

Article

Eco-Friendly Polyurethane Foams Enriched with Waste from the Food and Energy Industries

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Abstract: In recent years, there has been considerable focus on ensuring that energy is used in the most efficient manner possible. This is due to the fact that globally, over 70% of energy is generated from fossil fuels. Consequently, the matter of designing and utilizing materials that will negate energy losses within the construction industry is of paramount importance. Simultaneously, the necessity for a sustainable approach to the design and production of materials is strongly emphasized. This paper presents an innovative approach to the use of a combination of mineral and plant-based fillers in polyurethane foam technology as a thermal insulation material with the potential to be used in construction to reduce energy consumption. Polyurethane composites containing fly ash from biomass combustion and the addition of rice, sunflower, and buckwheat husks as plant fillers were proposed. The structure of the obtained materials was studied, and the most important physical properties were analyzed. These included apparent density, dimensional stability, water absorption, and the effects of UV radiation and water influence on the carbon, hydrogen, nitrogen, and oxygen content. Moreover, the mechanical properties of the materials were investigated, including compressive strength and brittleness. Additionally, the foams were subjected to flammability tests using a cone calorimeter. Furthermore, additional parameters were determined, including the limiting oxygen index and the vertical and horizontal flammability tests. The results demonstrate the beneficial effects of combining mineral and vegetable fillers in polyurethane foam.

Keywords: thermal insulation; circular economy; waste management; biocomposite; polyurethane; cellular materials



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1. Introduction

According to the International Energy Agency (IEA), the world consumes more than 600 EJ per year, of which about 30%, or 180 EJ, is used by the construction sector. Proper energy management in this sector is crucial. Moreover, the IEA reports that energy losses in this sector can reach up to 30–50%. Energy losses in the construction sector are related, for example, to ventilation and thermal bridges, and almost one third of energy losses are related to inadequate building insulation. Therefore, it is necessary to use insulation materials with the lowest possible thermal conductivity coefficient. Such material may be rigid polyurethane foam. In addition, various laws and regulations have been implemented to encourage manufacturers to produce sustainable materials. Material sustainability is an approach to the design, production, and use of materials that considers environmental, social and, economic sustainability. This approach aims to minimize negative environmental impacts and economic inefficiencies [1,2]. From a practical point of view, this means using

renewable, recyclable, or biodegradable materials, reducing the consumption of natural resources, and reducing CO₂ emissions and other pollutants [3]. One potential solution for these issues is the utilization of natural, renewable resources to produce materials. Solid fillers are employed in the manufacture of polymers, among other applications. They may be presented in a variety of forms, including powders, spheres, fibers, or flakes, and are typically incorporated during the mixing or molding processes of polymers [4]. Fillers can be organic or inorganic and may exhibit differences in their chemical and physical properties [5]. The classification of fillers used in polymers depends on their structure, properties, and the function they are expected to perform in the final polymer product. The division of fillers can vary depending on the division criterion. Fillers used in polymers can be divided into several categories depending on their chemical composition, structure properties, and applications.

Studies on the modification of rigid polyurethane foam (RPUF) using waste materials are abundant in the literature [6–9]. The utilization of fillers in the production of polyurethane foams renders these materials more environmentally benign. Furthermore, the production of such fillers follows the European Union's strategy, which is predicated on a low-carbon policy. The fillers can be categorized into three distinct categories, namely, those of animal (such as egg shells, poultry feathers), vegetable (such as rice husk, potato protein, walnut shells), and industrial (such as steel slag, fly ash, textile) origin [10–17]. The modification of polyurethane foams requires an initial adjustment of the type and amount of fillers in order to obtain the desired properties of the final material, particularly those related to its most common use as a building insulation material, providing an appropriate structure and thermal conductivity coefficient.

The incorporation of fillers in the manufacturing of polyurethane foams renders RPUFs more environmentally friendly. The utilization of waste fillers in PUR is in accordance with the European strategy for sustainable development, which advocates for a resource-efficient economy. By the year 2050, the economy is projected to be free of greenhouse gases in order to protect the health and well-being of citizens from environmental risks. To achieve these goals, it is necessary to initiate the rational management of deposits and the use of available alternatives [18].

The selection of plant fillers for the modification of RPUF is often justified by their fibrous structure, high flexibility, light weight, and good adhesion to the polymer matrix. In addition, vegetable fillers primarily improve the mechanical properties of the final composite. Compressive strength is increased by fillers such as fibers (wood, palm) [19,20]. The addition of shell (coconut, walnut) and hemp fiber to the polyurethane system improves the tensile strength of the RPUF [21–23]. In contrast, sawdust enhances the structural integrity of the wall, while tea and bamboo leaves facilitate the acoustic properties of the polyurethane composite [24–26].

