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Design from waste: A novel eco-efficient pyramidal microwave absorber using rice husks and medium density fibreboard residues

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ABSTRACT

The sustainable future of contemporary society has been compromised due to environmental pollution from industrial systems and the generation of solid waste. Consequentially, the managed exploitation of natural resources to a sustainable level within the Earth's capacity remains a present and future challenge. Furthermore, the pursuit of materials free from toxic substances made from renewable sources is a tendency towards effective cleaner production and waste management. To address these problems, this article reports the results of exploratory and experimental research that developed a novel eco-efficient product - a pyramidal absorber of electromagnetic radiation - from rice husks and MDF (Medium Density Fibreboard) residues through design from waste principles. Key findings indicated that the technical performance of the absorber is better in the frequency of 2.45 GHz, resulting in a difference of −18.71 dB concerning the reflective metal plate used in the tests. This result is above the expected limit of −10 dB found in similar commercial products. This study is an innovation in improving the design from waste of pyramidal microwave absorbers used in radio frequency anechoic chambers. The product represents a new and sustainable alternative to similar products in the market that are produced from toxic materials extracted from non-renewable raw materials. The limitations and technical characteristics of usage for which the pyramidal absorbers of electromagnetic radiation are applicable should be considered.

1. Introduction

Environmental impacts resulting from industrial systems have intensified around the world in parallel with the growth in world population, and the resulting rise in the consumption of goods and waste generation, compromising a sustainable future for contemporary society (WBCDS, 2002). These environmental impacts have, over the years, motivated scientists and engineers to seek new technological alternatives for cleaner production and economic sustainability, through the proposal of projects in public research programs and the development of sustainable options. There are several alternatives solutions for environmental problems, including treating pollution, to reduce negative environmental effects generated by industrial activities, the use of clean technologies, and the development of new products using industrial waste (Ragaert et al., 2019; Manzini and Vezzoli, 2008; Keffer et al., 1999).

Any product may be considered eco-efficient, be it crafted or manufactured, be it for personal use or foodstuff, household, commercial, agricultural or industrial use, provided that it effectively contributes to the development of an economic and social model through the recycling or the recovery of industrial by-products (Ragaert et al., 2019; Zenga et al., 2018; Araújo, 2011). Within such a context, recent studies have highlighted the use of rice husks as a valuable added-value material for the utilisation of residues and reduction of domestic and industrial processing costs (Li et al., 2020; Menya et al., 2018; Babaso and Sharanagouda, 2017; Quispe et al., 2017; Nornikman et al., 2015; Vitali et al., 2013; Malek et al., 2011; Moraes et al., 2010). Around 134 million tonnes of rice husks are generated worldwide annually, of which 90% are

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discharged into rivers or burned in open air (Quispe et al., 2017). Another important issue is that "The search for materials made from renewable sources and free from toxic substances is a global trend towards cleaner production [...]" (Souza et al., 2018, p. 549).

In this same line, recent studies state that MDF (Medium Density Fibreboard) residues remain a serious problem concerning its discard and destination by the furniture industry (Pereira Jr et al., 2018; Kouchaki-Penchah et al., 2016; Zenga et al., 2018; Turner et al., 2015; González-García et al., 2011). The global MDF production in 2016 reached over 99 million m^3 from 50 countries (Selvatti et al., 2018), while in practice, only 40 to 60% of the total volume of raw wood was effectively used, and the rest became waste (Olandoski, 2001). Indubitably this is a serious environmental problem. The situation is even more critical for the industries localised in low- and middle-income countries, because of the lack of awareness of sustainability by society as a whole, a lack of investments in the adequate disposal process, and the lack of regulation and governmental control over disposals.

Also, the disposal and destination given to MDF wastes by the furniture industry are further complicated due to the presence of toxic substances as chemical additives and synthetic resins (e.g., urea-formaldehyde, melamine-formaldehyde, phenol-formaldehyde) used in MDF production (Zenga et al., 2018; González-García et al., 2011). As a result, nowadays, very little is known about the possibilities of using MDF residues combined with rice husks in the development of new eco-efficient products, especially for the electronics industry. Commercially, polyurethane or polystyrene are the most common foam-based material used in pyramidal microwave absorbers fabrication (Malek et al., 2011). In this regards, our study also extends the debate on the reduction of the use of polyurethane, either by industrial manufacturers of the different types of radiofrequency absorbers (Idris et al., 2016), because polyurethane is widely used in rigid and flexible foams, durable elastomers and high-performance adhesives that are widely present in pyramidal microwave absorbers. It is known that there are several serious environmental problems involving the disposal of polyurethane-based products (Rosa and Guedes, 2003). Then, instead of using non-renewable resources and chemical materials (Solis and Silveira, 2020), we proposed the alternative application of biomass wastes, i.e., wood and rice rusks to manufacture electromagnetic radiation pyramidal microwave absorbers. Therefore, to address these challenges, the central question in this investigation asks, *how to appropriately combine rice husks and MDF residues to develop an eco-efficient electromagnetic radiation pyramidal microwave absorber?*

This study applied the design from recycling principles to develop a novel eco-efficient product making use of rice husks and MDF waste as raw materials in the production of a composite material. The new eco-product is an electromagnetic radiation pyramidal absorber (Yah et al., 2018; Nornikman et al., 2015; 2011), widely used to cover the internal walls of anechoic chambers to minimise the reflection of sound and electromagnetic waves (Idris et al., 2016; Dongshin, 2014). An anechoic chamber is a room or space, isolated from external sources, designed to absorb both sound and electromagnetic waves (Chung and Chua, 2004). The absorption of sound and electromagnetic waves renders an anechoic chamber similar to an open space of infinite dimension, which is an important feature when external data may interfere with application results.

The research method used was based on the analysis of previous studies, experiments and performance tests conducted in a laboratory to obtain composite materials from residues in the construction of pyramidal absorber units. The new product developed proved to be technically viable and a sustainable alternative - considering the limitations and technical characteristics for which it is intended - to the products currently available that are manufactured from synthetic materials that cause severe environmental damage due to their lengthy decomposition in nature. The eco-product developed is an innovation in improving the design from residues of pyramidal microwave absorbers used in radio frequency anechoic chambers.

