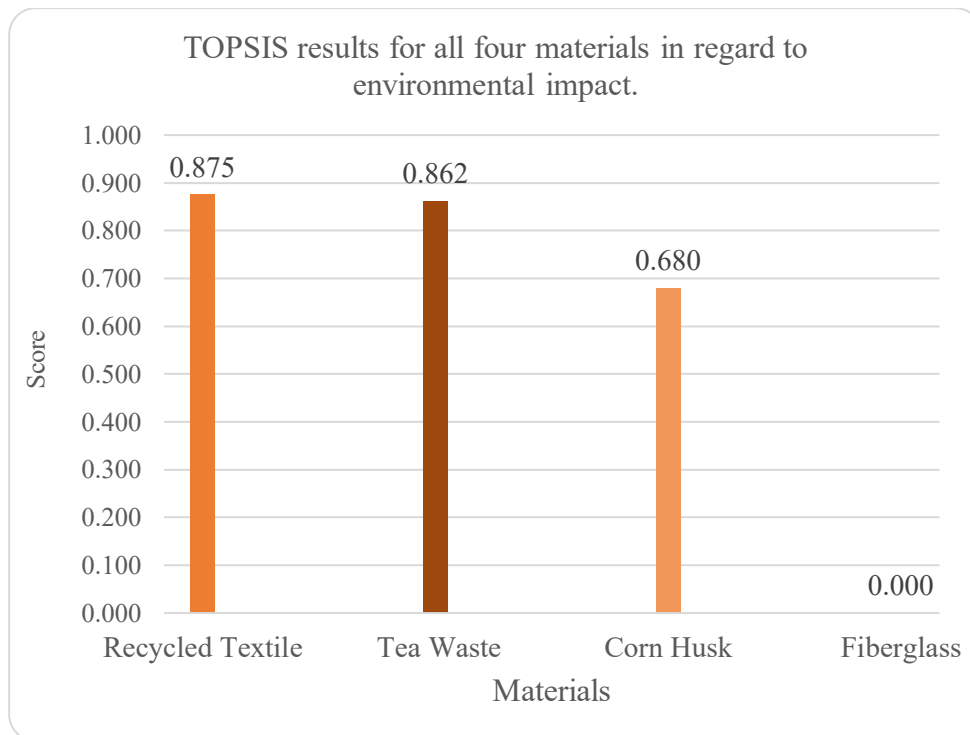


Figure 4.17 : TOPSIS results for all four materials in environmental aspect.

Both of tea waste and recycled textile acoustic panels showed excellent results in the environmental aspect. Followed by corn husk, which also reported impressive results. The reason behind having this difference in score for the CH material goes back to the preparation phase which had chemical usage and water consumption, even though it is in small amounts but the impact is still considered to give an indicate of what needs to be improved.

Lastly comes the FG acoustic panel with a score of 0. In the TOPSIS calculations the negative ideal is selected based on the lowest scores in the set of criteria, FG scored the lower in all of the 4 criteria, that is why it was rank as zero, because there is a “zero” distance from the lowest possible value in the chart.

4.2.3 Selecting the best material in regard to the cost aspect

Since there is only one criterion in the set which is the total cost, there is no need to run the TOPSIS method to figure out the most economical material, it can be easily observed by looking at the graph of the raw values which was previously mentioned in Figure 4.9. Thus, the ranking can be summarized here as following (from the most economical to the least): TW, FG, RT and CH.

4.3 Selecting the best SAM alternative

In the previous sections, the TOPSIS method has been shown to be the most easily applicable method, due to the fact that each criterion has its own measurement unit, thus, all criteria are difficult to evaluate at the same time, also, each scenario has its own advantages and disadvantages for each criterion. By applying TOPSIS method using EXCEL, the data were normalized and the calculations were made.

The results of selecting the best sound absorption material using TOPSIS method are shown in Figure 4.18. The weight ratio of the criteria here is completely user indexed. Four materials were considered, one of the materials (Fiberglass) is added for the aim of comparing with the commercially available materials.

The technical, environmental and economic criteria were the main comparison aspects. The decision support formulas created using EXCEL determine the most suitable material among the Four sound absorbing materials. For example, while TW material has the best results in economic aspect, the decision support programs help to understand the overall performance of the material (technical and environmental in addition to the economic). The decision support program makes a mathematical analysis and compares all the criteria and gives the best scenario result. Table 4.3 shows the decision matrix and Figure 4.17 shows the TOPSIS results for the best SAM among all Four materials.

Table 4.5 : TOPSIS decision matrix to select the best sound absorption material.

Criteria	Sub-Criteria	Recycled Textile	Tea Waste	Corn Husk	Fiberglass
Raw Material Properties	Density (Kg/m ³)	57	91,50	158,0	48
	Porosity (%)	0,90	0,59	0,79	0,98
Acoustic Panel Properties	Sound Absorption Capacity @2000 Hz	0,82	0,35	1,00	0,96
	Noise reduction Coefficient (500- 2000) Hz	0,37	0,20	0,42	0,70
	Thermal conductivity (W/mK)	0,13	0,36	0,05	0,04
	Airflow resistivity (Pa·s·m ⁻²)	2680	2264	14435	9000
	Thickness (mm)	17	30	20	25
Environmental Aspect	Water Consumption (L\FU)	0	0	15,8	34,5
	Chemical usage	2	1	3	5
	Global warming potentials (Kg CO ₂ eq\FU)	0,121	0,597	0,264	2,037
	Biodegradability	4	5	5	1
Economic Aspect	Total cost	2,04	0,53	2,76	1,92