Inorganic fillers are also very popular for modifying rigid polyurethane foam. For example, different types of ash of which the specific choice depends mainly on the requirements for the final properties of the foam, as well as on the local availability of the filler. A. Kairyte et al. produced polyurethane composites with the addition of biomass bottom ash, which resulted in a reduction in the reactivity of the foam. They also found that this type of ash increased the compressive strength of the foam and reduced the thermal conductivity but, unfortunately, increased the water absorption of the final product [27]. J. Paciorek-Sadowska et al. modified RPUF with a grain fly ash fraction and demonstrated its improved compressive strength and reduced flammability for ash composites compared to a reference foam [11]. Other studies on the use of fly ash in RPUF are available in the literature, and these also indicate a reduction in flammability and an improvement in mechanical properties [16–30]. Ash from agricultural waste has also been added to the RPUF. Examples include soybean hull ash and rice hull ash [31,32].

In summary, the utilization of a combination of vegetable and mineral fillers in polyurethane foams can be advantageous, offering a multitude of benefits. The combination of diverse types of fillers can facilitate the optimal equilibrium of desired properties. Con-

sequently, this study proposes the use of a polyurethane composite containing a mineral filler, fly ash from biomass combustion, and the addition of different types of biomass: rice husks, sunflower husks, and buckwheat husks. Such a combination has not been previously investigated and could thus lead to the acquirement of an optimal composite. Accordingly, this manuscript presents a comprehensive analysis of the physical, mechanical, and flammability properties of the proposed samples group. Additionally, this study may identify a new way of producing sustainable insulation materials that could help reduce energy consumption in the construction sector.

2. Materials and Methods

2.1. Characteristics of Fillers

In synthesized polyurethane foams, both biomass ash and raw biomass were used as fillers. The ash used in this study was biomass ash (BA) from one of Poland's power plants, which has a biomass thermal utilization unit that primarily burns forest and agricultural biomass. By contrast, the study also used raw biomass in the form of crushed and dried sunflower husks (SH), rice husks (RH), and buckwheat husks (BH). The husks are a by-product of food production and were purchased for the purpose of conducting this study.

2.2. Modified Rigid Polyurethane Foams

The EKOPRODUR PM4032 system, which consists of a polyol premix (component A) and an isocyanate (component B), purchased from the PCC Group (Brzeg Dolny, Poland), was used to synthesize rigid polyurethane foams. To determine the properties, ten samples were produced, including one reference and nine containing the following fillers: BA, SH, RH, and BH at a concentration of 5–15%. The fillers in the foams were added in amounts of 50% each by weight. Further details are presented in Table 1.

Table 1. Characteristics of rigid polyurethane foams.

Sample	Component A [g]	Component B [g]	BA [g]	SH [g]	RH [g]	BH [g]	Description
PU	60	72	—	—	—	—	unmodified foam
PU_5S	60	72	3.48	3.48	—	—	foam containing 2.5% BA and 2.5% SH
PU_10S	60	72	7.32	7.32	—	—	foam containing 5% BA and 5% SH
PU_15S	60	72	11.52	11.52	—	—	foam containing 7.5% BA and 7.5% SH
PU_5R	60	72	3.48	—	3.48	—	foam containing 2.5% BA and 2.5% RH
PU_10R	60	72	7.32	—	7.32	—	foam containing 5% BA and 5% RH
PU_15R	60	72	11.52	—	11.5	—	foam containing 7.5% BA and 7.5% RH
PU_5B	60	72	3.48	—	—	3.48	foam containing 2.5% BA and 2.5% BH
PU_10B	60	72	7.32	—	—	7.32	foam containing 5% BA and 5% BH
PU_15B	60	72	11.52	—	—	11.52	foam containing 7.5% BA and 7.5% BH

2.3. Methods

The morphology of the fillers used in this study was analyzed via scanning electron microscopy (SEM–JEOL, Peabody, MA, USA) to characterize the fillers. Furthermore, in order to establish the elemental composition, the C, H, and N contents of the fillers were determined by a LecoCHN628 (Leco Corporation, St. Joseph, MI, USA), whereas the oxygen content was calculated using the results obtained from the Leco CHN628. The elemental analysis tests were repeated three times for each type of filler, and the average result of the trials is presented. Particle size analysis of fillers was performed via laser diffraction and the Mastersizer 2000S apparatus (Malvern Instruments Ltd., Malvern, UK).