The remaining part of the paper proceeds as follows. The following section presents the theoretical background regarding the electromagnetic radiation pyramidal absorber as well as the depth and limits of the research in this subject. Next, the research methods adopted are described, including the procedures for data collection and quantitative experiments performed in a laboratory. This study then proceeds to analysing the results and technical parameters obtained from tests. The fifth section discusses the findings, contributions achieved for science and industrial practice in the field. The paper closes presenting the conclusions, the general research implications, and suggestions for future research in this topic.

2. Electromagnetic radiation pyramidal absorbers

This section presents the conceptual definition and the most recent advances in scientific knowledge regarding electromagnetic radiation pyramidal absorbers as well as the attempts of literature to develop absorbers from materials free from toxic substances applying renewable sources. Many organisations are interested in electromagnetic wave absorbing materials, due to their extensive use in military and civil applications as anechoic chambers, and for radiation-proof electromagnetic shielding (Ding et al., 2016). Various studies have been conducted to find the ideal electromagnetic wave absorber, of thin and light layers, with good absorption and a wide frequency range. As a general rule, these absorbers are made from polymers and absorbent composite materials, such as nanotubes, ferrets and extra-fine metal powder. Electromagnetic wave absorbers are utilised for coating anechoic chambers which are used for electromagnetic testing or for attenuating or shielding areas subject to intense sources of radio frequencies that are harmful to human health (Migliano et al., 2002). Anechoic chambers are used in the analysis of new antenna and electromagnetic interference, electromagnetic compatibility tests for land vehicles and aircraft, microwave ovens, among other applications (Chung and Chua, 2004).

The components present in absorbent materials that attenuate or absorb electromagnetic waves are complex (Iqbal et al., 2013; Folgueras and Rezende, 2006). These electromagnetic materials promote the exchange of electromagnetic radiation energy for thermic energy due to the intrinsic characteristics of particular components. Once hit by an electromagnetic wave, these absorbers have their molecular structure excited, and the incident energy is converted to heat, providing a low reflection of the incidental wave (Schleher, 1999).

The elaboration and production of an electromagnetic radiation absorbent materials have as a fundamental principle - the composition and synthesis of constructive materials - through the arrangement of dielectric and magnetic materials that will provide the profile for the impedance of a particular incident electromagnetic wave (Migliano et al., 2002). The evolution of the technology for obtaining these absorbent materials is consistent with studies that involve experiments on the elaboration of new materials, in particular, composites and the development of methods and techniques for obtaining coatings of better quality and ever more comprehensive range absorption. Although there are several types of radiation absorbent materials in the market, according to Malek et al. (2011), this type of product is still made with materials that demand the use of non-renewable raw-materials and synthetic components. These absorbers are manufactured by the addition of carbon to a plastic polyurethane and polystyrene foam.

Some previous studies demonstrated the viability of the utilisation of waste from synthetic materials and different types of food waste to develop electromagnetic radiation absorbers. Nornikman et al. (2011) state that agricultural residues - often not considered useful - are commonly discarded or burnt after harvest. Rice husks have been investigated as a material to be used in the construction of radio-frequency pyramidal absorbers. A mixture of rice husks and polyester residue was used to obtain the material composite. The experiments showed that the reflection loss attained by using the proposed composite was significant, being better than −30 dB. These tests were conducted in the 7–13 GHz microwave range. Microwaves are electromagnetic waves that have wavelengths between 300 mm and 1 mm, corresponding to the frequency between 1 GHz and 300 GHz (Chambers, 1999).

The experiments conducted by Nornikman et al. (2010; 2011; 2015) corroborate the need for new research to investigate the performance of rice husks for the construction of the absorbers, due to the influence of temperature, humidity and other environmental parameters. They argue that it is imperative to ensure the viability and robustness of this composite in complying with various international norms before commercialisation. The results evidence that rice husks have great potential to be used as material for radio-frequency pyramidal absorbers. Liyana et al. (2012) report a type of pyramidal absorber from the use of sugar cane bagasse. They considered this agricultural residue to be a beneficial alternative to the material currently manufactured with chemical products (Solis and Silveira, 2020), confirming that sugar cane bagasse can be applied in pyramidal absorbers. In that work, experiments were conducted to test the dielectrics of sugar cane bagasse (electrical constant and tangent loss). The resulting pyramidal absorbers could be used in the frequency ranges between 0.1 GHz and 20 GHz. The results demonstrate that this material obtained a reflection loss rate better than −30 dB.

An experiment in the construction of pyramidal absorbers from the elaboration of a composite material obtained from the mixture of banana leaves with polyester, and methyl ethyl ketone peroxide (MEKP) as a hardening agent was also identified (Farhany et al., 2012). This study analysed previous experiments made with rice husks and showed a reflection loss better than −30 dB in a frequency range from 1.89 to 20 GHz. The pyramidal absorber developed proved to be better than −97.59 dB in a frequency range from 0.504 to 14.933 GHz. The authors state that the pyramidal absorber based on banana leaves had the best performance for reflection loss in the range between 5 and 10 GHz with a reflection loss of −46.17 dB. The worst performance was observed between 0.01 and 1 GHz with a reflection loss of −16.031 dB for rice husks. In the same range, the best performance when using banana leaves was −63.28 dB. The frequency where an excellent result was achieved, reaching a reflection loss of 123.47 dB, was 4 GHz.

Nornikman et al. (2015) claim that the residues based on rice husks have potential as an alternative material in the construction of pyramidal absorbers for microwaves. Their results showed that it is possible to achieve a reduction in production costs and contribute to the preservation of the environment. What was demonstrated is that the reflection loss of the pyramidal absorber produced with rice husks is significantly better than −10 dB in every frequency range between 0.01 GHz and 10 GHz. It was reported that the height of the pyramidal absorber alters its performance. Already, Nuan-on et al. (2017) developed an absorber from water hyacinth, a natural compound. This material is made up primarily from carbon (approximately 32–35% in weight) and possesses high levels of microwave absorption. The samples for the tests were obtained using an agent with water hyacinth to produce the absorbers. The performance was determined in accordance with the reflection coefficients. The results were compared to those of the commercially available microwave absorbers in the frequency range from 0 to 20 GHz. The microwave absorber presented a greater coefficient of reflection of −10 dB in the range of 818 GHz.

