SOUND ABSORPTION OF MICRO-PERFORATED PANEL MADE BY OIL PALM FIBRE

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DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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LIST OF ABBREVIATIONS

MPP	Micro-perforated panel
SAC	Sound absorption coefficient
EFB	Empty fruit bunch
PLA	Polylactic acid

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ABSTRAK

Kajian ini membentangkan prestasi penyerapan bunyi panel mikro berlubang atau dipanggil sebagai “micro-perforated panel’ atau MPP yang dibuat oleh serat kelapa sawit. Pertama sekali, sampel dibuat dari serat kelapa sawit dan berlubang dengan menggunakan mesin Kawalan Angka Komputer atau CNC dengan diameter lubang 1 mm. Selepas itu, eksperimen tiub impedans telah dijalankan dan hasil yang diukur menunjukkan bahawa panel penyerap bunyi dengan struktur MPP menjana prestasi akustik yang lebih baik, berbanding dengan panel menyerap bunyi tanpa struktur MPP. MPP dengan nisbah penembusan 0.8 % menjana pekali penyerapan bunyi atau SAC yang paling tinggi dengan puncak pada 0.77 pada frekuensi 600 Hz, berbanding dengan panel tanpa struktur MPP, yang menghasilkan puncak SAC 0.20 pada julat frekuensi yang sama. Kemudiannya, keputusan yang diramalkan dan diukur yang diperoleh daripada persamaan pemodelan MPP dan eksperimen tiub impedans masing-masing dibandingkan. Beberapa penyelewengan berlaku antara keputusan kerana gelembung udara yang terperangkap di dalam sampel semasa proses fabrikasi. Selain itu, diperhatikan bahawa kesan getaran panel dengan ketara mengubah prestasi penyerapan bunyi MPP nipis yang mempunyai ketebalan panel 1 mm. Sementara itu, ia tidak mengubah MPP tegar yang mempunyai ketebalan panel 3 mm. Selain itu, diperhatikan bahawa apabila kedalaman rongga udara meningkat, SAC maksimum MPP beralih ke julat frekuensi yang lebih rendah. Lebar jalur puncak SAC juga diperbesarkan. Selain itu, disedari bahawa puncak SAC menurun dan beralih ke arah julat frekuensi yang lebih tinggi apabila nisbah perforasi MPP meningkat. Hasil kajian membuktikan struktur MPP dapat membantu meningkatkan prestasi penyerapan bunyi serat kelapa sawit pada julat frekuensi terpilih dengan memilih parameter yang betul seperti kedalaman rongga udara dan nisbah perforation.

SOUND ABSORPTION OF MICRO-PERFORATED PANEL MADE BY OIL PALM FIBRE

ABSTRACT

This study presents the sound absorption performance of micro-perforated panel (MPP) made by oil palm fibre. Firstly, samples are fabricated from oil palm fibre and perforated by using Computer Numerical Control (CNC) machine with a hole diameter of 1 mm. After that, an impedance tube experiment is carried out and the measured results show that the sound-absorbing panel with MPP structure generates a better acoustic performance, comparing to the sound-absorbing panel without MPP structure. MPP with a perforation ratio of 0.8 % shows the greatest peak sound absorption coefficient (SAC) of 0.77 at the frequency of 600 Hz, comparing to the panel without MPP structure, which produces a peak SAC of 0.20 at the same frequency range. The predicted and measured results obtained from the modelling equation of MPP and impedance tube experiment respectively are then compared. Some deviations occur between the results due to the trapped air bubbles inside the samples during fabrication process. Moreover, it is observed that the panel vibration effect significantly modifies the sound absorption performance of thin MPP, which has a panel thickness of 1 mm. Meanwhile, it does not alter the SAC of rigid MPP, which has a panel thickness of 3 mm. Apart from that, it is observed that as the air cavity depth increases, the maximum SAC of the MPP shifts to a lower frequency range. Besides, it is noticed that the peak SAC is decreased and shifted towards a higher frequency range when the perforation ratio of MPP increases. The results of the study proved that the MPP structure can help to enhance the sound absorption performance of oil palm fibre at a selected frequency range by choosing the right parameters like air cavity depth and perforation ratio.

CHAPTER 1

INTRODUCTION

1.1 Background Study

According to World Health Organization, noise pollution can be considered as the main cause of health problems such as sleep disturbances, stress and even heart attacks [1]. As such, noise control should be carried out by installing a sound absorber. The sound absorber can help to reduce the radiated sound energy through the visco-thermal effect [1]. Besides, a sound absorber is commonly applied to the construction of buildings in the form of walls, floors and ceilings. This is to control and maintain the quality of acoustics inside the buildings.

The common sound-absorbing panel was first made by original asbestos-based materials. After that, in the 1970s, due to health issues caused by the materials, it is then replaced by synthetic fibres [2]. Until recent years, the utilisation of natural fibres as sound absorption materials become a focus to researchers. This is because the fibres are natural and biodegradable compared to other sound absorber materials. According to the study of Life Cycle Assessment (LCA) on a range of synthetic and natural sound absorption materials, it is found that natural fibres produced less carbon footprint compared to synthetic materials. This is because the production of natural fibres do not rely on petrochemicals and hence consumes less energy [3].

Oil palm fibre is chosen in this study because it can be obtained easily in Asian countries, especially in Malaysia. Moreover, oil palm fibre proposed comparative sound absorption performance compared to other natural fibre such as coconut fibre [4]. Besides, the high production of oil palm fibre, which is one of the by-products during the processing of palm oil also causes an environmental problem due to its disposal issue. As a result, it is possible to investigate the waste material's performance as a green and long-lasting sound absorber.

Moreover, another feasible alternative for sound absorption purposes known as micro-perforated panel (MPP) is introduced. The MPP is first proposed by Maa in the year 1975, laying out its theoretical foundation and design approach [5]. MPP is a flat plate that consists of small holes with sub-millimetre sizes, distributed evenly on the plate and backed by a stiff wall with an air space in between. The perforation ratio, σ, the diameter of the perforated hole, d, panel thickness, t, and air cavity depth, D are all related to the acoustic performance of MPP, as shown in Figure 1.1. The entire area of the perforated hole on a unit area of the panel is known as the perforation ratio [6].

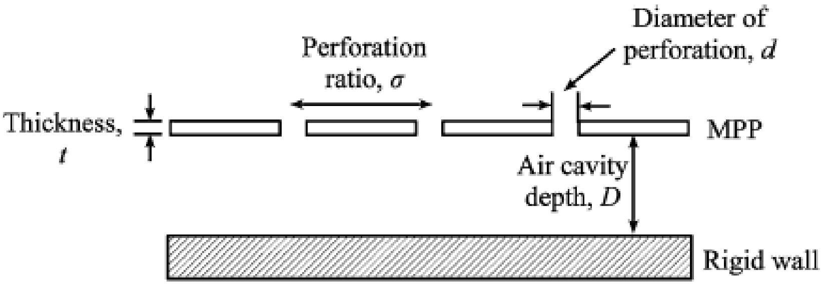

Figure 1.1 Four major parameters affecting sound absorption coefficient (SAC) of MPP [7]

In comparison to perforated panels, MPP is a wideband sound absorber that provides enough acoustic resistance and low acoustic mass reactance without the need for extra fibrous and porous materials [8], [9]. It offers the benefit of being able to alter the peak frequency of sound absorption and having good noise reduction abilities [10]. Besides, MPP is usually made of metallic materials. However, such materials used to create MPP are not biodegradable since metal production tends to release a massive amount of carbon into the environment, causing negative environmental effect [11]. As such, the increasing concern on the environmental issues and the health concern of synthetic fibre and metallic material usage as well as the proven advantages of MPP itself leads to the idea of fabricating a sustainable MPP through the utilization of oil palm fibre.

