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# Enhancing flexible polyurethane foams with bio-based sage filler: Effects on microstructure, mechanical properties, and sustainability

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## ABSTRACT

This study explores the incorporation of sage (*Salvia officinalis*) as a bio-based filler in flexible polyurethane foams (FPUFs). Sage was added to FPUFs in varying concentrations (5, 10, and 15 wt.%) to examine its influence on the foaming process, microstructure, density, water absorption, and compression behavior. Results revealed that sage delayed the foaming reaction, reduced exothermic reaction temperatures, and enhanced foam expansion. Microstructural analysis showed finer cell structures and denser foam matrices with sage incorporation. Foam filled with 5 wt.% of sage exhibited reduced compression resistance; however, increasing the filler concentration led to improvements in compression resistance. Sage also increased water absorption due to its hygroscopic nature, though this effect plateaued at higher concentrations. These findings demonstrate the potential of sage as a sustainable additive to produce high-performance FPUFs suitable for various industrial applications.

**Keywords:** biocomposites, FPUF, *salvia officinalis*.

## INTRODUCTION

Polyurethane (PU) foams represent a significant segment of the polyurethane industry, accounting for approximately 85% of its output. These materials are highly valued for their lightweight nature, excellent insulation, soundproofing properties, and high resilience, making them essential in sectors such as household goods, transportation, and packaging [1]. PU foams are synthesized through polyaddition reactions between polyols and isocyanates, with their structure influenced by component interactions during the foaming process. This process involves gas bubble expansion within a liquid matrix, with the foam's properties, such as density and cell structure, determined by factors like blowing agents and production techniques [2]. PU foams are categorized as either rigid or flexible, depending on the balance of flexible and rigid segments in their polymer chains [3]. Flexible polyurethane foams (FPUFs), widely used in furniture and automotive cushions, are valued for their elasticity, softness, and low density [4]. The hardness of these foams increases proportionally with density, with each 1 kg/m³ increase in density leading to an approximate 0.1 kPa rise in hardness [5]. Traditionally, inorganic fillers have been employed to enhance density and hardness. These fillers act as nucleating agents during foaming, influencing cell structure and size [6]. However, their use often compromises other properties, prompting researchers to explore alternative materials and structural modifications to optimize thermal resistance, mechanical strength, and fire retardancy while minimizing environmental impact. This includes incorporating bio-based materials, fillers, and additives to enhance properties such as flexibility, strength, and chemical resistance.

Recent studies have demonstrated the effectiveness of bio-fillers in FPUFs. For instance, Maamoun et al. [7] introduced waste seashells as bio-fillers, which enhanced compressive strength

and sound absorption below 500 Hz. Similarly, periwinkle and African star apple seed shells increased foam density from 19.20 kg/m³ to 26.45 kg/m³ (at 50% filler) and improved indentation hardness, although tensile strength and elongation decreased. These fillers also reduced flammability, offering an eco-friendly alternative [8]. In another study, *Sepia officinalis* bone powder combined with aluminum hydroxide improved flame retardancy, tensile strength, and thermal stability, making the foam safer and more durable [9].

Further research explored bamboo and gelatin fillers to enhance moisture-wicking properties. Bamboo increased porosity and wicking performance, while gelatin slightly improved wicking and elongation [10]. Cellulose nanofillers also proved effective, enhancing the compressive modulus at low concentrations [11]. Additionally, the incorporation of *Camelina sativa* straw and pomace enhanced foam density, tensile strength, and hardness, while improving cellular structure and skin thickness [12]. Studies on chitin, hazelnut shells, and lignin revealed that chitin and hazelnut shells significantly improved tensile and tear strength, although lignin and chitosan showed lower compatibility, limiting mechanical performance [13]. These bio-fillers are suitable for applications such as mattresses, car seats, and insulation.

Ground corncake, derived from corn oil production, demonstrated potential as a bio-filler by producing foams with smaller, more regular cells and comparable or improved mechanical properties [14]. Beyond mechanical and thermal improvements, antimicrobial properties have also been a focus. For example, sage (*Salvia officinalis*), known for its antibacterial and antifungal properties due to compounds like thujone and camphor [15–16], has been incorporated into rigid PU foams. This resulted in composites with enhanced physicomechanical properties and potential antimicrobial benefits, making them suitable for applications in bedding and public seating [17]. These advancements highlight the versatility of PU foams and the growing importance of bio-based and multifunctional additives in creating more sustainable and high-performance materials.