Yah et al. (2018) investigated the performance of organic green coconut fibre and a composite of charcoal as a material for absorbers. Like husks, coconut residue is employed in agriculture and horticulture as an organic natural fertiliser, while coconut shells are burned into charcoal. The authors state that measurement results demonstrate that coconut fibre shows properties with promising potential to be developed as an adequate material for microwave absorbers. Mishra et al. (2020) also verified that agriculture residues are rich in carbon and are of significant potential as micro-wave absorbing material. The study comprises the synthesis and characterisation of epoxy composites based on coconut as absorbent materials. The findings indicated functional absorption capacity of the materials in a frequency range between 8.2 and 12.4 GHz, with a maximum frequency loss −23.5 dB in the 10 GHz frequency.

Alternatively, Malek et al. (2011) used tyre rubber residue and rice husks to develop pyramidal absorbers. The work investigated the reflexibility and the performance for reflection loss from the conception of the composite material. The loss of rebound obtained from tyre rubber powder mixed with rice husks was considered significant and, also, produced results better than −30 dB. The fabrication process of a pyramidal electromagnetic absorber made by natural rubber also was evidenced (Salayong et al., 2018). They consider that having generated aggregated value latex from Thai rubber and reducing the number of chemical absorbers using absorbers based on natural rubber is advantageous. The absorbers were built from latex with a black carbon filter. The absorber proposed consisted of a rubber foam structure that showed adequate characteristics to be used as an absorbent. Reflexibility was measured in frequency ranges from 6 to 18 GHz. This development proved to be viable for all frequency ranges of interest, and the reflexibility was considered comparable to the commercially available absorbers.

The results from literature in the area indicate the absence of previous studies applying MDF residues combined with other materials, particularly, rice husks, aiming to develop an electromagnetic radiation pyramidal absorber. The next chapter presents the procedures of collection and analysis of data as well as the research methodology considered.

3. Materials and methods

In this research, we demonstrated the results of an exploratory and experimental study that developed in the laboratory a novel eco-efficient product, a pyramidal absorber of electromagnetic radiation, using rice husks and MDF residues. Initially, in addressing the research objective guiding this study, a search process for literature review in the field was adopted. A search strategy including databases, keywords, period, eligibility, and exclusion criteria was performed. A Web of Science and Scope were used because their coverage differs the most in engineering, technology and also do not necessarily index the same scientific journals (Mongeon and Paul-Hus, 2016). The search period considered was initially between 1995 and 2018, although a continuum search process in literature was carried out by the research team along with the research project realisation. A complementary search process in the grey literature in Google Scholar also was performed. The keywords and Boolean operators for searching included "Pyramidal Microwave Absorber" AND "Rice Husks" in the Title and Abstract of databases. As a result of the examination of the literature, the research and development methods applied in this investigation were based on the methodology and techniques proposed by Nornikman et al. (2011), Malek et al. (2011), Liyana et al. (2012) and Farhany et al. (2012). The materials selected for the construction of the pyramidal absorbers were rice husks and MDF residues, with the latter being made from the agglutination of wood fibre with synthetic resins and other chemical additives. The experiments were conducted in the laboratories of the Integrated Colleges of Taquara, including the Laboratory of Innovation and Optimisation of Products and Processes, the Laboratory of Signal Analysis, and the Laboratory of Analysis of Materials. The analysis conducted to obtain the composite material were performed during eighteen months as part of a government-funded research project.

Notably, MDF residue represents a significant problem because of its discard and destination, as given by the furniture industry (Kouchaki-Penchah et al., 2016; Zenga et al., 2018). Besides, the calculated emission factors of MDF waste are over 502 kg CO2e/t (gross) and −444 kg CO2e/t (net) (Turner et al., 2015), while rice husks can be used in different applications (Menya et al., 2018).

The frequency range selected for the electromagnetic radiation attenuation to the pyramidal absorber developed was from 800 MHz to 6 GHz. This range was determined considering the ample application of Radio Frequency Identification *(RFID)* technology in industrial production systems that utilise Ultra High Frequency (*UHF*) bandwidth. RFID technology is the object of various international researches and investments from both industry and scientific community, with a continuous growth rate for such equipment in the last few years with the advent of Industry 4.0 technologies.

Thus, the first phase of development of this research was experimental, since the physical, chemical, and electromagnetic characteristics of the material resulting from the composite obtained from mixing rice husks and MDF residue are not yet known. Natural rice husks were initially submitted to a milling process which resulted in the Experimental material (Material E).

Next, granulometric analysis of the rice husks, the MDF's powder and Material E (milled rice husks) was conducted. The proceedings adopted involved dehydrating the sampled material in drying-ovens at 60 °C for 120 h and sieving. The sieving process was performed with a set of five sieves continually shaken for 10 min. The sedimental mass taken from each sieve was subsequently weighted, and the percentual for each type of material utilised was calculated. The classification of the grains was based on Wentworth's (1922) granulometric scale adapted by the authors. The next section shows the results of the remaining steps of the development and the analysis of the performance of the novel product.

4. Results

This section elicits how the conceptual model of the pyramidal absorber was determined, the procedures for obtaining the experimental material, and the laboratory test results. Hence, the stages of conceptual product development and the tests performed to the selection of composite material are described.

4.1. Conceptual product development

Parallel to the granulometric analysis, the conceptual model for the construction of the absorbers was determined (see supplementary material published with this article in Fig. 3), together with a matrix for the experimental production of the prototype. The dimensions of the model were based on the studies of Nornikman et al. (2010; 2011), Malek et al. (2011), Liyana et al. (2012), and Farhany et al. (2012).

A customised matrix of the product project was developed from the tri-dimensional iconic model of the pyramidal absorber. The form was designed with four cavities to enable the mouldering of four pyramidal absorbers in every test (see supplementary material published with this article in Figs. 4, 6 and 7). This configuration increased the production capacity of this matrix in comparison to those matrices developed previously (Nornikman et al., 2011; Liyana et al., 2012), which have only one cavity each.