The morphology of the polyurethane foams was analyzed via scanning electron microscopy (SEM–JEOL, Peabody, MA, USA) to evaluate the effect of fillers on the structure of the foams.

Physical properties were determined for the resulting foams with fillers. Apparent density was measured according to EN ISO 845:2009 [33], dimensional stability at elevated temperatures according to PN-92/C89083 [34], and water absorption of the foams according to ASTM D570-98 [35]. In order to determine the physical properties of the materials obtained, three trials were carried out for each material, and the average result is presented.

Furthermore, by determining the elemental contents of C, H, and N and calculating the O content using the Leco CHN628, the aging process of thermal insulation materials was studied. The foams were exposed to artificial UV radiation and water spray and subjected to actual atmospheric conditions for comparison. For all the materials analyzed, three samples were carried out for each element in Section 3, and the average result is shown.

Mechanical properties of the samples were tested for brittleness in accordance with ASTM C 421-08 [36]. In addition, compressive strength was tested on an Instron 5967 (Instron, Norwood, MA, USA) in accordance with EN ISO 14125:1998 [37]. The tests to determine the mechanical properties were repeated three times for each sample, and an average result is presented in this paper.

Flammability tests were also conducted. The limiting oxygen index (LOI) was tested in accordance with EN ISO 4589-2:2006 [38]. Moreover, pliability was tested on an MLC cone microcalorimeter (TA Instruments, New Castle, DE, USA) in accordance with EN-ISO 13927 [39]. Vertical flammability testing was performed in accordance with EN 60695-11-10:1999 [40] using the UL 94V method. Horizontal flammability testing was also carried out in accordance with EN-ISO 9772:2012 [41]. Subsequently, fire reaction tests were conducted by determining the heat of the combustion on an isoperibolic calorimeter (LECO AC500, LECO, St Joseph, MI, USA). The measurement was performed in accordance with ISO 1716:2018 [42]. All flammability tests were repeated three times for each sample, and the results, presented in an averaged form, are presented in this article.

3. Results and Analysis

3.1. Characterization of Fillers

Figure 1 shows the elemental content of C, H, and N in raw biomass and biomass ash. The elemental composition of husks and ash differs significantly, with the greatest differences observed in the carbon content. In the case of husks, the content of this element ranges from 41 to 48%, while in the case of ash, it is much lower at 2%. The lower carbon content is because the carbon contained in the biomass has been oxidized in the combustion process. The hydrogen content in all the husks is 6%, while for BA, it is 1%. The nitrogen content of all the fillers used in the study is below 1%. Available data indicate that biomass used in power plants for energy production contains 44–50% carbon [43], which is consistent with the fillers used.

Figure 2 shows the particle size distribution of the fillers used in the study.

The BA filler has particles in the 1–100 µm range, with a distinct peak around 10 µm. The RH filler has a wider particle size range, extending from 0.1 to 1000 µm, with several smaller peaks, indicating a more differentiated structure. The SH filler shows larger particles, mainly in the 10–1000 µm range, with a major peak around 100 µm. The

BH filler has particles in the 1–1000 μm range, with a prominent peak at around 100 μm , indicating a more uniform and finer structure. The differences in particle size distribution are significant between these fillers. BA has more homogeneous particles, while BH and SH show a large size diversity. RH tends to have larger particles, while BH is the finest and most homogeneous among the husks. These differences can affect the mechanical and chemical properties of the composite materials in which they are used.

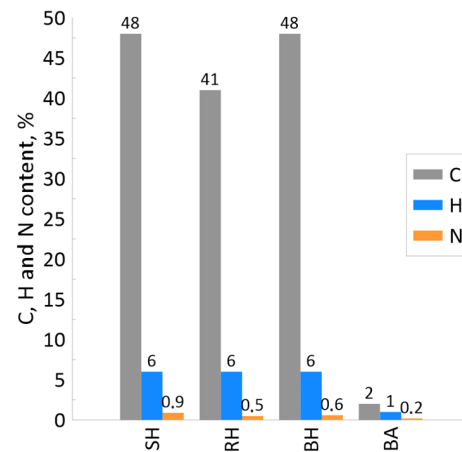


Figure 1. The content of C, H, and N in the fillers.