With this objective, the study focused on developing bio-based flexible polyurethane foams (FPUFs) and evaluate the extent of modifications made to the foam matrix through a series of tests. These tests included assessments of thermal behavior during the foaming process, as well as measurements of density, water absorption, and compression properties. By investigating the incorporation of plant-based materials and agricultural by-products as potential fillers, this research seeks to enhance the properties of FPUFs for specific applications. Additionally, the study contributes to the growing body of knowledge on sustainable alternatives, offering environmentally friendly substitutes that could reduce the reliance on conventional petroleum-based materials in polyurethane foam production.

## MATERIALS AND METHODS

### Fabrication of biocomposites

A two-component flexible polyurethane system EKO PROFLEX 140 (PROGMAR, Leszno, Poland), consisting of polyol (part A) and isocyanate (part B), was selected as the matrix material for the biocomposites developed in this study. The additive used to modify the matrix was sage (*Salvia officinalis*). The sage leaves were obtained in a dried form but underwent further drying at 40 °C for 4 hours in an SLW 53 STD forced-air dryer (Pol-Eko, Wodzisław Śląski, Poland). The dried filler was ground using a four-blade grinder and subsequently sieved with a Multiserw sieve shaker (MULTISERW-Morek, Brzeźnica, Poland) to obtain particle sizes ranging from 150 to 200 μm – Fig. 1a. The biocomposites were fabricated by mixing the polyol and isocyanate in a 100:50 ratio using a Dispermat LC30 high-speed dissolver mixer (VMA-Getzmann GmbH, Reichshof, Germany). Sage was introduced into the polyurethane matrix at concentrations of 5, 10, and 15 wt.% by adding it to the polyol and mixing for 30 seconds at 200 rpm, after which the isocyanate was incorporated, and mixing continued for 10 seconds at 150 rpm. The prepared mixtures were then cast into polyethylene molds and allowed to cure – Fig 1b. Samples were subsequently prepared for testing under stable conditions of 20 ± 2 °C and 40% relative humidity. Moreover, the presented results are expressed as mean values with the corresponding standard deviation.

### Research methods

#### *Foaming process analysis*

The impact of the sage filler on foaming time and temperature variations was analyzed using a FLIR A615 thermal imaging camera equipped with IrControl software (Teledyne Technologies,


**Figure 1.** The introduced filler (a) and the fabricated foams (b)

Thousand Oaks, CA, USA). Surface temperature data were recorded for foams produced in triplicate for each type, while internal core temperature variations were not assessed, as illustrated in Fig. 2. Moreover, the shape factor ($S_f$) was calculated based on the following formula:

$$S_f = \frac{H}{D} \tag{1}$$

where: $H$ – the height of the foam after tack-free time, $D$ – the diameter of the foam after tack-free time.