Nornikman et al. (2011) proposed a matrix that has only one cavity, and besides, it also opened and closed by meanings of doing and undoing screws at every operation. Therefore, in our project, a new mechanism was incorporated - a lever with a lock - on the left-hand side of the matrix to lock the system when the matrix was closed shut. Additionally, a hinge was incorporated on the right-hand side, to facilitate movement and as a support to its frontal part when opening the matrix. The efficiency and accuracy of the opening and closing mechanism of the matrix became necessary as the cavity mould for the pyramidal absorbers demanded uniformity between the two parts. In its inferior half, the cavity has an outlet for the drainage of the liquid resulting from the compression of the composite material. Finally, water, in the liquid state, was used for mixing the materials (rice husks and MDF residue) alongside starch, used as a bidding element (viscoelastic paste).

4.2. Selection of composite material

The second phase of the study and product development consisted of producing the composite material through the mixture of portions of the Material E and MDF powder, for the advance with the prototype production process. After combining the materials, the resulting composite, was obtained and analysed with a 500x magnitude electronic optic microscope.

To carry out the appropriate selection of materials for mixing the composite and obtaining the prototypes, a granulometric analysis of the natural rice husk was carried out after the milling processes. The procedure consisted of initially drying the sampled material in an oven at a temperature of 60 °C for 24 h and the subsequent screening process. This last stage was performed with a set of five screens stirred for 10 min (Table 1).

The selection of materials was carried out due to the greater mechanical resistance obtained in the tests of transverse compression performed on the specimens. The transverse mechanical resistance is an important attribute in pyramidal absorbers because, during the installation process, the handling for fixation is always done transversally by the technician in the field. Another critical factor is the longitudinal resistance and robustness due to the absorber maintaining the structural integrity after it is installed on the anechoic chamber surfaces.

Three prototypes were constructed with different grain diameter sizes of the natural rice husk: Specimen 1 (CP1) = $\geq$0.062 mm;

Table 1
Granulometric analysis of natural rice husk.

Sieve used (mm)	Grain Diameter (Wentworth) (mm)	Natural Rice Rusk (grams)	%
0.600	$\geq$0.062	1.1624	99.452
0.425	$\geq$0.125	0.0062	0.530
0.300	$\geq$0.250	0.0002	0.017
0.150	$\geq$0.500	0	0
0.075	$\geq$1.00	0	0
Sieve 0	*Background*	*x-x*	*0*
Total	**x-x**	**1.168**	**100**

Source: Adapted from Wentworth (1922).

Specimen 2 (CP2) = ≥0.125 mm; and Specimen 3 (CP3) = ≥0.250 mm. The grain diameter of MDF power was ≤ to 0.5 mm to the three prototypes. Next, after mixing the materials, MDF powder and rice husk, the specimens were subjected to a transversal compression test (Fig. 1).

The maximum load force supported by the specimen (CP1) was over 315.3 N and 1.87 mm deformation. Thus, based on the results, the rice husks ground with grain diameter ≥0.062 mm were chosen for the subsequent analyses, and experimental tests carried out in the research.

In the following stage of experimental tests, a set of prototypes was built with the same concentration of materials (i.e., 31.25 g of MDF powder; 31.5 g of ground rice husks; 12.5 g starch and 87.5 ml water). Starch diluted in water was used to amalgamate the materials. Next, the materials were weighted and added to the starch solution. After the mixture was produced, the matrix compartments were filled with the resulting composite. During the following stage, the absorbers went through a drying process with a temperature of 25 °C for approximately 120 h for each set of four units produced.

In the second phase of the study, sets of sixteen units of prototype absorbers were then produced and experimentally tested. Similar to the studies by Nornikman et al. (2011) and Malek et al. (2011) that utilised four sets of sixteen absorbers of each type for the experimental tests, the present study followed the same criteria. Each set of sixteen absorbers were placed over a 2 × 20 × 20 cm plate. In total, to conduct the tests, the production of sixty-four pyramidal absorbers for each type of sampling was necessary. The performance of experimental tests is detailed in the following section.

4.3. Results of experimental tests

In the third phase of the research, experimental testing was carried out, seeking to determine the electromagnetic characteristics and the mechanical robustness of the new pyramidal absorbers. A series of tests took place for the analysis and the determination of the parameters (i) for reflection loss, and; (ii) the absorption efficiency of the pyramidal absorbers in relation to a reflective metal surface. This metallic surface was constituted by four 20 × 20 cm sheets of copper. The area of incidence and reflection of 40 × 40 cm was then determined. The tests were performed in a controlled environmental condition of 22 degrees Celsius and relative air humidity of 63%. The incident area was demarcated on a test bench. On the left-hand side of the test bench, a Horn antenna (transmitter) was placed, and on the right-hand side, another Horn antenna (receiver) was placed. The antenna had a radiation angle of 45° to the centre of the area where the testing took place (Fig. 2). All experimental tests were carried out with the use of a Vectorial Network Analyzer - Agilent, model N5230C (300 kHz to 13.5 GHz). The tests followed the method used by Nornikman et al. (2011).

All experimental tests were carried out with the use of a Vectorial Network Analyzer - Agilent, model N5230C (300 kHz to 13.5 GHz). The tests followed the method used by Nornikman et al. (2011). For this reason, they did not take place in an anechoic chamber. Therefore, all possible variables that may cause interference were kept constant in the tests applied to the copper metal sheet reflector, as well as to these applied to the set of absorbers.

The first series of tests performed had the objective of determining the reflection loss attained, taking into consideration the radiation applied to the copper metal sheet, positioned in the centre of the testing area, and the respective reflection. Likewise, the second series of tests had the same objective, but with the set of absorbers positioned in the centre of the testing area without the metal sheet.