In short, research is conducted to study the sound absorption performance of the MPP samples made by oil palm fibre. The sound absorption performance of MPP made of oil palm fibre and a sound-absorbing panel made of oil palm fibre without MPP structure is compared. Moreover, the role of air cavity depth and perforation ratio in determining the MPP's acoustic performance is examined.

1.2 Problem Statement

Noise pollution is a well-known cause of anxiety that has been connected to health issues such as stress and insomnia. Several solutions have been discovered to control the noise such as the application of a sound absorber. However, the common sound-absorbing panel which is made of synthetic fibres or metallic materials is harmful to human health and their production has high global warming potential. Besides, high production of palm oil biomass such as oil palm empty fruit bunch causes an increasing environmental problem due to disposal issues.

Due to its proven advantages, a viable alternative known as micro-perforated panel (MPP) is introduced as the new sound absorption method. Due to the need for sustainable eco-friendly materials as well as the increasing concern on the disposal issues of palm oil biomass, research should be conducted to study the suitability of using oil palm fibre for making MPP. However, there is no research has yet considered the acoustic characteristics of MPP made by oil palm fibre. In this study, the sound absorption coefficient (SAC) of MPP made by oil palm fibre will be investigated which aiming for better sound attenuation, as compared to the common sound-absorbing panel without MPP structure which is made by oil palm fibre.

1.3 Objective

In this project, there are several objectives to be achieved, which are:

- To fabricate micro-perforated panel (MPP) samples made by oil palm fibre.
- To investigate the sound absorption coefficient (SAC) of the MPP samples made by oil palm fibre by using impedance tube experiment.
- To compare the sound absorption performance of fabricated samples with and without MPP structure made by oil palm fibre.

1.4 Scope of Project

In this project, the scope is on the modelling equation, fabrication and experimental work which require fundamental knowledge in MPP absorbers. Firstly, the modelling equation of MPP will be practised by using MATLAB to predict the theoretical sound absorption performance of the MPP samples. Besides, fabrication of samples with panel thickness 1 mm and 3 mm from oil palm fibre will be done. MPP samples with different perforation ratio will be perforated by using a CNC machine. After that, the fabricated samples will be implemented on the impedance tube with different air cavity depth and undergo an experiment. SAC of the sound-absorbing panel with and without MPP structure made by oil palm fibre will be compared. A comparison of the sound absorption performance between the theoretical and experimental study of the MPP samples will be done. The impact of air cavity depth and perforation ratio on the MPP samples' SAC will be studied.

1.5 Thesis Outline

In this project, five chapters are included. In chapter one, the background study is first discussed, followed by problem statements of the project, the objectives that need to be achieved, project scope and thesis outline.

Chapter two focus on the review related to the sound-absorbing panel made by natural fibre, description of the oil palm fibre, micro-perforated panel (MPP) and the MPP made by natural fibre. Previous works that have been done by other researchers are presented in chapter two.

Apart from that, chapter three discuss the methodology used in this study. It consists of modal analysis by using ANSYS software. The SAC of MPP samples is theoretically determined using the MPP modelling equation presented in this chapter. Fabrication steps of the MPP samples are presented. Then, an impedance tube experiment is carried out to obtain the SAC of the MPP samples experimentally.

Chapter four discuss the results obtained from the modal analysis, which is used in the modelling equation of MPP. A comparison of the sound-absorbing panel with and without MPP structure, where both panels are made of oil palm fibre is presented. The predicted and measured results obtained from the modelling equation and experiment respectively are presented. The effect of air cavity depth and perforation ratio on the acoustic performance of MPP is also discussed.

In chapter five, the conclusion is made based on the findings to determine whether the objective of this project is achieved or not. Then, suggestions are given to improve the future works so that better results can be obtained.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter is about the review of natural fibre as a sound-absorbing panel for noise control. Oil palm fibre is introduced as one of the natural and biodegradable acoustic materials. In addition, a micro-perforated panel (MPP) is proposed as a solution to the noise problem. Due to the need for a sustainable acoustic solution, MPP made by natural fibre is introduced. Research that has been done by other people are included in this chapter.

2.2 Sound-absorbing Panel made by Natural Fibre

Sound absorption is the process of absorbing sound energy by converting it to heat or transferring it away from a specified location. Sound absorbers can be applied as treatments to floors, walls, ceilings, partition surfaces and objects like chairs to provide an appropriate acoustic environment within a space. Therefore, installing sound absorbers is the most common acoustic method for noise control since it is more feasible and cost-effective than redesigning and rebuilding the complete structure [12]. Due to its good acoustic performance as well as its excellent properties in terms of durability, thermal conductivity, fire retardancy, and bacterium growth resistance, synthetic fibre is still considered the best sound absorptive material in common acoustic applications such as the building construction industry [1]. However, numerous studies have indicated that prolonged exposure to synthetic fibres can be harmful to our health since they can produce microscopic particles that are invisible to the naked eye [13]. Furthermore, the manufacturing process of synthetic fibre is extremely environmentally harmful. This is because they are manufactured using high-temperature industrial methods such as hot extrusion, and the source of synthetic fibre is usually generated from petrochemical processing, resulting in a substantial carbon footprint [2]. As a result, a recent study on sound absorber tends to look for natural materials is carried out to find environmentally acceptable and sustainable sound absorbers.

To fabricate sound absorber from natural fibre, loose fibres are pressed inside a mould with a certain thickness by applying pressure on the top surface of the fibres with a punch or by using a hot compression machine. Natural fibres derived from flora and fauna are biodegradable, non-harmful, and less detrimental to the environment. Natural fibre is noted for having a lower density than synthetic fibre, as well as being cheaper, more plentiful, and, most significantly, renewable [14]. According to a study analysed by Asdrubali et al. on the Life Cycle Assessment (LCA) on a variety of synthetic and natural sound absorber materials, natural fibre has a much lower carbon footprint than synthetic fibre [15], [16]. Table 2.1 shows the advantages of natural fibres.

Table 2.1 Advantages of natural fibre [16], [17]

Advantages
Are biodegradable, less expensive, and environmentally friendly, with a low specific weight.
Are widely available and have a high level of electrical resistance.
Have excellent thermal and acoustic insulation.
Have a low toxicity level and pose fewer risks to human health during production and handling.