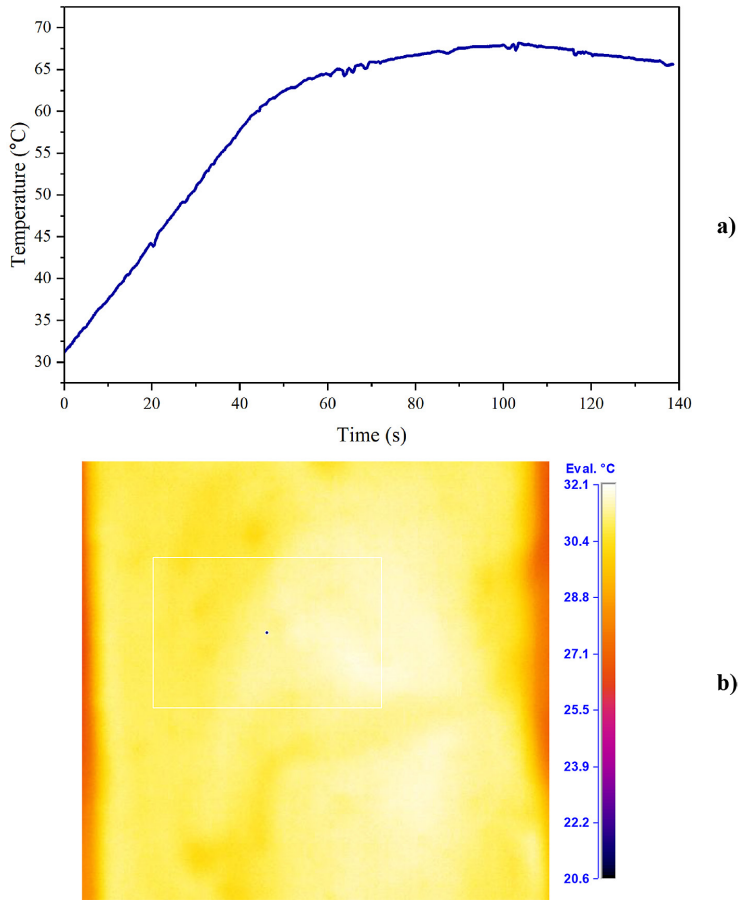


**Figure 2.** Temperature–time profile of the reference sample foaming process (a) and thermal image at the start of the process (b)

### *Microscopy observations*

Foam cross-sections were analyzed with a Leica DVM6 stereomicroscope (PIK Instruments Ltd, Piaseczno, Poland). Micrographs were captured perpendicular to the foam's rising direction.

### *Apparent density measurements*

Apparent density ($\rho$ , kg/cm$^3$) was measured according to ISO 845 standard using five samples (10 × 10 × 10 mm) from each foam employing an analytical balance (Ohaus Adventurer Pro, OHAUS Europe GmbH, Greifensee, Switzerland). The density was calculated as follows:

$$\rho = \frac{m}{V} \times 10^6 \quad (2)$$

where: $m$ – the mass of the test sample (g), $V$ – the volume of the test sample (mm$^3$).

### *Water absorption*

Water absorption was evaluated following ISO 16535 standard using five samples (10 × 10 × 10 mm) from each foam. Samples were predried at 23 ± 2 °C for 24 hours in an SLW 53 STD forced-air dryer (Pol-Eko, Wodzisław Śląski, Poland), weighed utilizing an analytical balance (Ohaus Adventurer Pro, OHAUS Europe GmbH, Greifensee, Switzerland), immersed in a water bath, and weighed again. The water absorption (WA, %) was calculated as:

$$WA = \frac{m_w - m_0}{m_0} \times 100 \quad (3)$$

where: $m_w$ – the test sample mass after immersion (g), $m_0$ – the initial sample mass (g).

### *Compression testing*

Static compression tests were performed in accordance with ISO 3386-1 standard using an AGX kN10D universal testing machine (Shimadzu Corporation, Kyoto, Japan) with TRAPEZIUMX-V software. The traverse speed was set to 100 mm/min. Testing was conducted on five samples (50 × 50 × 40 mm) per foam type after mechanical conditioning, with compression applied to 70% of the initial sample thickness. The compression stress (CV40, kPa) was calculated using:

$$CV_{40} = \frac{F_{40}}{A} \times 10^3 \quad (4)$$

where: $F_{40}$ – the force at 40% compression (N), $A$ – the initial cross-sectional area (mm$^2$).

## RESULTS AND DISCUSSION

### Foaming process analysis

Figure 3 presents the changes in reaction initiation time and temperature. The results clearly demonstrate that the addition of sage delayed the onset of the reaction, measured from the moment of isocyanate addition to the point at which temperature changes were observed. Additionally, the reaction start time exhibits an inverse correlation with the temperature recorded at reaction onset. This effect may be attributed to sage particles absorbing heat released during the reaction, thereby delaying its initiation. The one-way analysis of variance and the subsequent post-hoc testing