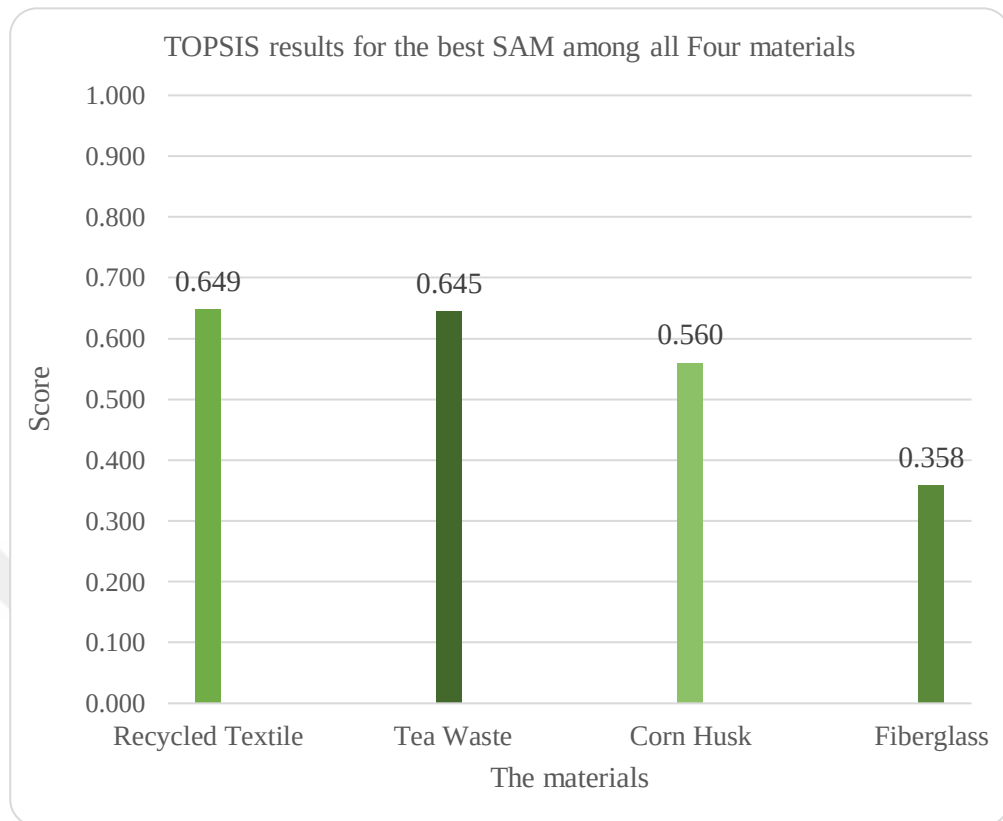


Figure 4.18 : TOPSIS results for the best SAM among all Four materials.

According to the decision support, with the weighting ratio decided by the user, the most appropriate sound absorption material among the 4 material is Recycled Textile material. This material performed well in all the aspects, especially in technical and environmental which had the majority of the weight and this supported in bringing the material to the forefront.



5. CONCLUSION AND FUTURE STUDIES RECOMMENDATIONS

5.1 Conclusion

This study intends to find, evaluate and compare between the new local and sustainable sound absorptive materials. The materials selected for this study are recycled textile, tea waste and corn husk. Recycled textile is proposed for its availability in Turkey and its porous structure which is a great quality for the aim of sound absorption. Tea waste and corn husk were proposed as food waste and agricultural waste, respectively with a promising acoustics characteristic in addition to being locally available. The advantage of using agricultural waste is basically its energy efficient, being natural and harmless to human health. The results would not only assist in the productivity and sustainability of the acoustics sector, but also participate in solving the environmental problems associated with solid wastes. This work was able to select the most suitable alternative material for sound absorbing application using a decision-making technique in order to rank different absorptive materials considering multiple criteria. The TOPSIS method was applied for the multi-criteria analysis. Technical, environmental and economic aspects with different weights for each criterion were considered. A ranking is formed due to the difference in the scores. The best sound absorption material according to the TOPSIS method scenarios is recycled textile. Tea waste performed very well in the environmental and economic but was relatively poor in performance, whereas corn husk showed excellent results in the technical aspect due to its fibrinous structure. A sandwich panel of both tea waste and corn husk would be an interesting composite to inspire researches and experiments as the theoretical data of this composite seems to be very promising.

5.2 Future Studies Recommendations

It is recommended that future work be carried out to investigate the acoustics characteristics of a corn husk and tea waste composite panel. Also, tea waste and recycled textile as protection layer to observe the change that will occur to the tea waste absorption capacity and how much it will improve.

To explore the technical, environmental and economic characteristics of using other natural materials such as date palm, jute, coffee waste and rice husk for the production of acoustics panels. To use other MCDM tools such as AHP and SAW with the same data available in this study and see the difference in results.

And lastly, particularly for the case of Turkey to test the hazelnut husks and shells as a sustainable sound absorbing material option as Turkey is the number one producer of hazelnut to the world especially in the Black Sea region around Giresun area.

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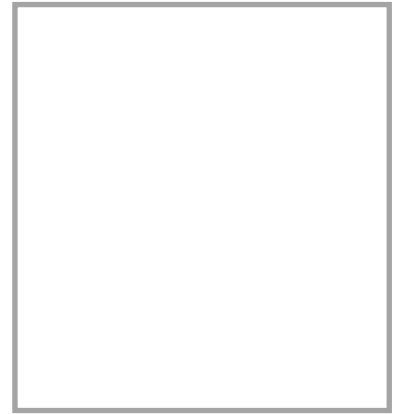
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