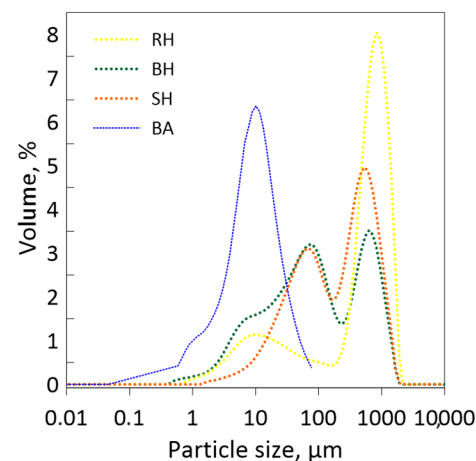


Figure 2. Particle size distribution of fillers.

Figure 3 illustrates the morphological characteristics of the fillers employed in the study. Figure 3a depicts the BA morphology, which displays particles and irregular shapes. In addition, the BA morphology shows the presence of spherical particles, which are typical of coal ash [44].

Figure 3b–d illustrate the microstructure of the husks following grinding. All filler types are characterized by the presence of irregularly shaped particles with a rough surface. In the case of BH and SH, short fibers with a slightly more developed surface can be observed. RH, however, does not exhibit such a developed surface. The other two fillers display a higher aspect ratio than RH. Sunflower husks have a generally developed surface area, as reported by other researchers [45]. The advantages of fillers include a higher form factor, which improves the adhesion of the filler particles to the polyurethane matrix, thereby enhancing the properties of polyurethane foams [46].

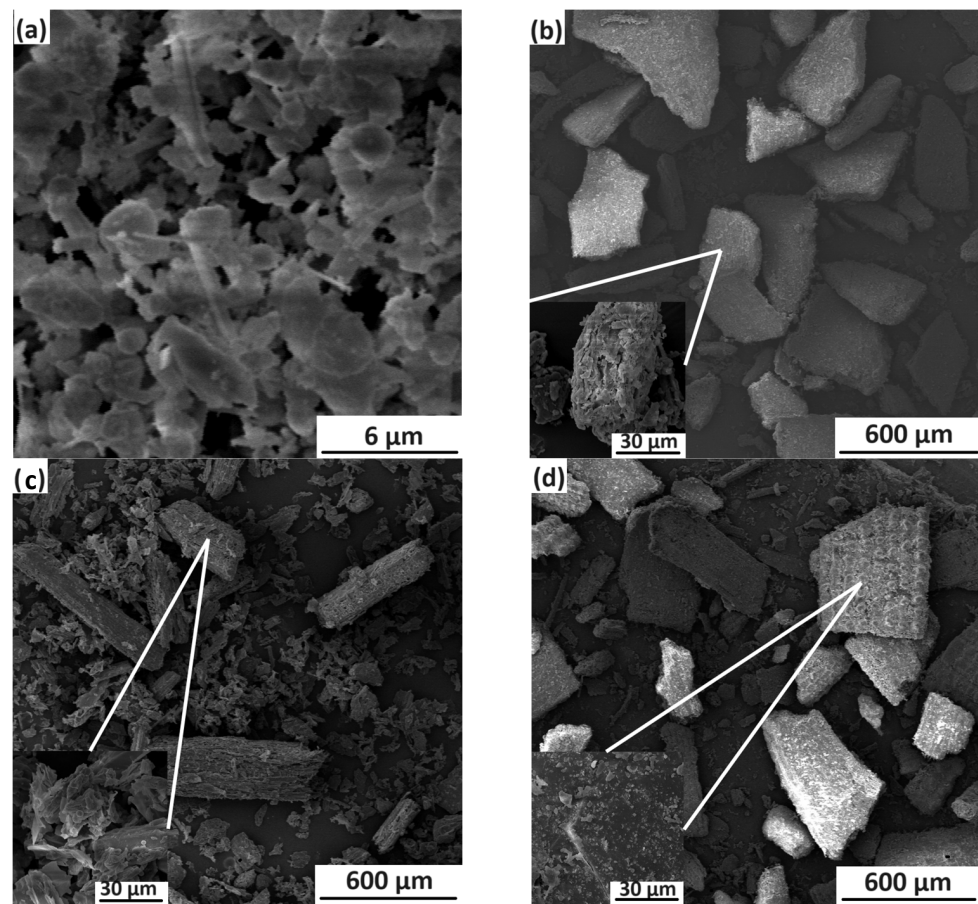


Figure 3. Morphology of fillers: (a) BA; (b) BH; (c) SH; (d) RH.

3.2. Characterization of Rigid Polyurethane Foams

Figure 4 illustrates the morphology of the foams. RPUF is composed of two principal phases: a continuous phase, which constitutes a flexible polymer matrix; and a dispersed phase, comprising gas bubbles encapsulated within the polymer structure. The size, shape, and distribution of the bubbles, as well as the degree of branching of the polymer network, influence the physical properties of the foam, including its density, hardness, and thermal insulation. The aforementioned properties are contingent upon the process and the components and additives employed in the synthesis of the foams.