Many researchers have investigated natural fibres as a substitute for synthetic materials in manufacturing sound absorbers due to the proven advantages of natural fibre. For instance, in Yang et. al.'s research, rice straws were tested for their ability to absorb sound [18]. For the frequency range of 500 to 8000 Hz, composite boards made of random cut rice straws and wood particles were found to have a greater sound absorption coefficient (SAC) than particleboards, fibreboard, and plywood. The acoustical performance of industrial waste tea leaf fibre was investigated by Ersoy and Kucuk [19]. They discovered that a 1 cm thick tea leaf fibre waste material with an air backing offers sound absorption roughly identical to six layers of woven textile cloth. For tea leaf fibre with a thickness of 20 mm, it provided a comparable SAC of 0.7 in the frequency ranges of 500 to 3200 Hz.

Furthermore, Bastos et. al. suggested using natural fibres such as coconut, palm, sisal, and acai to create noise control panels [20]. When compared to synthetic acoustic foam materials, the performance of natural fibres can be better in some circumstances. According to Berardi et. al., when the absorption coefficient was over 0.7 in the range of frequency between 1600 and 1880 Hz, a specimen made of broom fibres with a thickness of 120 mm and a diameter of 1.5 mm produced the best results [21]. Meanwhile, at all frequencies, the absorption coefficients of the finer samples were less than 0.6.

Furthermore, for specimens 40 mm thick, the normal incidence SAC of kenaf fibre was found to be more than 0.8 from 1.5 kHz onwards, exceeding the performance of synthetic rock wool material of the same thickness [22]. Putra et. al. studied experimentally the sound absorption performance of different densities and thickness of pineapple leaf fibre samples [1]. The results showed that by regulating the densities of the fibres and introducing an air space behind the samples, the fibres could obtain an average SAC of 0.9 above 1 kHz. They found that the sound absorption properties of pineapple leaf fibre were comparable to those of commercial rock wool fibres and synthetic polyurethane foam. Overall, various studies showed that a variety of natural fibres proposed good acoustic performance, as compared to synthetic materials. Besides, a range of natural fibres for building applications have already begun to be commercialised, however, the majority of the products studied in prior studies are still seldom used in the building practice [23].

2.3 Oil Palm Fibre

Oil palm empty fruit bunch (EFB) fibre was chosen for MPP sample fabrication in this project because of the ease with which it can be obtained in Asian countries, particularly Malaysia. The oil palm tree is a monocotyledon that grows on around 11 million hectares of land in 42 nations across three different continents: Asia, Africa, and South America [24]. According to a United States Department of Agriculture (USDA) commodity intelligence study, oil palm is the world's highest-producing edible oil crop, and Malaysia is the world's top producer and exporter of the oil palm, accounting for almost 30% of global oil and fat production [25]. Figure 2.1 depicts the spread of oil palm plantations in Malaysia for the year 2010.

Source: Centre for Remote Imaging, Sensing and Processing (CRISP), Singapore, 2010

Figure 2.1 Oil palm plantation distribution in Malaysia [25]

Oil palm industries generate massive quantities of biomass such as oil palm trunk (OPT), oil palm frond (OPF) and oil palm empty fruit bunch (EFB) as shown in Figure 2.2 [26]. Oil palm plantation produced the OPF and OPT, whereas oil palm processing produced the oil palm EFB. EFB is a by-product of the palm oil industry that is left over after the oil palm fruit is collected for the refining process [24]. Furthermore, using the retting process, oil palm EFB fibres can be produced from the EFB. Mechanical extraction or hammering, chemical retting, steam or vapour retting, and water or microbiological retting are all techniques for extracting fibres [27]. Oil palm EFB fibre was selected among three oil palm biomasses because it can be obtained easily from the oil palm industry and it showed excellent sound absorption capabilities.

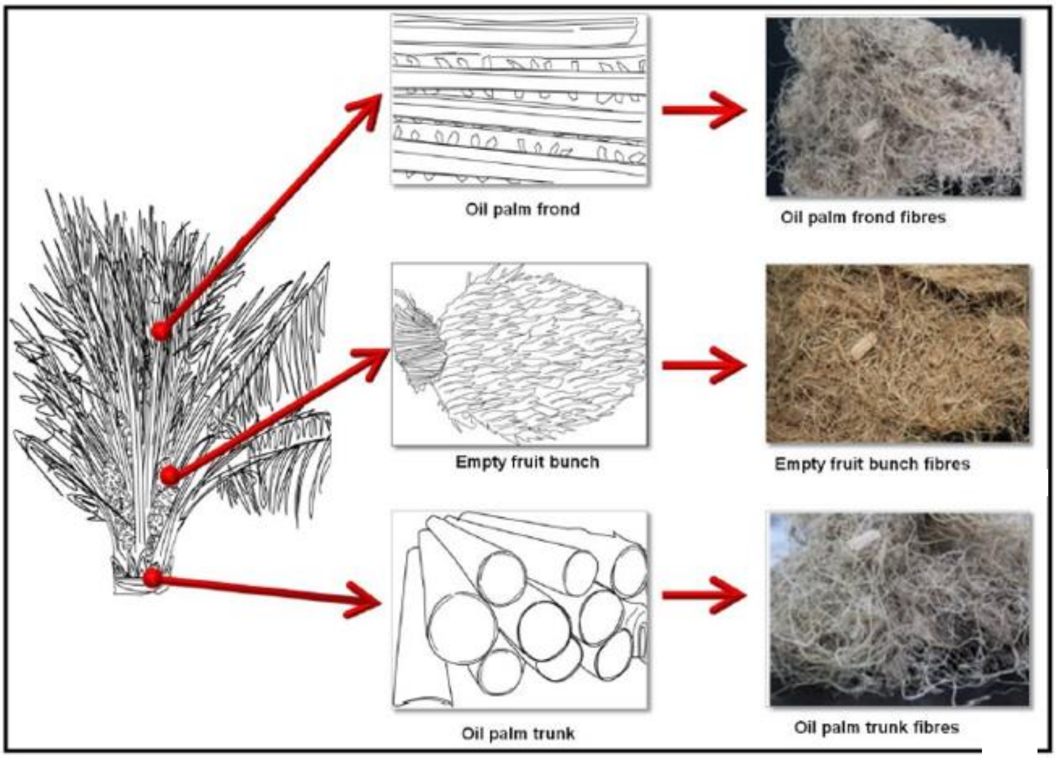

Figure 2.2 Oil palm biomass from an oil palm tree [26]

One hectare of palm oil plantation may generate 5.5 tonnes of oil per year, as well as 55 tonnes of total dry fibrous biomass as a by-product. EFB occupied up to 73 % of the fibres in diverse dry fibrous biomass from oil palm trees [4]. Moreover, a huge amount of oil palm EFB fibre was generated as trash in Malaysia and its surrounding Southeast Asian countries. In some countries, these wastes were thrown into the river or open burning, which create water and air pollution to the country [28]. Therefore, due to the high production of oil palm EFB fibre, these fibres can cause an environmental problem because of their disposal issue.

Conventionally, oil palm EFB has been primarily employed as a combustion fuel in furnaces to provide electricity to plantation mills. However, such application will bring negative impact to the Earth, such as emission of carbon dioxide and global warming. Apart from that, oil palm EFB fibre is tough with a relatively large diameter, which shows similarity to the coir fibre [29]. Because of its high cellulose content and hardness value, oil palm EFB fibre is ideal for composite applications [27]. As such, due to its high production and disposal issue as well as the good material properties of oil palm EFB fibre, it is, therefore, possible to investigate the effectiveness of waste materials as a biodegradable and long-lasting sound absorber.

