

DEVELOPMENT OF WATER-SOLUBLE FOOD PACKAGING FROM PVA AND MUNG BEAN HULL AGROWASTE

Andra-Gabriela ZORCĂ¹, Alessia-Ioana ENESCU¹, Ion Sorin JINGA^{1,*},
Cristina BUSUIOC¹, Iuliana Mihaela DELEANU¹

¹ Faculty of Chemical Engineering and Biotechnology, National University of Science and Technology POLITEHNICA Bucharest, Romania; andra.zorca@stud.chimie.upb.ro (A.G.Z.); alessia.enescu@stud.chimie.upb.ro (A.I.E.); sorin.jinga@upb.ro (I.S.J.); cristina.busuioc@upb.ro (C.B.); iuliana.deleanu@upb.ro (I.M.D.);

* Correspondence: sorin.jinga@upb.ro; (I.S.J.).

Received date: May 16th 2026; Accepted date: July 13th 2026; Published date: Sept. 30th 2026

Poly(vinyl alcohol) (PVA)-based films containing mung bean paste, potassium sorbate, and ultrasound-treated mung bean paste were developed and characterized. Increasing PVA content increased water solubility (average dissolution time of 49 min) and swelling degree (50–240%). Water vapor permeability ranged from 0.2039 to 9 g·m⁻¹·s⁻¹·Pa⁻¹, with the lowest value for PVA80-MBH-SK-US. SEM showed a fibrous lamellar morphology, while FTIR spectra exhibited characteristic polysaccharide bands with minor changes after soil burial. After one week, PVA80-MBH-SK-US and PVA60-MBH-SK-US retained 90% and 75% of their initial mass, respectively. All films completely degraded after two weeks under natural soil conditions.

Keywords: Polyvinyl alcohol, mung bean hulls, agrowaste valorization, water soluble packaging, biodegradability.

© 2026 by the authors. This article is distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

One of the most significant environmental issues today is water pollution caused by microplastics. The substantial increase in global plastic production (such as polyethylene terephthalate, polystyrene and polyvinyl chloride) directly impacts aquatic ecosystems, as these materials are ingested by organisms such as fish, crustaceans, and zooplankton—a process that inevitably leads to a rapid spread through the food chain, ultimately affecting human health as well [1]. These plastics are used in a wide variety of fields ranging from everyday items such as pens and shopping bags found in every household to applications in agriculture, industry, transportation, electronics, and medicine (syringes, intravenous bags, etc.) [2]. However, the field most dominated by plastics remains packaging. While the plastic used to package toys, stationery, cosmetics, personal care products, electronics, and

household goods remains an environmental concern, the risks are even bigger when plastics are used in food packaging. Through direct contact with food, microplastics can migrate, releasing additives and chemicals that, if ingested, can affect consumers' health. These compounds accumulate in organs, predominantly in the intestinal tract, kidneys, and urinary system, leading to kidney problems, detoxification issues, or electrolyte imbalance [3, 4].

Both issues—water pollution and the impact on aquatic ecosystems, as well as consumer exposure to harmful substances in their daily diet—can be addressed by exploring the use of water-soluble, eco-friendly, and non-toxic materials. One such example is polyvinyl alcohol (PVA), a synthetic, semicrystalline, and more environmentally friendly polymer obtained by hydrolyzing polyvinyl acetate [5]. It is known for its good chemical stability, its ability to form films across a wide range of concentrations while maintaining optimal properties and water retention, as well as its transparency and resistance to oils and organic solvents [6]. It is biocompatible and non-toxic and does not release major toxic substances. The only drawbacks of this polymer are its limited mechanical properties and high water vapor permeability, which can be easily improved by incorporating various additives into the film composition [5, 7].

One of these additives could be the mung bean, a legume widely cultivated in most Asian countries, which is a rich source of protein—including peptides with ACE-inhibitory activity—fiber, polysaccharides, essential vitamins and minerals (Ca, Mg, Fe), as well as bioactive compounds such as flavonoids (vitexin, isovitexin, quercetin, dulcinoside) or phenolic acids (gallic acid, hydroxycinnamic acid) [8]. It possesses hypoallergenic and antihypertensive properties, being capable of inhibiting the angiotensin-converting enzyme, as well as hypoglycemic properties with the ability to modulate glucose metabolism. Since hulls are a byproduct of mung bean processing, utilizing them in food packaging could lead to a cheap and environmentally friendly alternative to traditional plastics. Incorporating them into a water-soluble matrix such as PVA could address the issue of plastics ending up in aquatic ecosystems while also improving the matrix's mechanical and barrier properties. Mung bean hulls can be incorporated into films in both powder and paste forms, although the latter might be considered more suitable for achieving a more uniform dispersion in the matrix [9,10,11]. Another important additive is potassium sorbate, the unsaturated salt of sorbic acid, a compound commonly used in food packaging due to its tendency to be organoleptically inert (it does not alter the taste, smell, or texture of the film) as well as its strong antibacterial properties, being very effective against molds, yeasts, and anaerobic bacteria. These properties can help extend the shelf life of products. As a hygroscopic compound, it can increase both the water vapor transmission rate (WVTR) and water vapor permeability (WVP) of films, a fact that is, however, offset by its use in small quantities [12]. It can increase UVB protection and is also