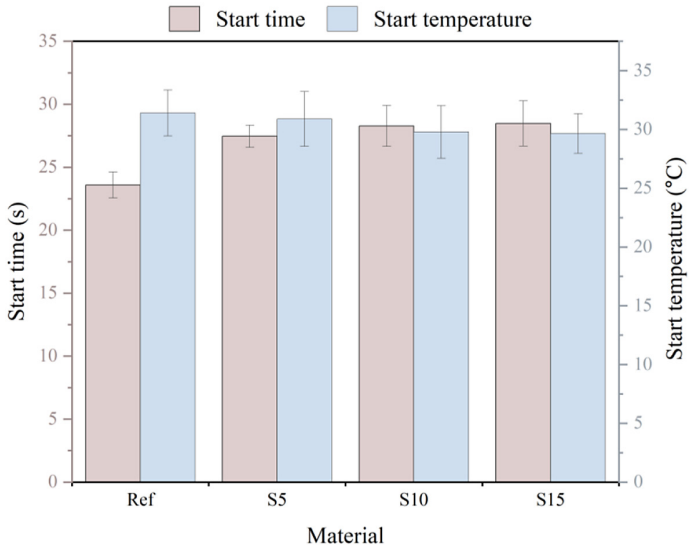


**Figure 3.** Start time and corresponding temperature recorded for the obtained foams

reveal a statistically significant effect of the filler on the reaction initiation time ($p < 0.05$), indicating no significant differences among the composites analyzed (S5, S10 and S15). Additionally, the influence of the filler on the reaction initiation temperature was not found to be statistically significant ($p > 0.05$).

The rise temperature of the reference foam reaches nearly 70 °C, while the addition of sage reduces this temperature to approximately 62 °C for S15, as shown in Figure 4. The observed variations in rise time and temperature correspond to shifts in reaction initiation time and temperature. The addition of sage results in a lower reaction temperature and an extended polymerization time compared to unmodified FPUF. These effects may be attributed to active compounds in sage (such as phenols, flavonoids, and essential oils), which could interfere with the foaming reaction pathway. Additionally, due to the hygroscopic nature of sage, moisture present in the filler may react with isocyanate to produce carbon dioxide, consuming isocyanate groups that would otherwise react with polyols to form the foam structure [18–19]. Statistical analysis indicates that the filler significantly influences both the rise time and temperature ($p < 0.05$). However, Tukey's post-hoc test reveals no significant differences among the composites.

Tack-free time and temperature were recorded once the foam surface had fully dried,