Besides, oil palm EFB fibre was selected for MPP sample fabrication in this study due to its good sound absorption properties as shown in the investigation of previous researchers. However, there are very limited researchers who studied the acoustic characteristics of the oil palm EFB fibre. For instance, Abdul Latif [30] showed that panel made from oil palm fibre has good SAC in the range of 0.7 to 0.9 from 1600 Hz to 5000 Hz. He claimed that increasing the thickness of the air gap increased low-frequency sound absorption. It is noticed that the oil palm EFB fibre has a good acoustic performance at a low frequency range. Moreover, sample sound absorbers made by oil palm EFB fibre with different densities and thickness were created to investigate the impact of the chosen parameters on their SAC [4]. The samples would have similar absorption performance to commercial synthetic rock wools, as measured by using an impedance tube, with the panel manufactured from oil palm fibre. They achieved an absorption coefficient above 0.9 on average above 1000 Hz. Sound absorption performance for samples of thickness 10 mm which is made of oil palm empty fruit bunch with different densities was investigated by Tufoi [4]. In his study, he found out that the SAC of a sample with a density of around 400 kg/m^3 can reach above 0.5 for the frequency range of 1000 to 2000 Hz. However, sample with a density below 400 kg/m^3 and above 600 kg/m^3 presented a SAC value of below 0.2 at the frequency range of 500 to 1500 Hz. Figure 2.3 shows the measured SAC of oil palm empty fruit bunch fibres obtained by Tufoi with different fibre densities for 10 mm thick samples.

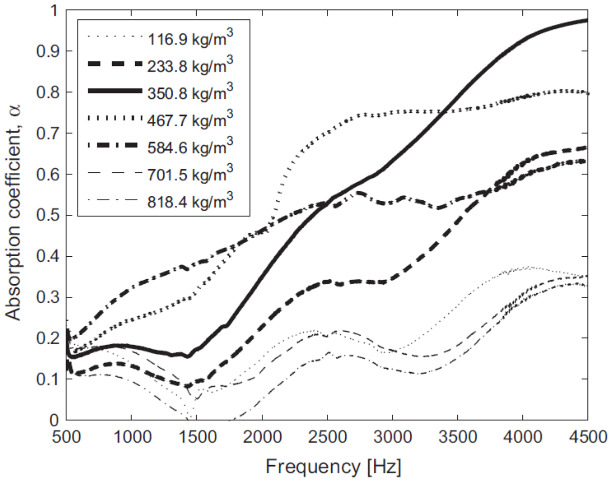

Figure 2.3 Measured SAC of oil palm empty fruit bunches fibre with different fibre densities for a sample thickness of 10 mm [4]

Apart from that, it was necessary to use a binder to fabricate the samples because oil palm fibre has weak mechanical processing capabilities. Polyester, polyethene, and polypropylene are commonly utilised as composite matrix materials, but these polymers are not biodegradable [31], [32]. In this study, biodegradable polylactic acid (PLA) was used as the binder for the MPP samples. PLA is made from sugarcane, corn starch, and tapioca roots, which are all-natural and sustainable materials [32]. It has been experimentally proven that due to the presence of soil bacteria and fungi, it will disintegrate in two weeks and be completely gone in three to four weeks upon soil burial [33].

2.4 Micro-perforated Panel (MPP)

MPP is one of the most potential sound absorption solutions, as it replaces porous sound absorbers like synthetic fibre, which can have major health consequences [34]. MPP usually is a thin, flat panel that consists of a huge number of micro-perforated holes. Micro-perforated holes typically have a diameter of less than or equal to 1 mm, and the total number of micro-perforated holes covers less than 1% of the panel surface area [35]. Besides, for an MPP to absorb sound properly, there must be an air space between the panel and a rigid wall [36]. Such an air cavity usually has a depth of between 1 to 30 mm [34].

MPP differs from standard sound-absorbing materials, which it is environmentally friendly, non-combustible, durable, fibre-free, and aesthetically beautiful [37]. Furthermore, it has been demonstrated to have the advantages of variable sound absorption peak frequency as well as robust noise reduction abilities without the need for porous materials [10]. Moreover, Plastic, chipboard, acryl glass, and metal sheets are some of the materials that can be used to make MPP [36]. As a result, MPP is particularly appealing for construction purposes. MPP, for example, could provide sound absorption without blocking sunlight if a transparent material is applied [38]. Moreover, MPP has also been utilised in corrosive and hostile conditions, such as on work sites as noise barriers [39], as an acoustic barrier in engine casings and inside mufflers [40].

Apart from that, the MPP's acoustic absorption mechanism is based on micro-perforation and resonance. It is fundamentally identical to the Helmholtz resonator. [41]. The micro-perforated holes on the MPP surface can be viewed as narrow cylindrical tubes with a separation distance greater than the hole diameters [42]. Furthermore, Rayleigh researched the propagation of sound in a thin tube with a hole that was shorter than the wavelength of the generated sound, and Crandall simplified his work subsequently [34]. Maa was the first to propose the application of MPP in the 1970s, based on Rayleigh and Crandall's concept [5]. The diameter of the perforated hole was decreased to sub-millimetres to expand the width of the absorption peak.

To estimate the SAC of MPP, Maa established an approximate theory, but the approach proved impractical for actual use [5], [8]. As a result, he developed a new model that is more practical and useful, with an error rate of roughly 5% [9]. Maa's first conceptual framework worked only for MPP with circular holes and a minimal perforation ratio. However, due to the disturbance on the viscous boundary layer surrounding the edges of the perforated hole, the interaction between neighbouring perforated holes may change the acoustic properties of MPP [43]. Therefore, end correction which considering the additional resistance and mass reactance must be included in the prediction model [9].

When the MPP has great stiffness, Maa's theoretical model was proved to accurately determine the SAC of the MPP. However, the SAC of the thin MPP is not correctly described by the equation. The vibration effect must be considered for the thin MPP [44]. On the absorption coefficient curve, an unexpected peak due to the flexible panel vibration effect was discovered in the simulation and experimental results of various prior works [45], [46]. For instance, an additional absorption peak in the low frequency range of 20 to 80 Hz was observed due to the vibration effect of the panel [47]. The study, however, only looked at the absorption effect of the perforated holes and ignored the vibration effect.

The papers of Sakagami [48], Lee [45], [49], Bravo [46] and Tan and Ripin [50] provided the theoretical and experimental investigation of absorption due to the vibroacoustic effect. Lee derived the absorption equation based on the modal analysis solution of the classical plate problem combined with the wave propagation equation using an analytical model of a rectangular flexible MPP with a stiff hexahedron enclosure filled with air [36], [45], [49]. Vibration's effect on MPP's sound absorption ability has been modelled as the mass reactance and mechanical loss [51]. They are the imaginary and real components of the sound impedance of the MPP, respectively. In the analogous electro-acoustical circuit presented by Tan, the mass reactance is added in parallel to the acoustic impedance of the micro-perforation [50]. According to their findings, the sound absorption peak induced by panel vibration can be used to increase the MPP's absorption bandwidth by setting its specifications so that the structural resonant frequency is greater than the absorption peak frequency generated by the micro-perforations [36].