safe for human consumption, the acceptable intake being 11 mg sorbic acid/ kg body-weight per day [13,14].

Although mung beans are known for their rich nutritional profile and health-promoting bioactive compounds, there remains a lack of studies on their effects on the structure and properties of the polymer matrices into which they are incorporated. In this context, the present study aims to investigate the effect of mung beans on a water-soluble polymer matrix (PVA) by incorporating them in the form of a hull paste while also evaluating the interactions between this subproduct, the polymer matrix, and potassium sorbate. Since both the mung bean paste and potassium sorbate have the potential to form aggregates within the matrix, the study further investigates how ultrasonic treatment influences the uniformity, structural integration, and functional properties of the resulting film. Various formulations were used, with the amount of mung bean hull paste being kept constant, while the amount of 10% PVA solution and the other factors were varied.

2. Materials and methods

2.1. Materials

The materials used in this study included poly(vinyl alcohol) (PVA; 95% hydrolyzed, Mv 95,000) purchased from Sigma-Aldrich and potassium sorbate used directly upon purchase. Mung beans (*Vigna radiata* L.) were obtained from a local market in Bucharest.

2.2. Methods

2.2.1. Mung Bean Hulls (MBH) preparations

Mung bean (*Vigna radiata* L.) seeds were purchased from a supermarket in Bucharest, Romania. The seeds were washed with deionized water and soaked overnight before being dehulled. The wet hulls were subsequently ground in a blender and passed through a 100 µm sieve, with some of them undergoing ultrasonic (US) treatment in order to observe the US impact on the vegetal material structure and properties.

2.2.2. Preparation of PVA-MBH-based packaging materials

A 10% (w/w) PVA solution, which served as the base matrix, was prepared by dissolving PVA powder in heated deionized water (at 90°C) under constant stirring for 45 minutes. This solution was used as the control sample (PVA). After cooling, the same amount of mung bean hulls paste (23g MBH) was added to all samples and further stirred to achieve a homogeneous dispersion. In certain

samples, 0.2% wt potassium sorbate (SK) was added as a preservative and stabilizer, and a control sample containing only PVA and SK (PVA-SK) was also included. To evaluate the effect of PVA concentration on the properties of the resulting films, samples were prepared with different amounts of matrix solution (60 and 80 g PVA), similar MBH content, and variable SK concentration (the amount of SK being almost negligible as a mass fraction). The compositions of the resulting samples can be seen in Table 1. The next step involved pouring the solutions and dispersions onto glass plates and drying them in an oven at a temperature of 40°C until the matrix had hardened enough to be peeled off without causing significant damage to the films.

Table 1. Codification and the composition of the PVA-MBH films.

Sample code	Parameter, m.u.			
	Sol. PVA 10%, g	Mung bean hulls (MHB), g	Potassium sorbate (SK), g	Ultrasonicated (US)
PVA	100	23	0	No
PVA-SK	100		0.2	No
PVA80-MBH	80		0	No
PVA80-MBH-US	80		0	Yes
PVA80-MBH-SK	80		0.2	No
PVA80-MBH-SK-US	80		0.2	Yes
PVA60-MBH-US	60		0	Yes
PVA60-MBH-SK-US	60		0.2	Yes

2.3. Characterization of water-soluble composite films

2.3.1. Morphological and structural properties of PVA-MBH-based packaging materials

2.3.1.1. Scanning electron microscopy (SEM) coupled with EDX

The morphology of the PVA- and mung bean-based packaging was determined using an FEI Quanta Inspect F50 scanning electron microscope (FEI Company, Hillsboro, OR, USA). It has a spot size of 3.5 and is operated at 30 kV in secondary electron detection mode. After fragmenting the samples in air or liquid nitrogen—a choice made based on their brittleness—they were mounted on metal holders and coated with gold via cathodic sputtering to improve electrical conductivity and facilitate analysis. The equipment also includes an EDX detector (Oxford Instruments).