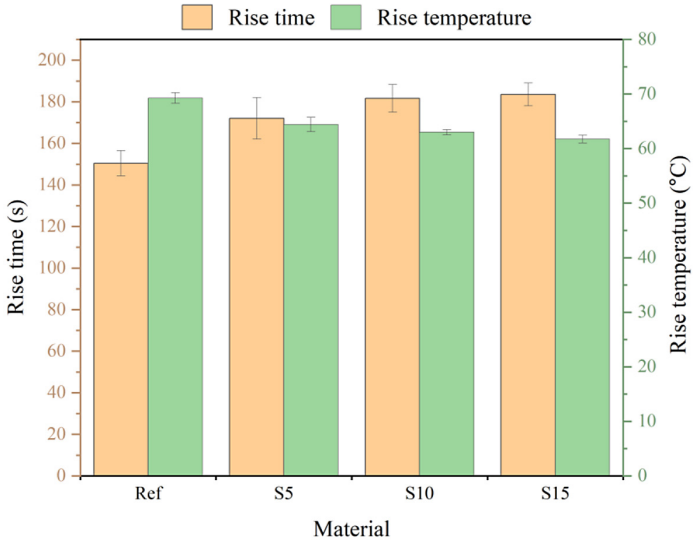


**Figure 4.** Rise time and corresponding temperature recorded for the obtained foams

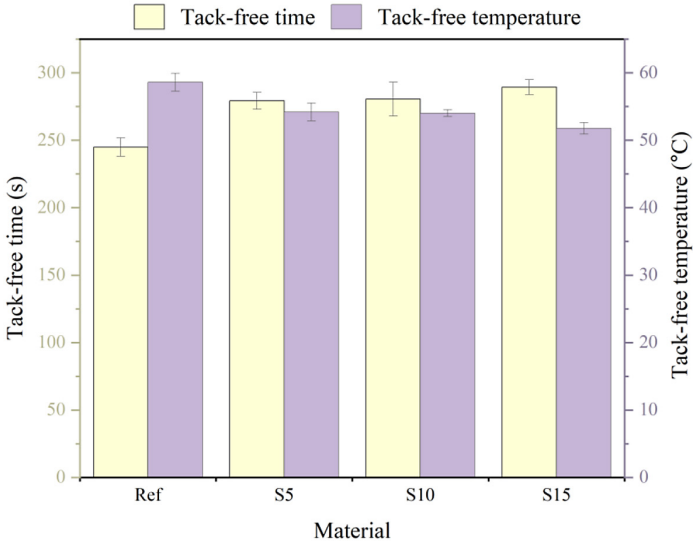


**Figure 5.** Tack-free time and corresponding temperature recorded for the obtained foams

verified by gently pressing with tissue paper. The results presented in Figure 5 indicate that the addition of sage alters the properties under investigation. Notably, S15 exhibits a longer tack-free time and a lower temperature compared to FPUF. Thermal imaging analysis further demonstrates that the incorporation of sage reduced the reaction temperature of the flexible PU foam. Although ANOVA and post hoc tests confirmed the significance of the filler on the tested properties ($p < 0.05$), no significant differences were observed among the composites.

As shown in Figure 6, the incorporation of sage leads to an increase in the shape factor relative to unmodified PU foam. The addition of 5 wt.% sage increased the shape factor by approximately 12%, while for S10 and S15, the increase was 8%. Statistical analysis confirms significant differences between the reference material and composites filled with 5 and 15 wt.% sage ($p < 0.05$). In addition, post hoc analysis indicates no significant differences among S5, S10 and S15. These findings suggest that the addition of sage facilitates the expansion of FPUF, likely due to the enhanced production of carbon dioxide associated with the moisture content in sage. Additionally, the sage particles may serve as nucleation sites, promoting increased cell formation and, consequently, a larger foam structure.

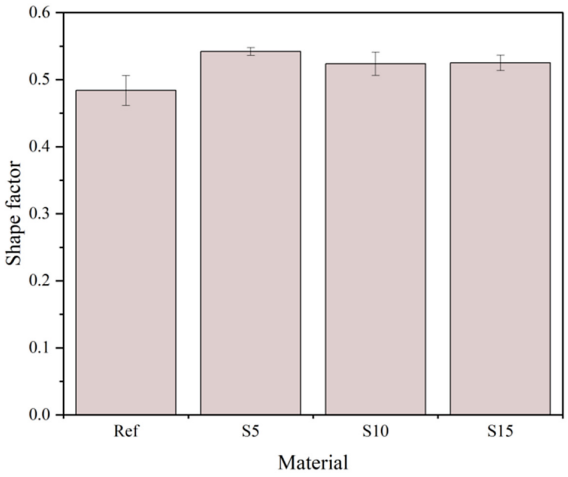


**Figure 6.** Variation in shape factor based on the filler content

## Microscopy observations

The micrographs of the tested foams in Figure 7 illustrate the effects of sage incorporation into the PU matrix. The reference foam exhibits an open-cell structure, which remains consistent even with the addition of sage. In the sage biocomposites filler particles are positioned within the cell walls, and cell size is reduced compared to the reference material. Owing to the inherent properties of sage, individual agglomerates can be observed within the matrices. Furthermore, the cell structures in the biocomposites appear ruptured,