Apart from that, the acoustic performance of MPP mostly depends on four major parameters, which are panel thickness of MPP, hole diameter, perforation ratio and air cavity depth [6]. A lot of research has been conducted to investigate the ways to improve the sound absorption performance of the MPP. Based on the study of Wong [52], due to a very high acoustic resistance at the neck of the perforated holes, a thick MPP was found to have poor acoustic performance. He discovered that increasing the thickness of the panel without changing the hole diameter lowers the SAC and changes the peak frequency to a lower frequency range. According to Qian [53], by adopting an ultra-micro perforation, a single MPP may satisfy strong absorption in a wide frequency range, showing that MPPs have a huge potential as wideband absorbers for noise control when space is limited. Tayong [54], [55] found that decrement of spacing between adjacent perforated holes or increment of perforation ratio can reduce the sound absorption performance of MPP due to flow disruption around the edges of perforated holes. Besides, changes in air space behind the MPP can produce more resonance peak and enhance the overall acoustic performance of MPP [36]. It is observed that as the air cavity increases, the maximum value of SAC shift to the lower frequency band [6].

MPP is usually made out of steel or aluminium [56]. Besides, the sound absorption of a 3D printed MPP backed with an air gap and attached porous material was investigated by Liu [57]. Above the frequency of 2000 Hz, the results revealed an overall SAC of 0.8. The porous sound-absorbing material layer and the air gap are responsible for the significant improvement in acoustic absorption at low frequency. The materials used to produce the MPP, on the other hand, are not recyclable, and metal processing emits a significant amount of carbon into the atmosphere. Apart from that, the technique of generating sub-millimetre size holes using etching, jetting, or laser technology makes the production of MPP from metallic material challenging and potentially expensive [58]. As such, the increasing concern on the environmental issues and the health concern of metallic material usage as well as the difficulty of fabricating the MPP from metallic material leads to the idea of fabricating a sustainable MPP through the utilization of natural fibre, especially oil palm fibre.

2.5 MPP made by Natural Fibre

For the past ten years, there is very limited research focusing on the sound absorption performance of MPP made by natural fibre. In the year 2018, Chin and Yahya [34] studied the sound absorption performance of MPP made by kenaf fibre and in the year 2020 [59], they investigated the sound absorption performance of MPP made by coconut fibre. Figure 2.4 shows the MPP specimen made by coconut fibre in the study of Chin in the year 2020. Both studies showed that the increased composition percentage of fibres enhanced the sound absorption performance of the MPP as porosity value increased. However, a greater amount of fibre used will increases the difficulty of mixing the fibre and binder, especially when using oil palm fibre which is harder than the kenaf fibre. As such, a composition percentage of 30:70 for oil palm fibre and PLA respectively were used in this study [59]. Besides, the researchers observed that the usage of kenaf fibre and coconut fibre to make MPP showed a good sound absorption performance, as compared to the synthetic fibre. However, there is still no study related to the acoustic performance of MPP made by oil palm fibre.

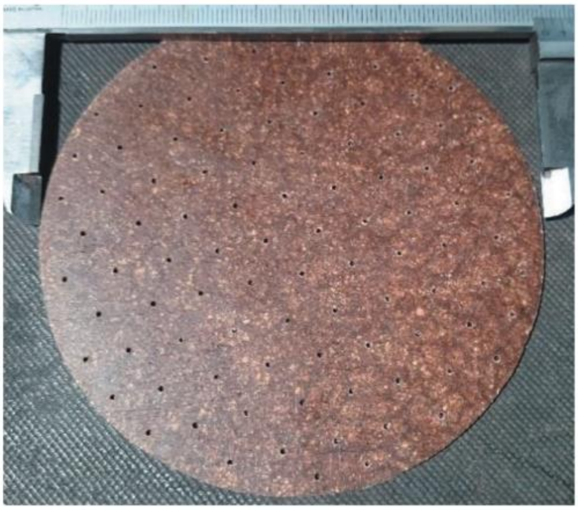

Figure 2.4 Example of MPP specimen made by coconut fibre [59]

2.6 Summary

From the literature, it can be summarized that:

- The sound-absorbing panel made by natural fibres are environmentally friendly and sustainable as well as proposing a good acoustic performance, as compared to synthetic materials.

- Oil palm empty fruit bunch (EPF) fibre is chosen for MPP sample fabrication in this study due to its high production and good sound absorption performance.
- Biodegradable polylactic acid (PLA) should be used as binder to mix with the oil palm fibre for the fabrication of MPP samples.
- End correction and panel vibration effect should be included in the modelling equation of micro-perforated panel (MPP) to estimate the sound absorption properties of the MPP samples effectively.
- Several parameters such as panel thickness of MPP, hole diameter, perforation ratio and air cavity depth could affect the sound absorption performance of the MPP.
- A composition percentage of 30:70 for oil palm fibre and PLA respectively should be used in this study.
- Comparing to the common sound-absorbing panel, MPP structure is showed to have the advantages of variable sound absorption peak frequency and robust noise reduction capabilities.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, modal analysis, modelling equation of MPP, fabrication of MPP samples and impedance tube experiment are presented. Figure 3.1 shows the overall flowchart of this study.