2.3.1.2. FT-IR Spectroscopy (FTIR)

A Thermo Scientific Nicolet iS50 spectrophotometer (Thermo Fisher Scientific Inc., Waltham, MA, USA) was used to determine the FTIR spectra of the samples. Measurements were performed with 32 scans using the ATR (Attenuated

Total Reflection) mode in the range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1} . The software used to process the obtained data is OriginPro 8.

2.3.2. Water resistance properties of PVA-MBH-based packaging materials

2.3.2.1. Swelling degree (SD)

The swelling degree was assessed by measuring the water absorption capacity of the dried films. Squared samples with a side length of 5 cm were cut and weighed (m_{dsi}) before immersing them in 50 mL of deionized water for 1 h at room temperature (25°C). The samples are blotted to remove excess water from the surface of the films and then weighed (m_{ss1}). The swelling degree is calculated using the formula:

$$SD = \frac{m_{\text{ss1}} - m_{\text{dsi}}}{m_{\text{dsi}}} \cdot 100 \quad (1)$$

Where: SD is the swelling degree (%) of the films, m_{ss1} is the weight of the sample after immersion in deionized water for 1 h (g) and m_{dsi} is the weight of the sample before immersion (g)

2.3.2.2. Water solubility rate (WSR)

Square samples with a side length of 2 cm were cut out and immersed, under stirring, at room temperature (25°C) in 100 mL of deionized water. Considering the initial mass of the films as well as the time required for complete dissolution in water, the solubility of the samples was calculated using the formula:

$$WSR = \frac{m_i}{t_{\text{dis}}} \cdot 100 \quad (2)$$

where WSR is the water solubility rate of the samples (g/min), m_i is the initial mass of the samples (g) and t_{dis} is the time required for complete dissolution in deionized water (min)

2.3.2.3. Water vapor permeability (WVP)

Circular samples with a diameter of 3.5 cm were cut from the films and subsequently sealed in cups containing pre-dried silica gel (0% RH). These cups were kept in a desiccator at a temperature of 25°C and a humidity of 94% RH and were weighed once a day for 5 days.

The difference in mass was used to calculate the water vapor transmission rate (WVTR) according to ASTM E96 (E96 Standard Test Methods for Water Vapor Transmission of Materials, n.d.) using the equation:

$$WVTR = \frac{\Delta m}{\Delta t \cdot A} \quad (3)$$

Where: WVTR is the rate of water vapor transmission through the material, $\Delta m/\Delta t$ is the change in mass per unit time ($\text{g} \cdot \text{s}^{-1}$), and A is the sample area (m^2)

Using the WVTR results, the water vapor permeability (WVP) was calculated using the formula:

$$WVP = \frac{WVTR \times \delta}{\Delta p} \quad (4)$$

Where: Δp is the water vapor partial pressure difference across the two sides of the coatings (Pa), and δ is the thickness of the sample, which was measured using the micrometer Mitutoyo Mfg Co. Ltd. to the nearest 0.001 mm at room temperature.

2.3.3. Biodegradability assessment in soil

Determining the environmental behavior of water-soluble packaging is relevant to the suitability of these materials for food packaging, as the goal is for them to break down efficiently after use, thereby reducing pollutants from the food industry.

The soil burial test was conducted under real environmental conditions and was intended as a preliminary assessment of the biodegradation behavior rather than a standardized biodegradation test.

To this end, films made from PVA and mung bean hull paste were cut into 4x4 mm square samples and buried at a depth of 2 cm in a planter that was exposed to normal outdoor summer weather conditions. The samples arrangement in the planter is shown in Figure 1. In the first experiment, which lasted 2 weeks, complete degradation of the samples was observed. The experiment was repeated, this time with the samples recovered after one week of exposure.



Figure 1. Experimental setup of the soil burial test after one week, showing the arrangement of the samples prior to soil coverage.

The samples containing mung bean hull paste retained most of their initial structure, while the samples containing only PVA and potassium sorbate (PVA and PVA-SK) exhibited the most advanced degree of degradation. Although the inclusion of mung beans in the packaging structure reduces their biodegradability, the samples still exhibited rapid decomposition between the first and second weeks of the experiment. The recovered samples were cleaned by brushing to remove soil particles adhering to the packaging and analyzed using SEM and FTIR to highlight the morphological and structural changes induced by the environmental factors to which the packaging was exposed.

3. Results and discussions

3.1. Morphological and structural properties of PVA-MBH-based packaging materials

3.1.1. Scanning electron microscopy (SEM) coupled with EDX

The microstructure of the hydrophilic films was determined using scanning electron microscopy (SEM), which revealed significant differences between the pure PVA matrix and the samples containing various additives. The PVA matrix has a smooth and compact surface, with no visible pores but with small defects most likely caused by the stress applied to the material during peeling from the Petri dishes, in agreement with previous studies [15,16,17]. The addition of potassium sorbate results in a slight smoothing of the surface. However, this change is subtle because the composition contains only a small amount of potassium sorbate.