Both the transmission and reception series of tests were carried out on the following frequencies: 600 MHz; 700 MHz; 800 MHz; 868 MHz; 915 MHz; 1 GHz; 2 GHz; 2.45 GHz; 3 GHz; 4 GHz; 5 Hz; 5.8 GHz and 6 GHz. Frequencies of 868 and 915 MHz, as well as 2.45 and 5.8 GHz, were added to the tests due to their nominal use in systems with RFID technology.

After all experimental tests took place in every frequency, with both metal sheet reflector and pyramidal absorbers, it was possible to ascertain by comparative analysis the performance in relation to reflection loss resulting. In applications of the electronics and telecommunications sectors, the return loss refers to the power in the signal returned or reflected by a discontinuity in a transmission line. It is related to the reflection coefficient and the standing wave ratio. For practical applications, a high return loss is desirable to obtain a better absorption of sound and electromagnetic waves.

The difference observed between the return/reflection loss of the metal sheet and the absorbers set was −18.71 dB (module variation between −36.11 in Fig. 3 and −54.82 in Fig. 4). The results obtained from the preliminary analysis demonstrate that the absorber set proved technically efficient, considering the acceptable limits for radiation absorbers are −10 dB. The viability of the prototype was determined in the central frequency operating

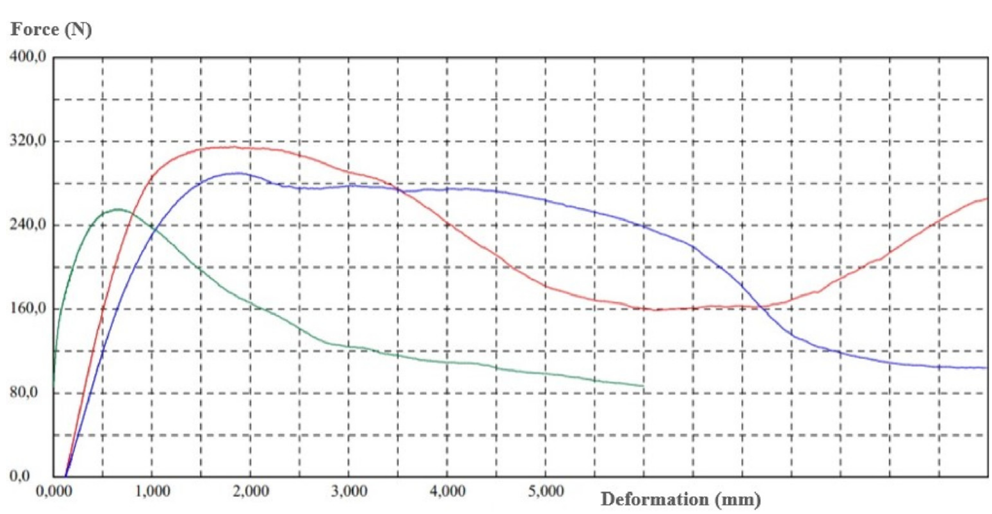

Fig 1. Transverse compression tests for the selection of composite material.

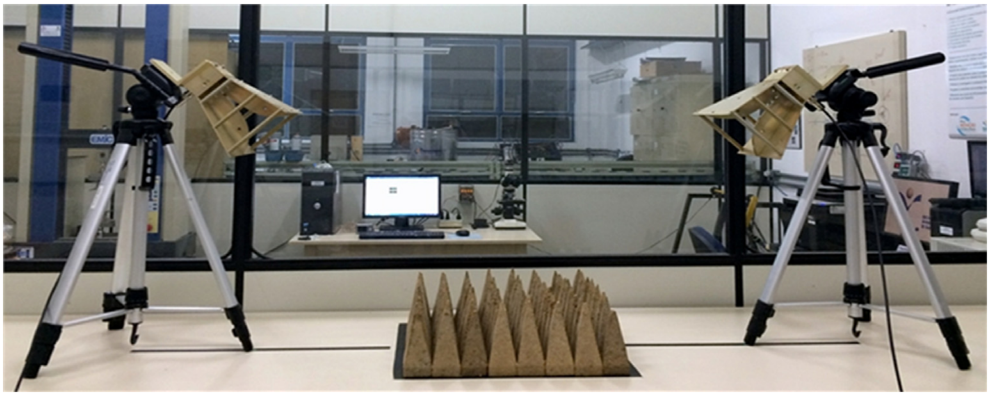

Fig. 2. Pyramidal absorbers in the centre of the testing area.

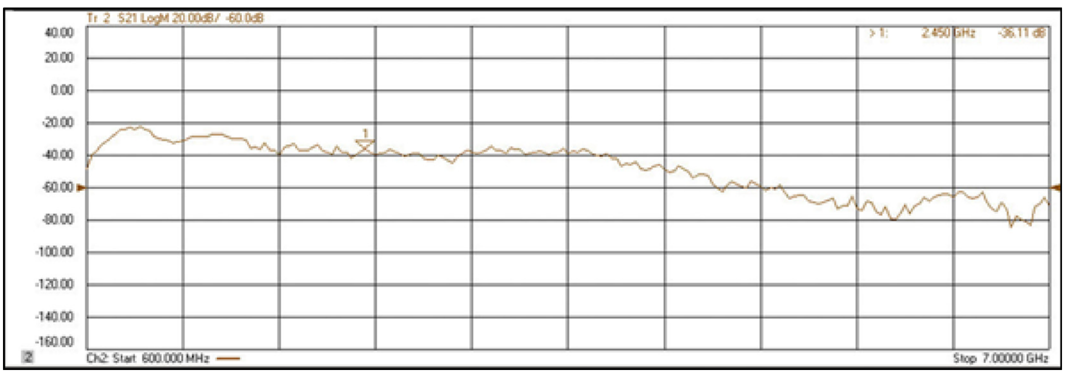

Fig. 3. Return loss for frequency 2.45 GHz on metal sheet −36.11 dB.