The reference foam exhibits the largest cells, which are similar in shape and size. The introduction of a filler mixture as low as 5% causes a modification in the structure. As the filler concentration increases, the structure becomes more fragmented, exhibiting greater heterogeneity in terms of cell shape and size. With the addition of a filler mixture of 15%, there is an elongation of cells in the direction of foam growth. This phenomenon is most pronounced for PU_15S and is typical for foams grown in a confined area [47,48].

Table 2 presents the apparent density results for the resulting polyurethane composite. It can be observed that foams with fillers tend to have a higher apparent density value than unmodified foams. Furthermore, this effect is compounded by the higher concentration of filler in the foam. The apparent density is highest for foams with SH. The observed rise in apparent density may be attributed to two factors: first, the apparent density of the foam, which was increased by the apparent density of the filler; second, the modification of the foam structure (Figure 3). Other studies have indicated that the addition of starch and biomass ash, such as rice husk ash, can also increase the apparent density of foams [49].

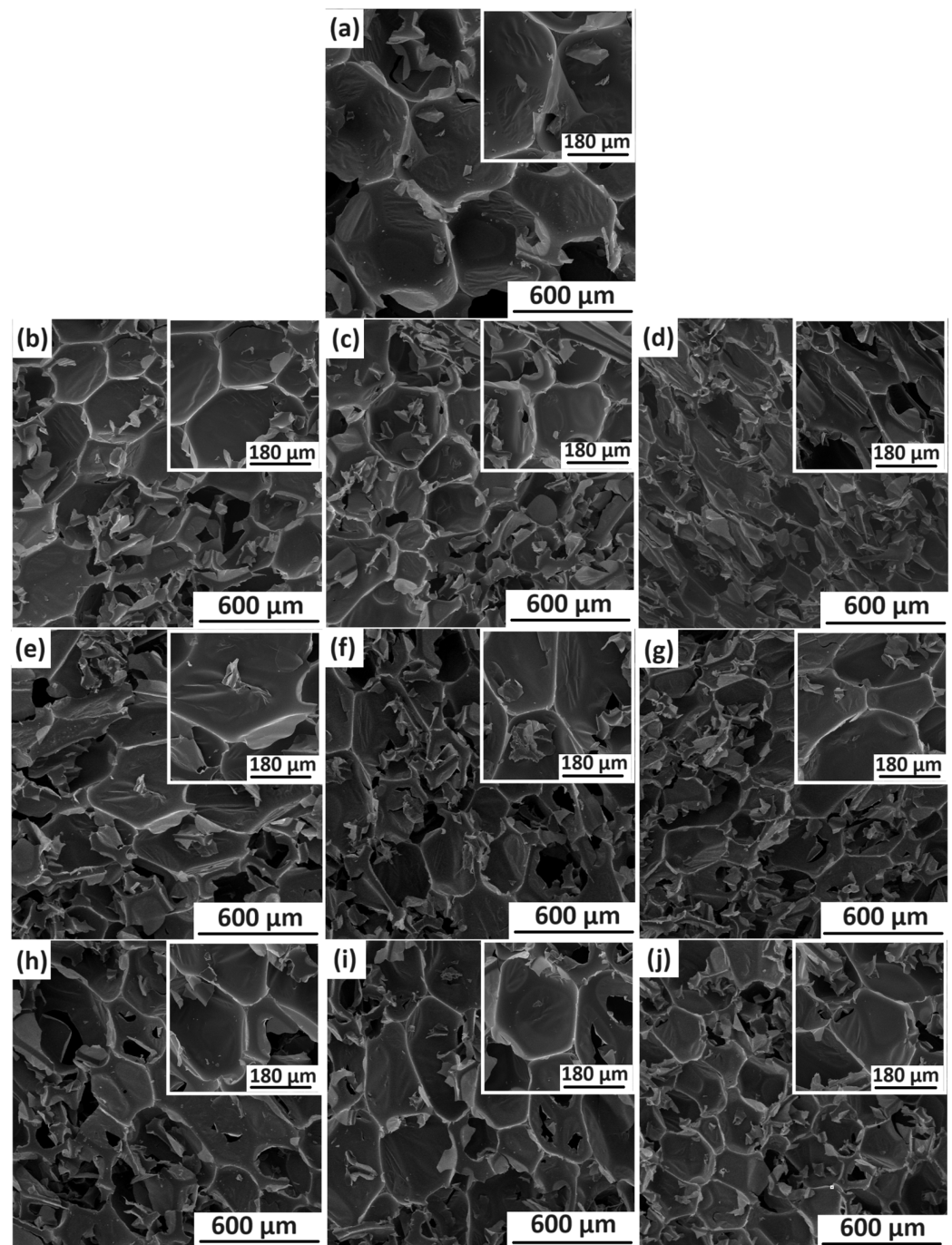


Figure 4. Morphology of RPUFs: (a) PU; (b) PU_5S; (c) PU_10S; (d) PU_15S; (e) PU_5B; (f) PU_10B; (g) PU_15B; (h) PU_5R; (i) PU_10R; (j) PU_15R.

The dimensional stability of foams at elevated temperatures is a crucial aspect of their practical application. This encompasses the capacity of the foams to retain their shape, size, and weight in the face of varying temperature conditions. Table 2 presents the changes in length observed after 20 and 40 h of annealing at 150 °C, along with the changes in weight. The studies presented demonstrate that the addition of 5% fillers is the most beneficial. After 20 h of annealing, foams containing BA and RH exhibited the greatest stability, even when 15% fillers were present. However, after 40 h, the change in length is greater than after 20 h. Furthermore, weight loss is also lower for foams with a 5% filler addition. The introduction of higher filler concentrations results in a higher weight loss for the foams than for the reference foam. In other studies, where the effect of scales on dimensional

stability was analyzed, similar results were obtained, namely, that the scales inhibit the change in length of the foams. With regard to the parameter of weight change, it can be stated that the scales have no significant effect on this parameter or, indeed, that they make it worse [50].

Table 2. Apparent density, dimensional stability, and water absorption of rigid polyurethane foams.

	Apparent Density [kg·m ⁻³]	Dimensional Stability		Loss in Mass		Water Absorption [%]