In contrast, samples containing mung bean hull paste exhibit a radical change in microstructure, with very similar SEM images regardless of their composition, as shown in Figure 2. These are characterized by a complex fibrous-lamellar structure, with fibers arranged on multiple layers. Although the ultrasonication process applied to the mung bean hull paste contributes to its fragmentation and homogenization, this step does not result in significant changes to the film's microstructure, which remains comparable to samples containing paste that has not undergone this process. As in the comparison between the PVA and PVA-SK samples, potassium sorbate has only a marginal influence on the material's characteristics, being overshadowed, like the ultrasonication process, by the impact of the mung bean hull paste.

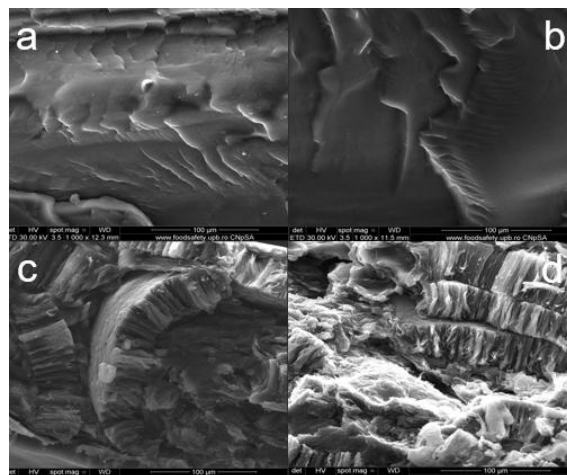


Figure 2. SEM images of representative samples: (a) PVA, (b) PVA-SK, (c) PVA80-MBH and (d) PVA80-MBH-SK-US.

Elemental analysis using energy-dispersive X-ray spectroscopy (EDX), shown in Figure 3., supports the SEM investigation by providing information regarding the elemental composition of the packaging. In the case of the pure PVA matrix, the elements C and O were detected with the highest peaks, as expected from its chemical structure [18], along with small amounts of iron and gold. However, gold (Au) is present in all samples due to the deposition of a conductive layer required for SEM analysis. The presence of iron in the matrix can be explained by minor contamination during the preparation or storage process.

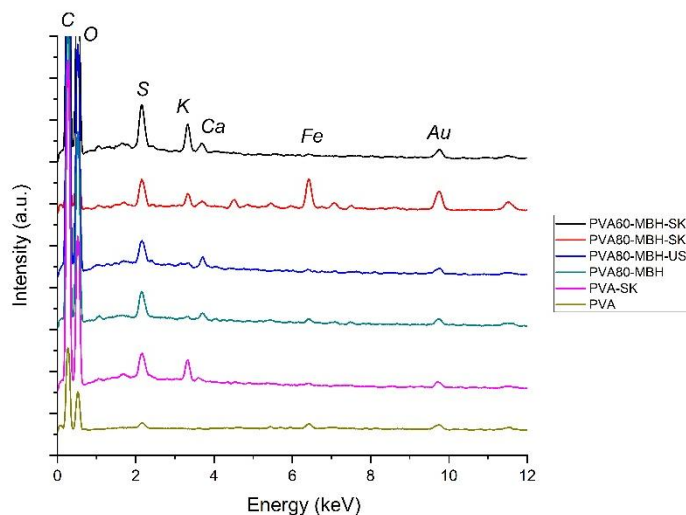


Figure 3. EDX spectra of PVA-based films with different compositions.

The signal corresponding to potassium (K) was found in the EDX spectra of all samples containing potassium sorbate, indicating the significant chemical contribution of this additive to the material's composition.

The third highest peak, corresponding to sulfur (S), was detected in all the samples analyzed, including the pure PVA matrix, where it appears, however, in relatively small quantities. This presence can be attributed to residual impurities in the PVA polymer powder. However, in the samples with additives, the signal intensity increases significantly, suggesting an additional source of sulfur that may be due to amino acids (cysteine, methionine) present in the mung bean hull paste [19]. The mineral profile is complemented by elements such as Ca, Mg, and Fe contained in the cell walls and mineral salts of the hull, in the chlorophylls, and in the plant's proteins and mineral complexes, respectively [20].

3.1.2. FT-IR Spectroscopy (FTIR)

The FTIR spectra of water-soluble packaging based on PVA and mung bean hull paste, which can be observed in Figure 4., show that these components clearly dominate the spectrum, while the addition of potassium sorbate or the application of ultrasonic treatment does not significantly affect the profile.