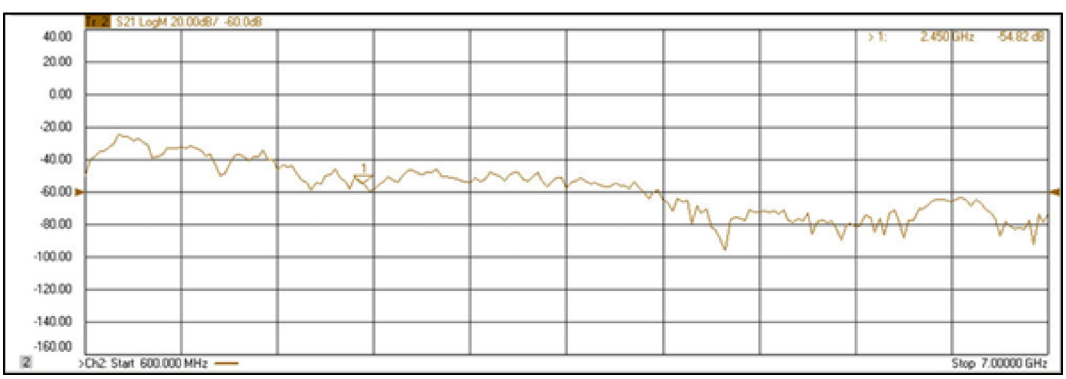

Fig. 4. Return Loss for frequency 2.45 GHz on absorbers −54.82 dB.

Table 2
Results from reflection loss of dielectric points locations (Range frequencies between 0.6 and 1 GHz).

Frequencies Analysed (GHz)	Metal Sheet (dB)	New Absorbers (dB)	Difference (dB)
0.6	−49.18	−49.66	−***0.48***
0.7	−33.23	−34.74	−***1.51***
0.8	−25.82	−28.52	−***2.70***
0.868	−23.24	−25.92	−***2.68***
0.915	−23.51	−28.09	−***4.58***
1	−24.34	−29.92	−***5.58***

Table 3
Results from reflection loss of dielectric points locations (Range frequencies between 2 and 6 GHz).

Frequencies Analysed (GHz)	Metal Sheet (dB)	New Absorbers (dB)	Difference (dB)
2	−35.84	−47.37	−***11.53***
2.45	−36.11	−54.82	−***18.71***
3	−39.26	−49.80	−***10.54***
4	−40.16	−55.20	−***15.04***
5	−58.74	−72.70	−***13.96***
5.8	−69.68	−83.58	−***13.90***
6	−73.84	−84.02	−***10.18***

at 2.45 GHz (widely used in RFID systems). Tables 2 and 3 demonstrate the results obtained with both experimental test series in the laboratory conducted in the copper metal sheet reflector and to the set of pyramidal absorbers developed.

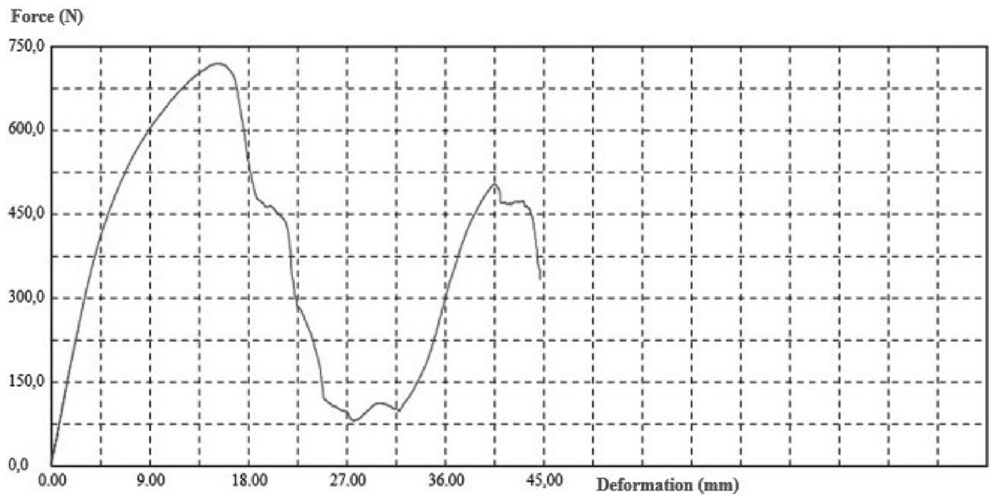

Fig. 5. Results of the tests for longitudinal compression of the pyramidal absorbers.

The results verified from the series of tests conducted demonstrated that the pyramidal absorbers developed attenuated electromagnetic waves incident in the entire spectrum of frequencies proposed in this research (0.6 MHz to 6 GHz). Additionally, the test results suggest that absorbers are most effective in the range from 2 GHz to 6 GHz. In this range, the frequencies are above −10 dB.

Taken together, these outcomes suggest that the composite elaborated in this research from milled rice husks and MDF residue powder illustrated a potential for use in specific industrial applications. Moreover, the best result obtained during the tests occurred in the 2.45 GHz frequency, attaining a difference of −18.71 dB concerning the metal reflector sheet. This result is above the expected limit of −10 dB found in similar products available commercially in the industrial market.

Considering that the experimental tests were conducted by comparing the results between a metal reflector sheet (that being the worst scenario where the reflections are at their most significant) and the absorbers developed using the composite material, it is possible to infer that the addition of these absorbers over other less reflective surfaces - such as wood, for example - would achieve better reflection losses, achieving results in even superior technical parameters related for example to the dielectric reflection loss.

4.3.1. Results of tests of resistance

The transverse resistance test was performed previously to select the grain diameter of the ground rice husk was used in the mixture of materials to obtain the prototypes (the supplementary material published with this article present these data with more detail in Figs. 1 and 2). Next, tests of compression over longitudinal on the pyramidal absorbers were carried out, so that the mechanical resistance could be determined in the material analysis. The samples were analysed in an EMIC universal testing machine model DL-500, with a maximum capacity of 5kN. The mechanical resistance tests took place in a room with a controlled temperature of 22 degrees Celsius and relative air humidity of 63%.

The tests were conducted to generate a graph of force applied concerning the deformation of the material. During the longitudinal test, a progressive force was applied at the top point of the pyramid, compressing it. The results of the tests were satisfactory and demonstrated that the material possesses adequate robustness for the operational handling and for being fixed to the anechoic chamber's surfaces.