		(Δl , 20 h, 150 °C) [%]	(Δl , 40 h, 150 °C) [%]	(Δl , 20 h, 150 °C) [%]	(Δl , 40 h, 150 °C) [%]	
PU	36.09	3.86	4.18	9.23	9.23	36.14
PU_5S	40.82	0.27	0.52	7.87	8.99	25.49
PU_10S	41.64	1.01	1.03	8.05	9.20	26.66
PU_15S	51.75	2.78	2.20	9.02	9.77	37.71
PU_5R	38.70	0.12	0.18	7.55	8.49	28.23
PU_10R	39.85	0.52	0.84	8.33	9.38	29.56
PU_15R	42.66	1.06	1.34	9.09	10.00	31.41
PU_5B	38.34	0.90	1.64	8.40	9.24	26.65
PU_10B	41.28	1.58	1.94	8.82	9.80	28.86
PU_15B	43.94	1.60	1.98	9.92	10.74	35.51

Table 2 also presents the absorbency of the foams following a 24 h immersion in water. The reference foam exhibited an absorbency of 36.1%, while the foams incorporating fillers exhibited absorbency values ranging from 25.5% to 37.7%, with the degree of absorbency dependent on the concentration of the filler. The foams containing 5% filler in the form of scales and ash exhibited the greatest resistance to water absorption. Conversely, with 15% filler, water absorption increased by up to 10%. This increase could be attributed to the fact that a higher amount of filler damages the foam cells, rendering the foam more susceptible to water absorption.

The ageing of insulation materials is a natural process that involves a gradual deterioration and changes in their structure and properties over time. The ageing process is accelerated by exposure to ultraviolet radiation, moisture, and atmospheric agents. Consequently, the ageing of insulating materials can result in a reduction in their insulating effectiveness. Figure 5 illustrates changes in the elemental content of C, H, N, and O for foams that have not been subjected to any modifying factors (Figure 3a), for foams that have been treated with artificial UV and water spray (Figure 3b), and for foams that have been exposed to real weather conditions (Figure 3c). In comparison to unmodified foams, accelerated ageing under laboratory conditions has been observed to culminate in a reduction in the effectiveness of insulating materials. The carbon content is observed to decrease, with a maximum of 2.5%. In addition to PU foam, the hydrogen content also increases in foams with fillers. Concomitantly, the nitrogen content declines, while the oxygen content rises. In the case of foams subjected to actual weather conditions, the carbon content also decreases, while the hydrogen content either increases slightly or remains at the same level. The nitrogen content of the majority of samples exhibited an increase, with the oxygen content rising to a greater extent than in the previous case. The observed decrease in carbon content and increase in oxygen content may be attributed to the phenomenon of photo-oxidation, whereby the foam components are oxidized under the influence of UV light.