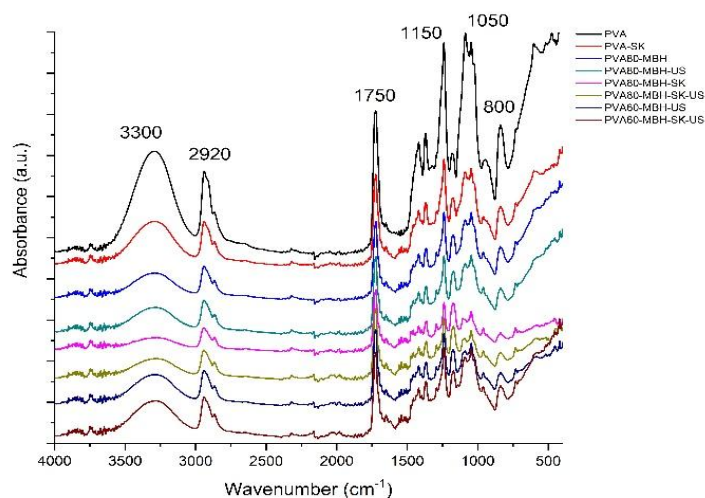


Figure 4. FTIR spectra of PVA-based films with different compositions.

The absorption bands correspond to those reported in the literature for raw PVA [21], confirming the preservation of the polymer's fundamental characteristics in this formulation. The interaction between PVA and mung beans is indicated both by the peak at 3300 cm^{-1} attributed to O-H stretching specific to the hydrogen bonds formed between the polymer chains and the polysaccharide components in the beans, and by the bands at 1050 cm^{-1} and 1150 cm^{-1} representative of the stretching

C-O and C-O-C bonds. The effect of mung beans on the FTIR spectrum is also confirmed by other studies [22] in which similar bands for O-H, aliphatic C-H, carbonyl, and C-O/C-C stretching were identified for mung bean starch, indicating that its functional components contribute significantly to the chemical structure of the water-soluble packaging.

Another peak supporting this interaction is the one at 1750 cm^{-1} corresponding to the stretching of the C=O group. Although potassium sorbate contains carbonyl groups, this peak cannot be attributed to it because the signal is consistently present in all samples, regardless of whether this compound is present in their composition. Furthermore, the amount of preservative added is considered insufficient to make a significant difference in the spectra, and it is considered that this peak corresponds to residual acetate groups derived from the 10% PVA solution.

Although both peaks at 2920 cm^{-1} and 800 cm^{-1} involve vibrations of C-H bonds, they reflect different mechanisms: the former represents the longitudinal stretching of atoms in aliphatic chains, while the latter illustrates the perpendicular deformation of hydrogen atoms in aromatic or unsaturated structures, both of which, however, originate from PVA or the polysaccharides in mung bean hulls.

The results indicate a general spectrum comparable to that of mung bean starch reported in the literature [23], with bands specific to O-H, C-H, and C-O groups, the main differences being the shift in their positions and the variation in peak intensity, most likely due to different compositions and processing methods (paste compared to starch).

3.2. *Water resistance properties of PVA-MBH-based packaging materials*

3.2.1. Water solubility rate (WSR)

Not all samples were selected to determine the rate of solubilization in water, but only those containing all the variables used in this study, the only difference between them being the amount of 10% PVA solution contained in the film. Thus, by comparing the PVA60-MBH-SK-US ($3.1 \times 10^{-3}\text{ g/min}$) and PVA80-MBH-SK-US ($4 \times 10^{-3}\text{ g/min}$) samples, an increase in the amount of film dissolved in water per minute was observed as the amount of PVA in the packaging increased. To observe the impact of removing a variable from the system on the solubilization rate, the PVA80-MBH-SK sample was also analyzed, which showed a value of $3.8 \times 10^{-3}\text{ g/min}$ comparable to the sample with the same PVA concentration and composition but subjected to ultrasound. This trend is consistently observed in both Table 2 and Figure 5., suggesting that the most significant influence on the WSR is exerted by the amount of PVA in the formulation and not by the additives or modifications made to the preparation method.

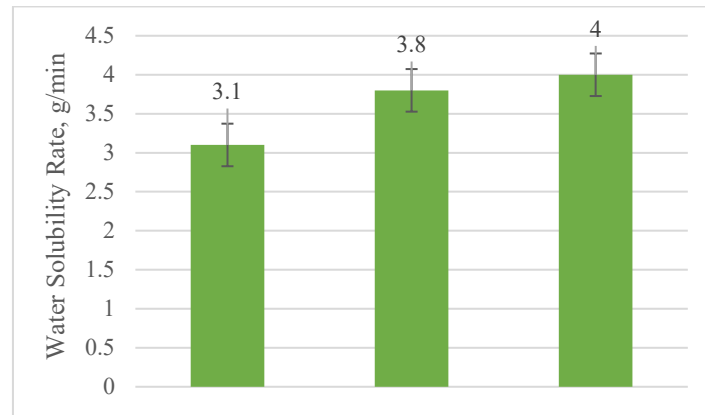


Figure 5. Water solubility rate of PVA-MBH samples.