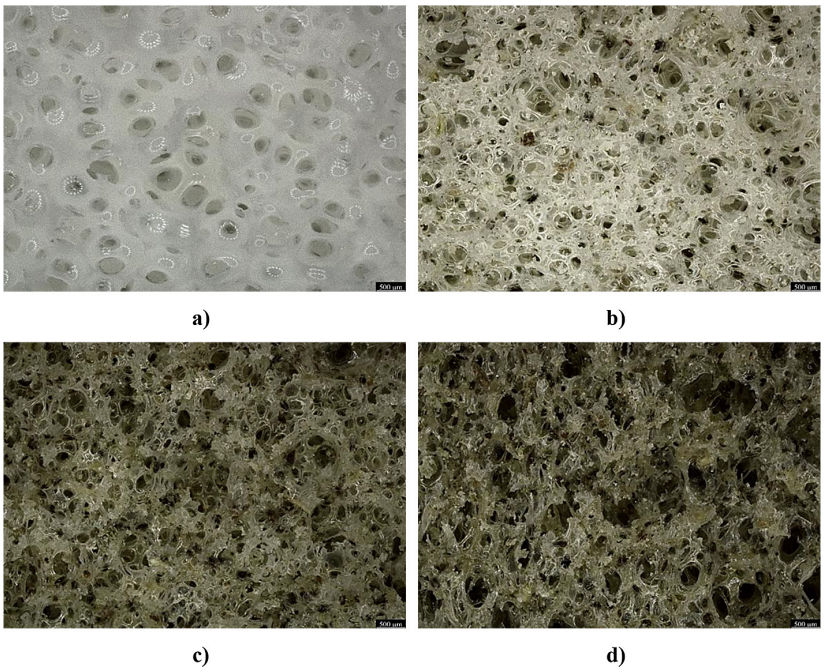


**Figure 7.** Micrographs of the obtained foams: Ref (a), S5 (b), S10 (c) and S15 (d)

likely due to the interaction of the filler with the foam matrix and the behavior of the foams during sample preparation. Additionally, as sage content increases, the foam structure becomes more irregular, with larger cells occasionally appearing. The denser structure observed in the biocomposites may also account for the variations in shape factor.

## Apparent density measurements

The findings illustrated in Figure 8 demonstrate the impact of sage addition on the apparent density of FPUF. The observed changes may be attributed to the presence of agglomerates at lower filler concentrations, which could locally alter density without significantly impacting the overall foam density. In contrast, higher filler content results in increased density due to the added mass from the sage particles. Additionally, the variability in the results increases with higher filler content, likely attributed to the presence of agglomerates within the FPUF matrix, which contributes to inconsistencies in the foam's mass. Tukey's post-hoc test revealed no significant differences between the composites and the reference material, though significant differences were observed among the composites themselves.

## Water absorption

The results of the water absorption tests, as depicted in Figure 9, demonstrate that the inclusion of sage significantly increased water uptake by approximately 30%, attributed to the hygroscopic nature of the filler. The addition of 5 wt.% sage results in a notable increase in water absorption compared to the reference material, while the 10 and 15 wt.% samples do not show significant increases beyond the levels observed in the 5 wt.% sample. Overall, the incorporation of sage has a statistically significant effect on water absorption ($p < 0.05$); however, the differences among the composite formulations are not statistically significant. This suggests that the quantity of sage introduced into flexible polyurethane PU foam does not have a significant impact on water absorption. This phenomenon may be linked to the greater porosity of the biocomposites, as illustrated in Figure 7. Additionally, the variability in the results diminishes with the introduction of sage into the PU foam and further decreases as the filler content increases. This suggests that higher filler content may contribute to a more uniform distribution of particles, leading to more consistent water absorption behavior.

## Compression testing

The mechanical performance of the produced foams was evaluated through compression testing, with the findings presented in Figure 10. The results reveal that the incorporation of 5 wt.% sage reduces the compression stress value by approximately 21%. This decline implies that the introduction of sage at this concentration lowers the foam's resistance to compression, potentially due to alterations in the foam's cellular structure or filler distribution that create weaker points, thereby diminishing its load-bearing capacity. However, with increased filler content, the compression stress value rises by 20% and 28% for the S10 and S15 samples, respectively. This suggests that at higher filler concentrations, the added mass and potential reinforcing effects