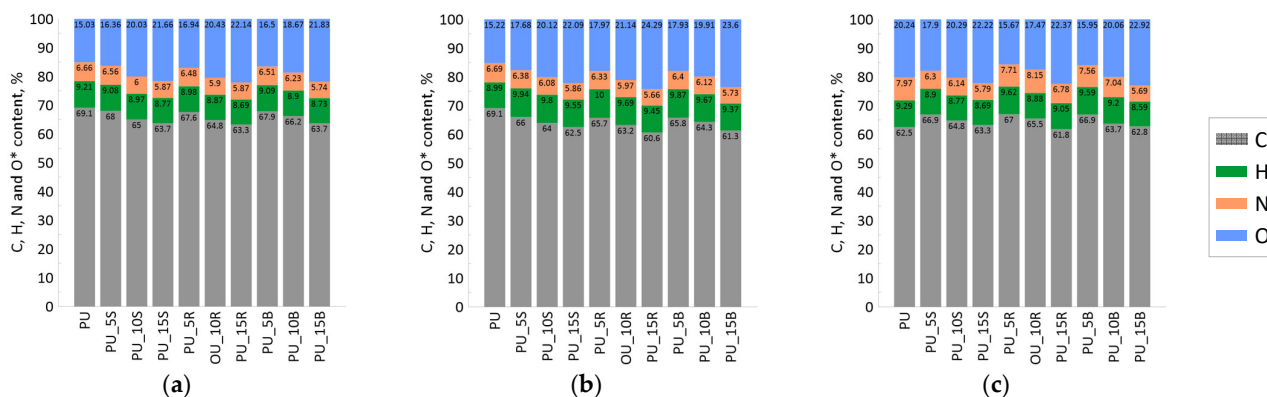


Figure 5. Elemental analysis of C, H, N, and O: (a) unmodified foams; (b) foams subjected to water spray and UV light; (c) foams exposed to real atmospheric conditions. * Calculated value.

Table 3 summarizes the brittleness results and shows the stress–strain curves for all specimens.

Table 3. Brittleness and compressive deformation of rigid polyurethane foams.

Brittleness [%]		Load, N	Compressive deformation, %
PU	16.98		
PU_5S	24.81		
PU_10S	19.07		
PU_15S	16.44		
PU_5R	24.81		
PU_10R	24.36		
PU_15R	17.47		
PU_5B	16.51		
PU_10B	18.70		
PU_15B	30.58		

The reference foam indicated the lowest brittleness (16.98%). Unfortunately, the addition of biomass and biomass ash worsened this parameter. Glowacz-Czerwinka et al. measured the brittleness of PU samples with the same biomass, which showed a similar trend: the addition of biomass worsened the brittleness [50]. In this paper, the addition of biomass ash further increased the reduction in brittleness, with the maximum brittleness being obtained for sample PU_15B (30.58%). The stress–strain curves exhibit distinct phases, including the linear elastic region, the plateau region, and the densification region [51]. Foams with higher brittleness tend to display a sharper transition from the elastic to the plateau region, as shown in the curves in Table 3, although unmodified foam, with its smooth transition between these regions, stands out. Nevertheless, the foams modified with biomass and ash had higher compressive strengths.

Table 4 shows the results of the flammability analysis of the polyurethane composite.

The gross calorific value was found to be highest for PU foam, with a subsequent decline in value as the filler addition increased. Among the modified foams, the lowest value was observed for those containing 7.5% BA additive (PU_15S, PU_15R, PU_15B), which is attributed to the high mineral content (non-combustible) present in these samples. A comparable decline in gross calorific values was observed by Kuźnia et al. upon the addition of fly ash from coal combustion [28]. The LOI, a measure of flammability for organic polymers and composites, quantifies the minimum oxygen percentage to sustain combustion and is also presented in Table 4 [52]. Table 5 summarizes the main results obtained from the cone calorimeter test, such as time to ignition (TTI), heat release rate (HRR), maximum heat release rate (p-HRR), and percentage of mass loss (PML).

Table 4. Gross calorific value, LOI, UL 94HB, and UL 94V of rigid polyurethane foams.

	Gross Calorific Value, MJ·kg ^{−1}	LOI, %	UL 94HB, mm·min ^{−1}	UL 94V
PU	26.26	20.4	12.32	N.R.
PU_5S	25.15	21.3	9.23	N.R.
PU_10S	24.49	21.3	8.23	N.R.
PU_15S	23.56	21.4	8.43	N.R.
PU_5R	25.71	21.2	11.04	N.R.
PU_10R	24.25	21.6	11.28	N.R.
PU_15R	23.57	21.2	11.15	N.R.
PU_5B	25.47	21.3	10.53	N.R.
PU_10B	24.25	21.4	7.86	N.R.
PU_15B	23.57	21.5	8.03	N.R.