Literature studies based on the dissolution rate of pure PVA solutions highlight the significant influence of solution concentration on this property. Thus, upon analyzing a set of samples with concentrations ranging from 1% to 25%, a faster dissolution rate was observed as the solution concentration increased. For a 10% PVA solution, the dissolution time was approximately 5.3 minutes [24]. The difference between this value and those determined for the PVA-MBH samples indicates the influence that the combination of factors applied to the samples has on the dissolution rate, as these factors reduce the values without significantly altering the overall behavior.

Table 2. Water solubility rate determined based on initial film mass and total dissolution time.

Sample code	Parameter, m.u.		
	m_i , g	t_{dis} , min	$WSR \times 10^{-3}$, g/min
PVA60-MBH-SK-US	0.1487	48	3.1
PVA80-MBH-SK	0.2100	55	3.8
PVA80-MBH-SK-US	0.1762	44	4

3.2.2. Swelling degree (SD)

The measurements began with the control sample of 10% PVA solution (PVA), which also exhibited the lowest degree of swelling among all the films analyzed (54%). This result is comparable to the values reported in the literature for 10% PVA solutions, which exhibited a water content of 64% after immersion in distilled water for one hour [25]. However, the absorption properties of PVA are directly influenced by the concentration of the initial solution and the structure of the polymer network, with the absorption capacity potentially increasing to 200–250% in the case of PVA hydrogels [26]. After adding potassium sorbate to this matrix (PVA-SK), the value tripled. This behavior can be explained by the hydrophilic nature of potassium sorbate, which tends to promote water diffusion into the polymer network.

Most of the sample values are approximately 4 times higher than the control sample (PVA). Comparing the PVA80-MBH and PVA80-MBH-US samples reveals a noticeable influence of the ultrasonication process on the barrier properties. The ultrasonicated sample exhibited a swelling degree 39% lower than the untreated sample. A possible explanation is that ultrasonication improved the dispersion of the insoluble mung bean fibers in the film-forming solution, resulting in a more uniform distribution of these components within the polymer matrix and consequently reducing water uptake.

At the same time, a comparison between PVA80-MBH and PVA80-MBH-SK samples, which differ in the amount of potassium sorbate incorporated, reveals a decrease in the degree of swelling as the amount of sorbate in the film increases.

The apparent contradiction may be explained by the different film formulations. While potassium sorbate increased the swelling degree in PVA films without mung bean extract, it decreased the swelling degree in PVA-MBH films. This difference is likely related to the interactions between PVA and the MBH extract, whereas the low potassium sorbate concentration (0.2 g per 100 g film-forming solution) is unlikely to exert a dominant effect.

Swelling degree exhibits a dependence on the PVA content in the film. By reducing the amount of 10% PVA solution from 80 g (PVA80-MBH-US with 200% SD) to 60 g (PVA60-MBH-US with 130% SD), a 70% decrease is observed, confirming the reduction in the films' water absorption and retention capacity. These results are presented in Table 1. However, the influence of PVA on a polymeric system is not linear. Extreme amounts reduce water retention capacity, while moderate amounts lead to balanced barrier properties. Thus, using low amounts of PVA results in a polymer matrix that is too weak to retain water effectively, while high amounts lead to a dense structure that limits water penetration into the film [27].

3.2.3. Water vapor permeability (WVP)

The lowest permeability values were observed for samples containing all formulation and processing factors (MBH, SK, and ultrasonication), regardless of PVA concentration, with values comparable to the control sample (10% PVA), which showed a permeability of 0.7623. Significantly higher WVP values ($3.92 \pm 0.9736 \times 10^{-10} \text{ g} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{Pa}^{-1}$) were determined for 5% pure PVA films [28], indicating that polymer concentration plays a crucial role in determining barrier properties. An increase in PVA concentration leads to a denser network and, consequently, reduces water vapor permeability through the material.

These results, shown in Table 3, suggest that the combined use of functional additives and the ultrasonication process leads to a more compact film structure with uniformly distributed pores. A significant difference can also be observed by

comparing the PVA80-MBH-SK-US and PVA60-MBH-SK-US samples, which differ only in the amount of PVA solution used. Reducing the amount of PVA solution leads to a significant increase in permeability, from $0.2039 \times 10^{-10} \text{ g}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ to $0.9736 \times 10^{-10} \text{ g}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$.