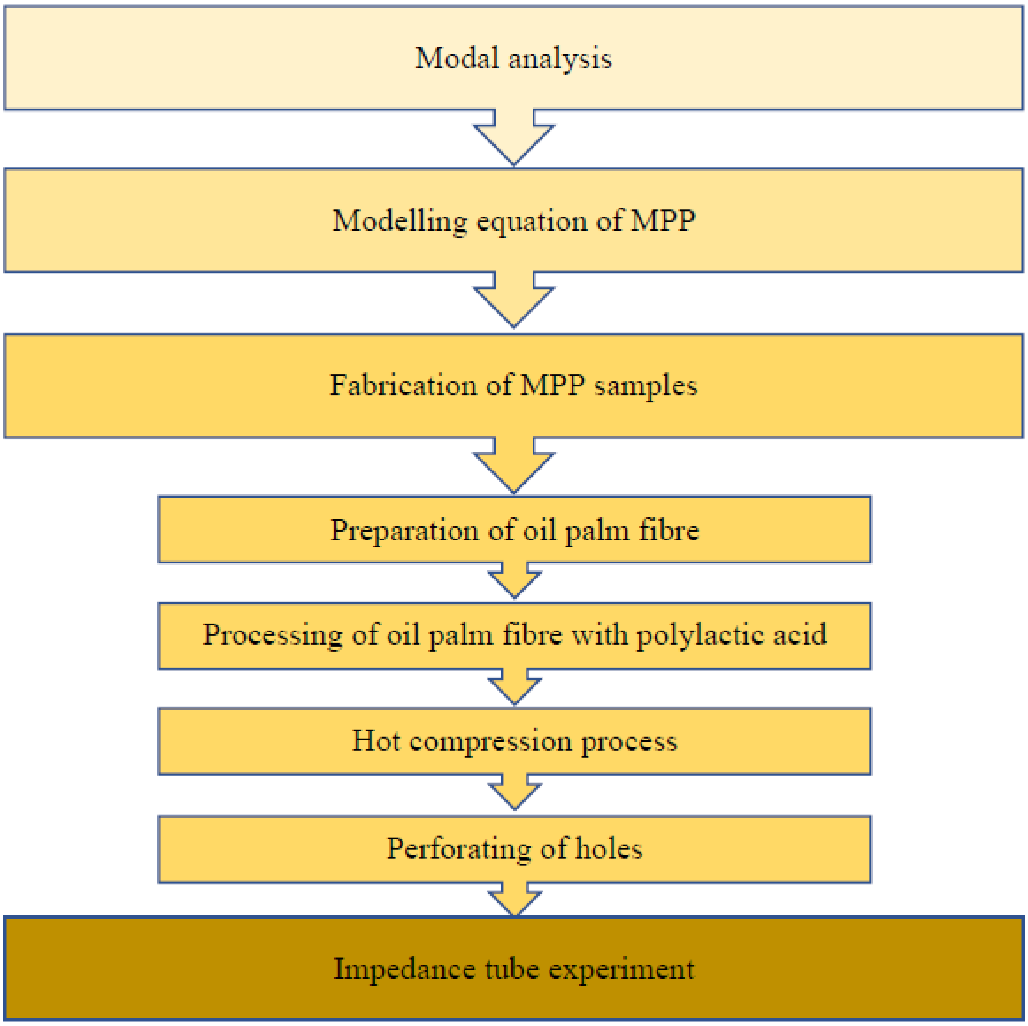

Figure 3.1 Flowchart of the overall project

3.2 Modal Analysis

For varied thicknesses of the MPP sound absorber, modal analysis was utilized to establish the normal mode forms and resonant frequencies at the specific (m, n) mode, ω_{mn}, which will be employed later in the MPP modelling equation. The results of the modal analysis were obtained by using the ANSYS software. The edge boundary condition of the MP was assumed to be simply supported with zero damping in this investigation. Besides, the MPP was round-shaped, with a radius of 18.7 mm.

Three mode shapes (m, n) of MPP made by oil palm fibre were considered for this study. The mode shapes considered were (1,1), (2,1) and (2,2). The symbol (m, n) denoted the number of nodal lines in direction of x and y respectively. According to Mahjoub [60], the density of oil palm fibre was 1150 kg/m^3, tensile strength was 71 MPa and Young's Modulus was 1.7 GPa. In the modal analysis of the MPP, the Poisson ratio was assumed to be 0.3.

3.3 Modelling Equation of MPP

In this section, the mathematical model for MPP, considering the vibroacoustic effect was presented. The vibroacoustic effect of MPP consists of the micro-perforation effect and the acoustical-structural interaction. The results obtained from Section 3.3.1 and Section 3.3.2 can be considered as theoretical results for the MPP samples. Apart from that, the sound absorption coefficient (SAC) of the MPP, without vibration effect was also calculated.

3.3.1 Micro-perforation Effect

Figure 3.1 (a) demonstrates the schematic diagram of MPP with hole diameter, d and distance between the centre of perforated holes, b which is backed with an air cavity depth of D. Based on Maa's theory [5], Figure 3.1 (b) shows how the MPP can be represented in an electrical equivalent circuit. The sound wave, p impinging on the plate is equivalent to sound pressure, $2p$ as created on the stiff wall and ρc act as the internal air [61]. The acoustic impedance of the MPP's micro-perforations is a complex quantity. Noted that R indicates the real part of the acoustic impedance, which is also representing the acoustic resistance. Meanwhile, M is the imaginary part of the acoustic impedance, which representing the acoustic mass reactance. By referring to Figure 3.1 (b), it is clearly shown that the acoustic impedance of the MPP is connected in series with the acoustic impedance of the backed air cavity, Z_D.

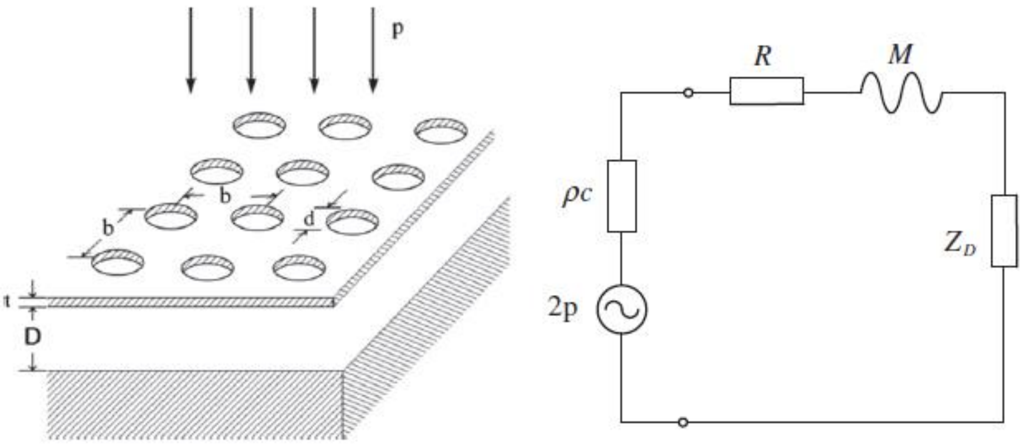

Figure 3.2 (a) Schematics diagram of MPP and (b) MPP equivalent circuit [5]

A perforated hole can be considered as a short tube. By assuming sinusoidal functions of time and zero velocity on the tube wall, the specific acoustic impedance of the micro-perforated holes was introduced,

$$Z_1 = j\omega\rho t\left[1-\frac{2}{k\sqrt{-j}}\frac{J_1(k\sqrt{-j})}{J_0(k\sqrt{-j})}\right]^{-1} \tag{3.1}$$

The specific acoustic impedance of the micro-perforated holes on the panel in Eq. (3.1) can be represented by an approximate solution for holes of sub-millimetre size,

$$Z_1 = \frac{32\rho\mu t}{d^2}\sqrt{1+\frac{k^2}{32}} + j\omega\rho t\left(1+\frac{1}{\sqrt{3^2+\frac{k^2}{2}}}\right) \tag{3.2}$$

Apart from that, end corrections must be added to the specific acoustic impedance of the holes. According to Qian and Kong [53], the friction loss caused by a portion of the air moving along the panel when it flows into and out of the perforated holes produces the end adjustment of the acoustic resistance. The additional part of the acoustic resistance is $2\sqrt{2\omega\rho\eta}$, if both sides of the perforated hole are ended in infinite plates. The end correction of the acoustic mass is caused by sound emission from the perforated hole's ends, which increases the hole's effective length by $0.85d$ when both ends are included. Therefore, the acoustic impedance of the micro-perforations on the panel normalized by the characteristic impedance of air, ρc can be written as:

$$Z_0 = \frac{Z_1}{\rho c} = R + j\omega M \tag{3.3}$$

$$\text{with } R = \frac{32\mu}{c}\frac{t}{d^2}\left(\sqrt{1+\frac{k^2}{32}}+\frac{\sqrt{2}k}{8}\frac{d}{t}\right) \tag{3.4}$$

$$\omega M = \frac{\omega t}{c}\left(1+\frac{1}{\sqrt{3^2+\frac{k^2}{2}}}+0.85\frac{d}{t}\right) \tag{3.5}$$

For Eq. (3.4) and (3.5), the perforation constant, $k = \sqrt{\frac{\omega}{4\mu}}d$ is outlined as the ratio of the hole's diameter to the thickness of the air at the viscous boundary's layer in the perforated holes. The kinematic viscosity constant of air is μ, the speed of sound is c, the density of air is ρ and the angular frequency is $\omega = 2\pi f$. According to Maa [5], the speed of sound, c is 340 m/s, the kinematic viscosity of air, μ is 1.56×10^{-5} kg/ms and the density of air, ρ is 1.204 kg/m^3. Besides, the frequency applied in this study is in the range of 50 to 2000 Hz.