Fig. 5 demonstrates the longitudinal compression test. It was possible to observe that the maximum load force supported by the prototype was over 720 N. No breaking force was observed, and the graph indicated a reduction in the maximum force, with subsequent recovery, in the range of approximately 480 N. This result occurred because the pyramid does not have a uniform cross-sectional area. In this case, it was observed that the tip of the absorber breaks first, causing the material to show fissures, thus reducing the mechanical resistance in the rest of the pyramid body.

To deepen the examination of these previous findings, an initial analysis of the surface of the pyramidal absorber to identify factors that may have contributed to the absorption or reflection of the electromagnetic waves was also performed. An electronic digital microscope was used to amplify the image by 1.000 times.

After the analysis of the images of the surfaces of the absorbers, the presence of cavities in all 64 tested samples was observed, randomly varying by geometry and quantity (see supplementary material published with this article in Figs. 8 and 9). The cavities do not show linear distribution nor are equal in area or depth. Each cavity possesses a different characteristic of the absorption area. Future studies will be taken to analyse the relationship between the geometry of the cavities to their electromagnetic absorption.

Regarding durability, the development of any type of biological organisms in the built prototypes was not visually verified until after six months of testing. The growth inhibition of these organisms is associated in the literature in the area due to the presence in MDF composition of products to improve resistance to fungi based on the chemical element Boron (Maffessoni, 2012), and the presence of phenol-formadehyde and melamine-formaldehyde resins, used for the adhesion of particles in the manufacture of MDF (Iwakiri et al., 2005; Muzel et al., 2014).

5. Discussion

Our findings demonstrated that the absorber developed from residues presented an average return loss of −13.40 dB in the frequency range of 2–6 GHz, with the best result being obtained in the frequency of 2.45 GHz with a return loss of −18.71 dB. These results indicate that the new eco-efficient product has superior return loss than the pyramidal microwave absorbers commonly found on the market that are manufactured with non-renewable raw materials and synthetic components (Malek et al., 2011). This finding provides additional evidence concerning the potential of application of composite materials combining rice husks and

MDF with the function of absorption or reflection of the electromagnetic waves.

The novel pyramidal microwave absorbers experimentally tested might be potentially applied in radio frequency anechoic chambers which are generally used for electromagnetic testing or for attenuating areas subject to intense sources of radio frequencies that are harmful to human health. Examples of sectors of conventional applications include telecommunications, high-precision electronics, military, and the electronic components industry. In a nutshell, considering the results achieved during the tests, the technical and environmental viability of the composite material analysed proved to be satisfactory.

The findings from this study make significant contributions to the current literature on waste generation management examining the use of design from recycling strategy (Ragaert et al., 2019) as an alternative for the development of new technological products. A key challenge for waste management is to maximise resource efficiency while simultaneously reducing greenhouse gas emissions (Turner et al., 2015). Design from recycling strategy was applied to successfully develop a new eco-efficient product contributing to minimising solid waste generation. Considering that the disposal of MDF waste by the furniture industry is still a critical problem due to the use of synthetic resins in the manufacture of MDF (González-García et al., 2011), the new product obtained in this research may contribute to reducing the environmental impact, in addition to generating potential economic cost savings when compared with the traditional production process of these types of absorbers.

The present study also provides additional alternatives concerning the challenges involving the discard and destination of residues by the furniture industry, especially in low- and middle-income countries, as well as regarding the quantity of residues generated by industries that manufacture MDF. Findings in our study may represent a stimulus, and an economical alternative for firms in the furniture sector interested, for example, in the production of eco-efficient products, in addition to contributing to reducing the environmental impact of MDF wastes in nature. In low- and middle-income countries generally, this type of residue is destined for specialised landfills or for controlled burning. In both cases, there are environmental impacts (Santos, 2018).

The eco-efficient product proposed also addresses the debate concerning the amount of the residues generated by the furniture industry worldwide. For instance, the global MDF production grew about 13% per year from 1995 (about 7.88 million m^3 by a total of 28 countries) to 2016 (reaching over 99 million m^3 from 50 countries) (Selvatti et al., 2018). This is a critical aspect because during the wood transformation process, only 40–60% of the total volume of raw wood is used, and the rest becomes discarded waste (Olandoski, 2001).

In order to address these enormous challenges, examples of public policies that could be designed to minimise the lack of investments, regulations and control for the adequate disposal process of MDF and similar products (e.g., Medium Density Particleboard (MDP), High Density Fiberboard (HDF)) and for the furniture industry, particularly in low- and middle-income countries, could include (i) political and financial support for firms to invest in more sustainable processes; (ii) environmental policies, fiscal tools and regulation specifics for the industries of cross-industrial sectors consuming MDF, rice husk and other biomass products; (iii) government support providing information to firms on good practices examples around the world of business opportunities in applying design from recycling principles; (iv) governmental financial support for pilot projects involving design from recycling; (v) and extended producer responsibility considering collection and recycling targets (statistical and dynamical targets) on firms complemented with taxation for disposal/non-disposal waste (Dubois, 2012).

An example of existing public policy in the state of Rio Grande do Sul, Brazil - where the study was carried out - aiming o solve the problem of the generation of MDF waste is the control of the burning of waste (CONSEMA n° 370/2017). However, although this governmental resolution authorises the furniture industry to carry out controlled burning of MDF waste, notoriously, the use of this waste in the recycling or reuse processes can contribute more significantly to the reduction of environmental impact when compared with the burning process. Besides, recycling and reuse will contribute to minimising pressure on the extraction of renewable natural resources.

This paper also contributes to addressing some drawbacks of existing absorbers available in the market that use toxic substances, such as polyurethane. Our findings, beyond introducing a sustainable alternative for the use of rice husks and MDF wastes, also contributes to the debate on the reduction of the use of polyurethane, either by industrial manufacturers of the different types of radiofrequency absorbers. This is relevant because the polyurethane is widely used in the manufacture of rigid and flexible foams, in durable elastomers and high-performance adhesives, which are widely present in microwave absorbers used for isolation in anechoic chamber surfaces. The disposal of polyurethane-based products is a serious environmental problem and deserves special attention due to its high resistance to natural degradation (Rosa and Guedes, 2003). As a result, instead of using non-renewable resources and chemical materials (e.g., petrol and other pollutant materials), we proposed an alternative application considering biomass waste, combining environmental-friendly raw materials.