As the active components are removed from the formulation, a progressive increase in permeability is observed. Thus, the samples containing mung bean hulls, regardless of whether they underwent ultrasonication, exhibit the highest values ranging from 5.3 to 5.9×10^{-10} , being close to the sample PVA-SK containing only the 10% PVA solution and potassium sorbate ($5.351 \times 10^{-10} \text{ g}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$).

Table 3. Physico-chemical properties of the PVA-MBH-based packaging materials as dried films.

Sample code	Parameter, m.u.		
	SD, %	WVTR, $\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$	WVP $\times 10^{-10}$, $\text{g}\cdot\text{m}^{-1}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$
PVA	54	8.465	0.7623
PVA-SK	151	10.843	5.351
PVA80-MBH	239	11.048	5.452
PVA80-MBH-US	200	11.526	8.857
PVA80-MBH-SK	223	9.787	1.751
PVA80-MBH-SK-US	200	10.615	0.2039
PVA60-MBH-US	130	10.662	5.825
PVA60-MBH-SK-US	215	10.136	0.9736

The effect of potassium sorbate is observed when comparing the PVA80-MBH-SK samples with the PVA80-MBH samples, with the sample lacking SK having a permeability approximately three times higher. However, this significant difference cannot be attributed entirely to potassium sorbate, but rather to its interaction with the polymer matrix rich in hydroxyl groups and with the proteins in the bean hulls, which are rich in amino and carboxyl groups capable of forming hydrogen bonds and ion-dipole interactions with the carboxylate groups of SK mung, leading to structural changes in the network. This premise is supported by a study [13], which examined the influence of potassium sorbate on the WVTR of PVA-collagen composite films. According to it, the addition of potassium sorbate exhibits nonlinear behavior; at low concentrations (up to 9% SK), it leads to an increase in the WVP of the films, while at high concentrations there is an increase in WVP attributed to network compaction resulting from excessive hydrogen bonding.

2.3.3. Biodegradability assessment in soil

After two weeks of soil burial, none of the film samples could be recovered, indicating complete degradation. However, after one week, most samples had already undergone extensive disintegration. Only the PVA80-MBH-SK-US sample

retained 90% of its initial mass, while the PVA60-MBH-SK-US film retained 75%, as shown in Figure 6. This suggests that the combined effect of ultrasonication, potassium sorbate incorporation, and the mung bean hulls paste addition may have contributed to improved structural integrity, resulting in greater resistance to degradation during the initial stage of soil burial.



Figure 6. PVA80-MBH-SK-US (a) and PVA60-MBH-SK-US (b) samples after 1 week of soil burial.

After one week of soil burial, SEM images (Figure 7.) reveal clear morphological changes from an initial fibrous and lamellar structure to a disorganized, fragmented, and non-uniform microstructure. Collapsed areas and irregular aggregations caused by the progressive degradation of the PVA matrix are observed. This evolution can be correlated with phenomena such as matrix swelling following water absorption from the environment, as well as the enzymatic action of microorganisms present in the soil. The film matrix, the base component most susceptible to moisture and bacterial activity, degrades more easily and rapidly, while the fibers in the mung bean hulls pulp, which are lignocellulosic in nature, such as cellulose and lignin, exhibit higher resistance to environmental factors and persist in the form of this disorganized network [29,30].

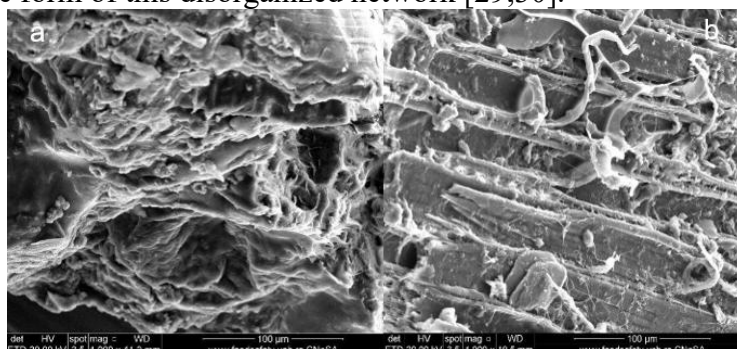


Figure 7. SEM micrographs of PVA–MBH samples after biodegradation test: comparison between 80 g (a - PVA80-MBH-SK-US) and 60 g PVA (b - PVA60-MBH-SK-US) content.