An MPP can be considered as a connection of holes in parallel according to Maa [9]. Therefore, the overall acoustic impedance of the micro-perforations on the panel can be expressed as:

$$\overline{Z_0} = \frac{Z_0}{\sigma} \tag{3.6}$$

3.3.2 Acoustical-structural Interaction

The vibration impact caused by the entering sound wave is ignored by the acoustic impedance equation in Eq. (3.6). The acoustic-structural interaction can be taken into account while considering the vibration effect of MPP, as proposed by Takahashi and Tanaka [62], Lee [45] [49], Tan and Ripin [63] and Bravo [46].

Figure 3.2 shows the mean particle velocity distribution, $\bar{V}$ about the panel velocity, v_p and the air particle velocity, v_0 averaged over each perforated hole of the MPP. With the pressure difference between the external pressure, p and the internal pressure, p_D, the MPP vibrates under acoustic stress [50].

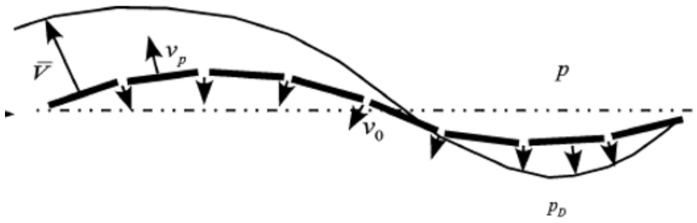

Figure 3.3 Analytical model of MPP [50]

The acoustic impedance of the panel due to vibration and normalized by the characteristic impedance of air, ρc can be expressed as:

$$Z = \frac{\left[\sum_{m=1}^{M}\sum_{n=1}^{N}\frac{\varepsilon_{mn}\varepsilon'_{mn}}{\eta_{mn}z_{mn}}\right]^{-1}}{\rho c} \tag{3.7}$$

$$\text{where } \eta_{mn} = \int_0^r\int_0^r X_m(x)^2 Y_n(y)^2 dxdy \tag{3.8}$$

$$\varepsilon_{mn} = \int_0^r\int_0^r X_m(x)Y_n(y)dxdy \tag{3.9}$$

$$\varepsilon'_{mn} = \frac{\varepsilon_{mn}}{r^2} \tag{3.10}$$

$$z_{mn} = \rho_p\frac{\zeta_{mn}\omega_{mn}\omega + j(\omega^2-\omega_{mn}^2)}{\omega} \tag{3.11}$$

The detailed derivation of Eq. (3.7) can be obtained in the work of Tan and Ripin [50]. For Eq. (3.7), the modal impedance of the (m,n) mode of the panel is z_{mn} while M and N are the numbers of structural modes. For Eq. (3.11), the resonant frequency at the (m,n) mode is ω_{mn} and the modal damping ratio is ζ_{mn}. Moreover, r is the radius of the panel. For a panel with simply supported boundary condition, the normal mode shape can be written as:

$$X_m(x) = \sin(\chi_m x) \text{ and } Y_n(y) = \sin(\chi_n y) \tag{3.12}$$

$$\text{where } \chi_m = \frac{m\pi}{r} \text{ and } \chi_n = \frac{n\pi}{r} \tag{3.13}$$

Besides, in Eq. (3.11), ρ_p is the panel surface density and was derived as:

$$\rho_p = \frac{m_p}{A_p} \tag{3.14}$$

$$\text{where } m_p = \rho_{CP} \times V_p \tag{3.15}$$

$$A_p = \pi r^2 \tag{3.16}$$

For Eq. (3.14), m_p is the mass of the panel and A_p is the area of the panel. In Eq. (3.15), the volume of the panel is $V_p = \pi r^2 t$, where t is the thickness of the panel. The density of the composite of oil palm fibre and polylactic acid (PLA) is ρ_{CP}. This equation can be obtained as:

$$\rho_{CP} = \rho_{OPF} \frac{\%OPF}{100} + \rho_{PLA} \frac{\%PLA}{100} \tag{3.17}$$

For Eq, (3.17), ρ_{OPF} is the density of oil palm fibre and is obtained as 1150 kg/m^3 according to Mahjoub [60] while ρ_{PLA} is the density of PLA and is obtained as 1240 kg/m^3 according to Chin Vui Sheng [59]. $\%OPF$ and $\%PLA$ are the composition percentage of oil palm fibre and PLA respectively.

Moreover, the acoustic impedance of the MPP, with the vibroacoustic effect was defined as:

$$Z_{MPP} = \frac{\overline{Z_0} Z}{Z_0 + Z} \tag{3.18}$$

Meanwhile, the acoustic impedance for the backed air cavity of the MPP, normalized by ρc can be derived as:

$$Z_D = -j \cot\left(\frac{\omega D}{c}\right) \tag{3.19}$$

where the air cavity depth is D.

The total acoustic impedance of the MPP can be obtained by summing the acoustic impedance of the MPP, Z_{MPP} and the acoustic impedance of the backed air cavity, Z_D:

$$Z_{total} = Z_{MPP} + Z_D \tag{3.20}$$

The resulting normal incidence SAC can be derived as:

$$\alpha = \frac{4Re(Z_{total})}{\left(1+Re(Z_{total})\right)^2 + \left(Im(Z_{total})\right)^2} \tag{3.21}$$

3.3.3 Sound Absorption Coefficient (SAC) of MPP, without Vibration Effect

Moreover, to compare the panel vibration effect towards the sound absorption performance of MPP with different panel thickness, SAC of MPP that does not take into consideration the vibration effect was also determined by using Eq. (3.21).

However, in the equation, Z_{total} was obtained by summing the acoustic impedance of the MPP, Z_{MPP} and the overall acoustic impedance of the micro-perforations on the panel, $\overline{Z_0}$:

$$Z_{total} = Z_{MPP} + \overline{Z_0} \tag{3.22}$$

The SAC of the MPP sound absorber will be compared with and without the vibration effect, and the findings will be presented in Section 4.3.2. Besides, the MATLAB code for the modelling equation of MPP, with and without panel vibration effect is shown in Appendix 1.

3.4 Fabrication of MPP Samples

In this section, each fabrication steps to make MPP samples from oil palm fibre was presented. The fabrication steps of the MPP samples consisted of preparation of oil palm fibre, processing of oil palm fibre with polylactic acid (PLA), hot compression process and perforating of holes on the samples. All the fabrication steps were explained in detail in this section.