An original implication and contribution of this study to the current literature is in complements and extends the scope of available works testing alternative materials to develop pyramidal absorbers. Previous studies, for example, applied tyre rubber residue and rice husks (Malek et al., 2011), the synthesis and characterisation of epoxy composites based on coconut as absorbent materials (Mishra et al., 2020), water hyacinth, a natural compound made up mainly from carbon (Nuan-on et al. (2017), organic green coconut fibre and a composite of charcoal (Yah et al., 2018), rice husks and polyester residue (Nornikman et al., 2011) among others. To the best of our knowledge, this is the first study investigating the use of MDF residues combined with rice husks seeking to develop pyramidal absorbers of electromagnetic radiation, obtained satisfactory technical parameters in terms of high return loss; that is a desirable parameter for a better absorption of sound and electromagnetic waves.

This paper complements previous studies approaching, in particular, the environmental pollution from industrial systems that used MDF (Selvatti et al., 2018; Zenga et al., 2018; Kouchaki-Penchah et al., 2016; Turner et al., 2015) and the associated challenges regarding solid waste generation (Li et al., 2020; Menya et al., 2018; Mishra et al., 2020; Quispe et al., 2017; Nuan-on et al., 2017). MDF is a panel produced from wood fibres added to toxic materials such as synthetic resins and chemical additives. The most widely used resins are urea-formaldehyde, melamine-formaldehyde, phenol-formaldehyde, diphenylmethane diisocyanate, among others. And the chemical additives commonly used are catalysts (e.g., ammonium chloride, ammonium sulfate), paraffin emulsion, burning retardants (e.g., ammonium phosphate, boric acid) and products to improve resistance against fungi (based on Boron) and insects (based on hexachlorocyclohexane) (Maffessoni, 2012). This study, therefore, contributes an alternative for the use of MDF wastes and its associated high environmental risks.

This investigation opens fruitful research avenues that may explore other alternative combinations of biomass materials to develop alternative eco-efficient products. In a nutshell, the product is conducive to environmental protection and sustainable development problems concerning the utilisation of bio-residues. In an overall perspective, findings in this paper contribute to the existing knowledge on eco-efficient electromagnetic radiation pyramidal microwave absorbers manufactured from renewable sources and free from toxic substances towards cleaner production and solid waste minimisation. A summary of the principal conclusions achieved, and future research suggestions raised in this discussion are provided in the next section.

6. Conclusions

This article presented the results of exploratory and experimental research that examined how to appropriately design and validate a novel eco-efficient pyramidal absorber of electromagnetic radiation based on the principles of cleaner and circular production applying design form waste logic. This investigation contemplated the development of a new product from the use of residues from the agriculture and furniture industries, rice husks, and MDF, respectively. The research methods implemented for the experimental tests and analysis adopted as methodological principles previous studies and experiments from literature in the area, focusing on obtaining composite materials from residues to be used in the construction of pyramidal absorbers. Two series of tests of emission (radiation) of microwaves and reception were performed at the following frequencies: 600 MHz; 700 MHz; 800 MHz; 868 MHz; 915 MHz; 1 GHz; 2 GHz; 2.45 GHz; 3 GHz; 4 GHz; 5 GHz; 5.8 GHz and 6 GHz. The frequencies 868 and 915 MHz, as well as 2.45 and 5.8 GHz, were included in the tests due to being nominally used in industrial systems that use RFID technology.

The conclusions achieved demonstrated that the pyramidal absorbers performed technically better in the frequency of 2.45 GHz resulting in a difference of −18.71 dB concerning the reflective metal plate used in the tests. This result is above the expected limit of −10 dB found in currently available products. Transverse and longitudinal compression tests were performed to determine the mechanical resistance, an important characteristic for pyramid absorbers. Such findings were satisfactory and demonstrated that they have adequate structural robustness for the operational handling and to be installed on anechoic chamber surfaces. According to the best of our knowledge, this study is a pioneer in performing transverse and longitudinal compression tests to examine the mechanical resistance parameters of pyramidal absorbers produced with MDF and rice rusks. A research implication resulting from the satisfactory results obtained with these tests is the possibility of developing new composite materials combining different compositions of MDF and rice rusks, incorporating transverse and longitudinal compression tests.

The article approached a relevant concern addressing the challenges associated with environmental protection and sustainable development by investigating solutions for biomass waste management problems and by developing new products using industrial waste and clean technologies. The main scientific and practical implication of this study is to enhance our understanding regarding opportunities for the development of new sustainable technological products combining rice husks and MDF residues aligned with the cleaner production and design from waste principles.

This report can be considered a pioneering study discussing the possibility of combining rice husks and MDF residues in pyramidal absorbers. The product proposed here consists of an eco-efficient alternative, taking into consideration the limitations and technical characteristics for which it is intended, compared to products currently available, which are constructed from toxic substances. Hence, one of the main implications that emerged from the findings was the development of a product for commercial purposes that extends the life cycle of MDF wastes. The results obtained also have implications for the literature that discusses the production of microwave pyramidal absorbers from materials free from toxic substances. Moreover, the research complements previous studies examining the problems regarding solid waste generation and environmental pollution from industrial systems that used MDF and rice rusks.

Lastly, future studies on the current topic are recommended. Findings obtained about the technical parameters of performance analysed were demonstrated to be satisfactory and suggest the continuity of studies on the use of industrial waste materials in a bid to replace those obtained by chemical processes that generate emissions and environmental pollution. Further research in this field would be of great help. In future investigations, it may be interesting to utilise different components as alternatives to rice husks. Investigations considering the life cycle costing also are welcome. Finally, rice husks are among those biomass residues that are the least used to obtain energy in developing countries. Thus, we recommend exploring alternative applications of rice husks as another interesting research avenue. The overall implication of this study supports the idea that the combination of MDF and rice rusks may be considered an alternative to develop environmentally friendly products.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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