Table 5. Cone calorimeter results of rigid polyurethane foams.

	TTI, s	HRR, kW·m ^{−2}	p-HRR, kW·m ^{−2}	PML, %
PU	4	63.88	77.70	85.70
PU_5S	8	69.80	84.25	84.20
PU_10S	6	67.60	82.56	78.40
PU_15S	6	61.11	79.03	73.10
PU_5R	8	65.07	84.60	81.21
PU_10R	6	62.05	80.53	79.20
PU_15R	6	59.74	82.10	72.60
PU_5B	9	51.80	67.03	78.60
PU_10B	7	59.35	74.45	76.10
PU_15B	6	67.65	84.79	76.40

The shortest TTI was observed for the reference foam, while the addition of fillers increased this parameter. Glowacz-Czerwonka et al., who investigated PU composites with husks (without ash), showed a similar trend: the addition of biomass increased the ignition time [50]. Furthermore, the HRR and p-HRR parameters are affected by the addition of biomass and biomass ash. The lowest HRR was obtained for PU_5B (51.08 kW·m^{−2}), while the value for the reference foam is 63.88 kW·m^{−2}. For the other samples, the values are similar to the PU sample (± 5 kW·m^{−2}). The PHRR, crucial for evaluating material, as regards its fire hazard, represents the percentage of maximum heat release rate at the time of peak heat release [53]. The p-HRR is in the range of 67–85 kW·m^{−2} for all samples analyzed and is, therefore, in line with the requirements for thermal insulation (<300 kW·m^{−2}) [54]. The highest value of weight loss during combustion was recorded for the PU reference sample (PML = 85.7%). For all other samples, the PML value is lower, which is mainly due to the presence of non-combustible substances in these samples, namely, biomass ash.

4. Conclusions

The results obtained from this study indicate that a mixture of different types of husks and biomass ash can be successfully introduced.

The initial stage of the study, which focused on filler analysis, revealed that raw husks exhibited the highest carbon content (41–48%), while biomass ash exhibited an average carbon content that was 22 times lower. Moreover, the analysis of the filler structure revealed that all fillers are distinguished by their molecular structure. In the case of ash, the particles are considerably smaller than those of husks. Furthermore, SH and BH are distinguished by a markedly greater surface area than the other fillers studied, which enhances their adhesion with the matrix and is reflected in the mechanical properties.

The second stage of the study involved the analysis of the foams. The structure of the foams was initially analyzed. The introduction of fillers into the rigid polyurethane foam

system caused a modification of the foam structure, whereby the cells are fragmented and elongated in the direction of foam growth.

Secondly, the most crucial physical characteristics of the foams were identified. The apparent density of the foam was found to increase by up to 44% when fillers were introduced, although the mixture of mineral and vegetable fillers impedes the linear dimensional change process. Conversely, these fillers exert no influence on the change in weight loss at elevated temperatures. Furthermore, the addition of up to 10% filler affects a reduction in water absorption by up to 29%; whereas with filler concentrations above 10%, water absorption is observed to increase in comparison to PU. A study of the ageing process of insulating materials has demonstrated that the incorporation of this type of filler does not accelerate the process; rather, it has a slight inhibitory effect.

The effect of this filler combination on the mechanical properties of RPUFs was then analyzed. The brittleness measurement demonstrated that the foams with fillers exhibited a greater degree of brittleness than the reference foam. The lowest brittleness was observed in PU_15B, which was twice as high as that of PU. With regard to compressive strength, the incorporation of fillers led to an improvement in this parameter. The highest compressive strength was observed for PU_5B, while the lowest was recorded for PU_15B, which exhibited a strength slightly higher than that of the reference foam.

The final stage of the testing process was the flammability test. The incorporation of fillers affected a reduction in the flammability value in comparison to unmodified foam. In contrast, polyurethane (PU) is a self-extinguishing material, and polyurethane materials with an LOI below 21% are considered self-extinguishing. Nevertheless, the incorporation of fillers elevates the LOI above 21%. The results of the calorimeter indicate that the incorporation of fillers into the foam composition leads to a delay in ignition of up to five seconds and a reduction in the heat release rate (HRR) parameter.

The research presented offers novel insights into the production of rigid polyurethane foams as sustainable materials.

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