3.4.1 Preparation of Oil Palm Fibre

Firstly, five packets of oil palm fibre, with 500 g for each packet was prepared. The oil palm fibre was washed with tap water to remove the soil particles on the fibres. To remove excess wax and other impurities on the fibres, the washed oil palm fibre was immersed in deionized water using a deionizer as illustrated in Figure 3.4. The oil palm fibre was immersed in the deionized water for around 24 hours.

Figure 3.4 Deionizer

After that, the oil palm fibre was rinsed with hot water at a temperature of 60 ˚C inside a water bath as shown in Figure 3.5. This process was carried out to remove excessive wax and oil contents of the fibres. This is because the oil contents inside the oil palm fibre might influence the acoustic performance of the fibres.

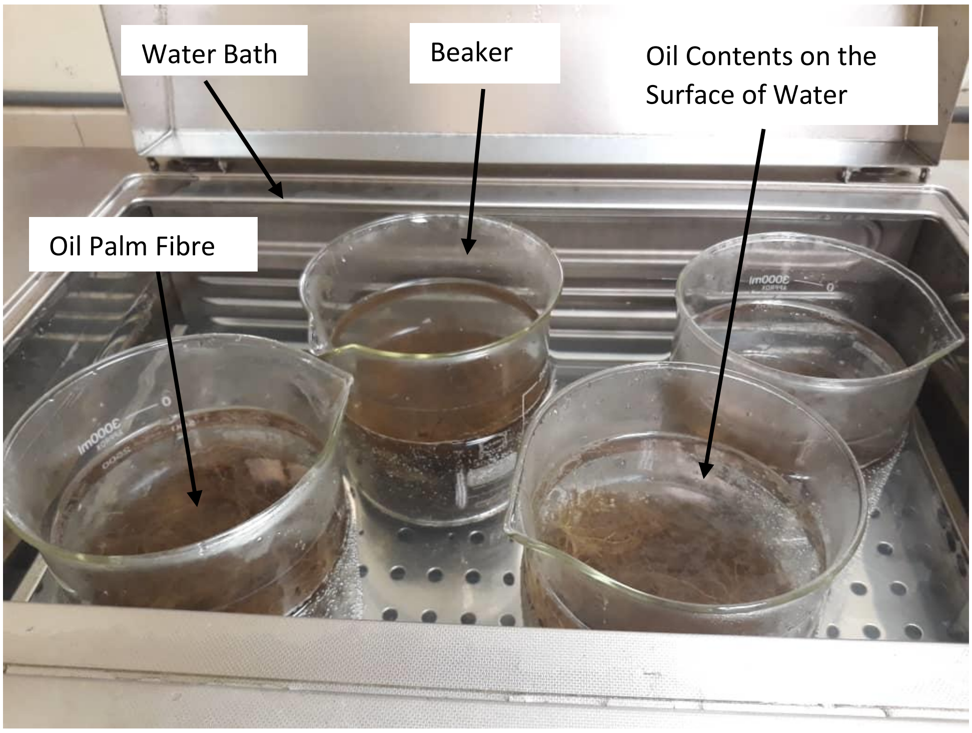

Figure 3.5 Oil palm fibre rinsed with hot water in the water bath.

After rinsing with hot water, the oil palm fibre was then soaked in acetone for 15 minutes. As shown in Figure 3.6, this step was done inside the wet cabinet. Acetone was used in this step to absorb the oil contents of the oil palm fibre. The oil palm fibre after soaking in acetone was moved to the aluminium plate.

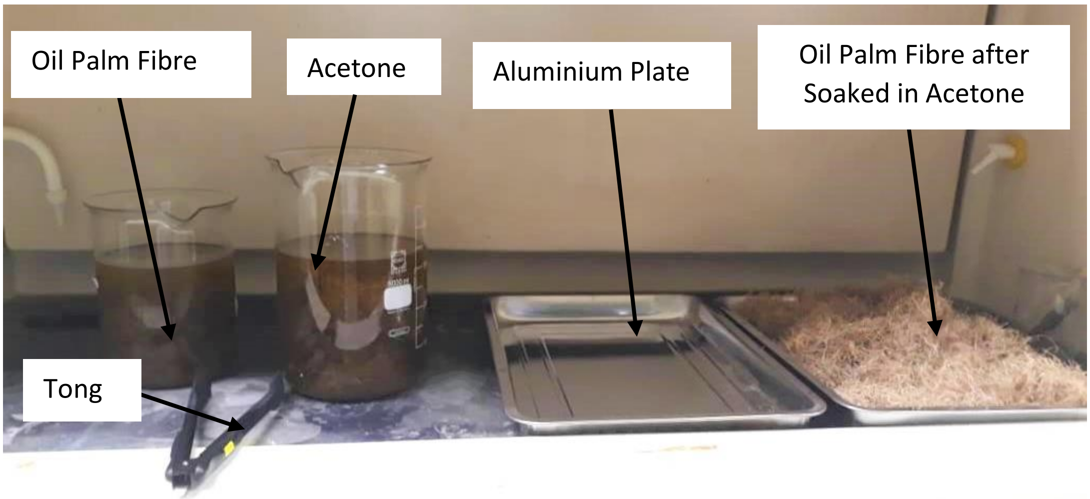

Figure 3.6 Oil palm fibre soaked in acetone inside the wet cabinet.

Then, the oil palm fibre was dried in an air circular oven at a temperature of 60 ˚C for 24 hours as demonstrated in Figure 3.7. The drying process was done to reduce or even minimize the moisture on the oil palm fibre.

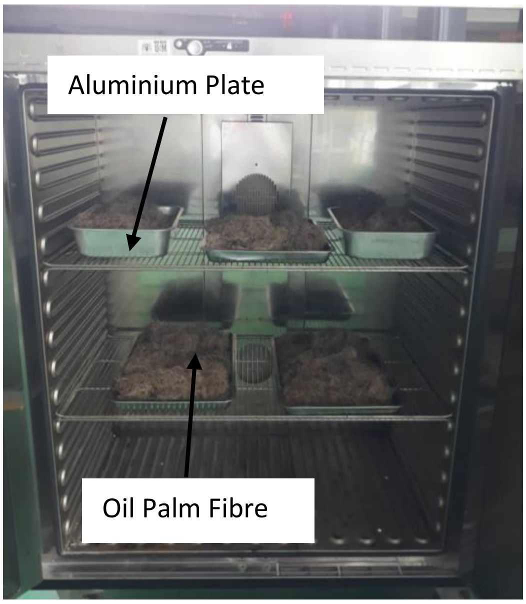

Figure 3.7 Oil palm fibre dried in air circular oven.

The dried oil palm fibre was then ground into smaller particles by using the crushing machine as shown in Figure 3.8 (a). After that, the ground oil palm fibre was then sieved into 1 mm by using a vibrating sieve machine as shown in Figure 3.8 (b). The mesh size of the tray on the vibrating sieve machine was set as 2 mm, 1 mm and 0.125 mm from the top to the bottom of the tray. The oil palm fibre was sieved by using an amplitude of 100 for 20 minutes.

Figure 3.8 (a) Crushing machine (b) Vibrating sieve machine