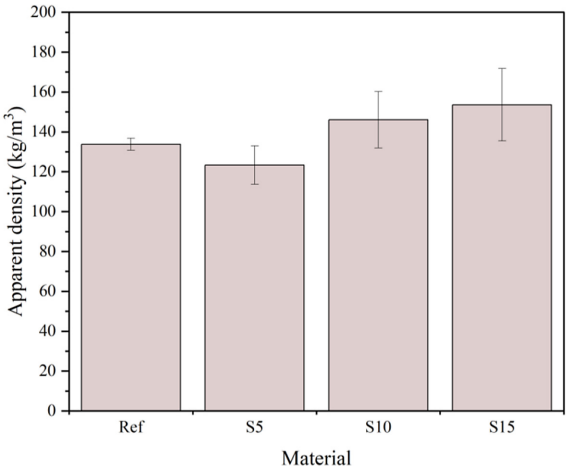


**Figure 8.** Apparent density of the obtained foams

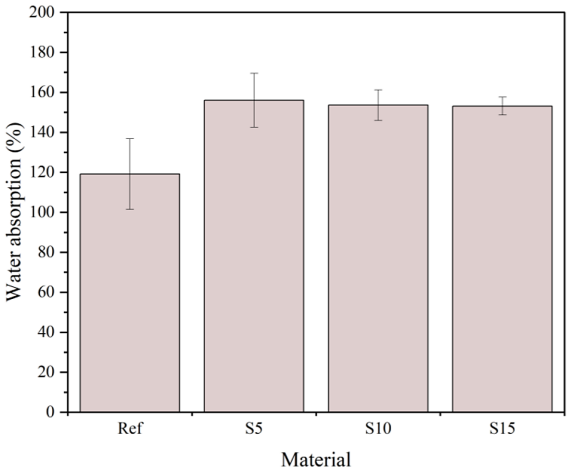


**Figure 9.** Water absorption of the obtained foams

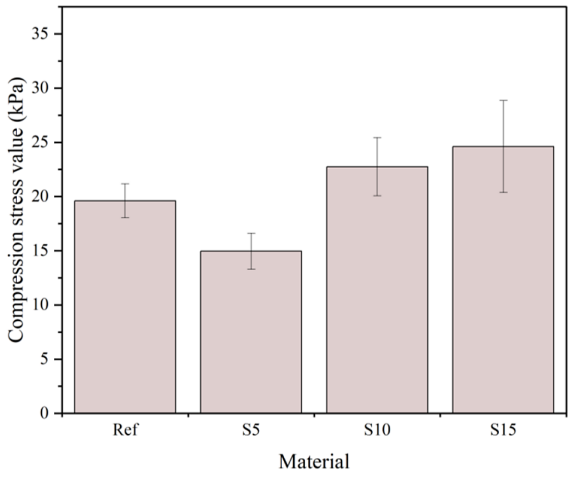


**Figure 10.** CV40 value of the obtained foams

of sage particles enhance the foam's resistance to compression, likely due to improved integration within the matrix and better distribution of the load. Furthermore, the variability in compression stress values is more pronounced in the S10 and S15 samples compared to the reference and S5 samples. Statistical analysis test confirmed the significance of the filler on the compression value ($p < 0.05$), with no significant differences observed between the S10 and S15 samples.

## CONCLUSIONS

Based on the findings of the conducted study, it can be concluded that the incorporation of sage into flexible polyurethane foam altered the properties of the foam to varying degrees. Although the addition of the filler was found to significantly affect the tested properties, the overall amount of incorporated sage was determined to be insignificant in terms of the degree of observed changes. The addition of sage was found to increase the time required for the completion of the foaming reaction while simultaneously decreasing the exothermic temperature released during the reaction. Furthermore, the presence of sage facilitated the expansion of the FPUF, likely due to the enhanced production of carbon dioxide, which is associated with the moisture content in the sage. When water reacts with isocyanates, a higher $CO_2$ formation occurs, contributing to foam expansion. From a microstructural perspective, the incorporation of sage particles resulted in the formation of smaller cells, with the additive being embedded within the walls of the cells. For lower-filled foam, the overall structure consists predominantly of smaller cells compared to the reference, with no larger cells or structural discontinuities evident, unlike samples S10 and S15. This configuration has the potential to improve the thermal insulation properties of the foam, as the smaller cells restrict gas movement, thereby reducing convective heat transfer.

The water absorption properties of the foam were also influenced, particularly at the 5 wt.% of sage level, where a noticeable increase in water absorption was observed, which can be primarily attributed to the hygroscopic nature of the sage filler. However, this effect appeared to plateau as the filler content increased to 10 and 15 wt.%.

Finally, the addition of sage to FPUF affected its compression stress properties. While the incorporation of 5 wt.% sage led to a reduction in mechanical strength, higher concentrations of sage enhanced or even exceeded the original performance of the reference foam. This improvement can be explained by changes in the foam's structure, filler interaction, and the more favorable distribution of particles at higher sage contents. These results suggest that sage is a promising bio-based filler that can modify the thermal, mechanical, and absorption properties of flexible polyurethane foams for various applications.

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