Given the similarity of the FTIR spectra of the water-soluble films before biodegradability testing, the PVA80-MBH-SK, PVA80-MBH-SK-US, and PVA60-MBH-SK-US samples were selected to investigate the impact of environmental factors and compositional differences on their chemical characteristics. Comparing the FTIR spectra before (Figure 4) and after biodegradability testing (Figure 8), it can be observed that the main peaks remain

unchanged, except for a slight shift of the band from 1150 cm^{-1} to 1200 cm^{-1} , suggesting minor adjustments in the C-O-C bonds likely due to the interaction of the mung bean hull paste with the soil. The bands at 3300 cm^{-1} corresponding to hydroxyl (OH) groups and those at 2920 cm^{-1} attributed to alkyl (C-H) stretches are still present in all samples, indicating that the main structure of PVA and the bio-components remains stable regardless of the environmental conditions applied.

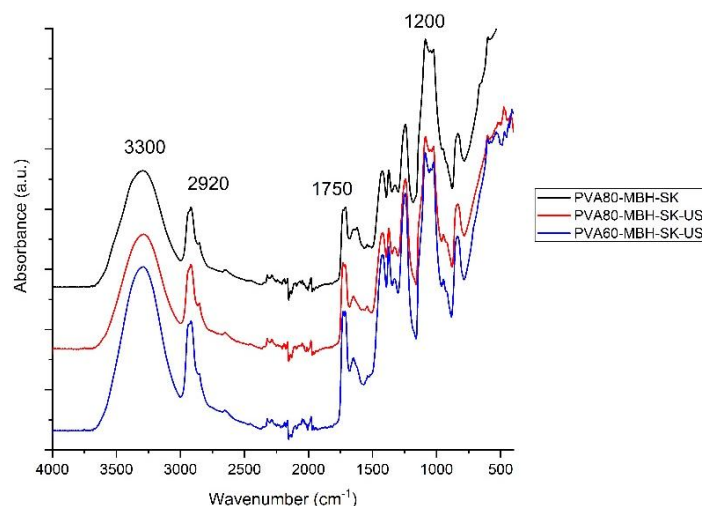


Figure 8. FTIR spectra of PVA–MBH samples after soil burial test.

4. Conclusions

The study aimed to highlight the impact of the variables used in the composition of the films on their properties, as well as to monitor the behavior of the films when exposed to the external environment. Thus, considering it an eco-friendly alternative to conventional food packaging, a 10% PVA solution was chosen as the matrix, to which a fixed amount of mung bean hull paste was added for all samples; the variables were the addition of potassium sorbate and the application of ultrasound for homogenizing the vegetable paste. These additives, as observed in the SEM images of the samples, did not have a significant influence on the microstructure of the samples, which was dominated by the fibrous components of the vegetable paste that remained nearly intact even after the samples were immersed in soil for one week. The microstructure becomes disordered and porous, with a high contribution from the lignocellulosic fraction provided by the mung beans. The FTIR spectra obtained before and after soil burial show minor shifts in the bands, suggesting physical changes induced by degradation. The inclusion of mung bean paste as a component in PVA-based water-soluble films led to a significant increase in the swelling degree of the samples (being 4 times higher than that of the pure PVA matrix), and the combination of all variables significantly reduces water vapor permeability through the material, with the removal of a single

factor gradually leading to an increase in this property. Therefore, although mung bean hulls paste was the key component in the packaging's performance, this material shows high potential for optimizing functional properties by adjusting the composition using different amounts of additives and conditions for the ultrasonication process depending on the desired durability and application.

Author Contributions

Conceptualization, A.G.Z. and I.M.D.; methodology, A.G.Z. and I.M.D.; data curation, A.G.Z.; formal analysis, A.G.Z.; investigation, A.G.Z., A.I.E., C.B., and I.M.D.; visualization, A.G.Z.; writing—original draft preparation, A.G.Z.; writing—review and editing, A.G.Z., I.S.J., and I.M.D.; supervision, I.S.J. and I.M.D.

Acknowledgments

The authors gratefully acknowledge the National University of Science and Technology POLITEHNICA Bucharest for providing the laboratory facilities and institutional support necessary for this research.

Conflicts of 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.

Publisher's Disclaimer

The statements, opinions, and data presented in this publication are solely those of the author(s) and contributor(s) and do not necessarily reflect the views of the publisher, editor(s), or affiliated institutions. The publisher and editor(s) disclaim responsibility for any errors, omissions, or consequences arising from the use of the information, methods, instructions, or products described in the publication.

REFERENCES

- [1] Najahi, H.; Banni, M.; Nakad, M.; Abboud, R.; Assaf, J.C.; Operato, L.; Belhassen, M.; Gomes, L.; Hamd, W. Plastic pollution in food packaging systems: Impact on human health, socioeconomic considerations and regulatory framework. *J. Hazard. Mater. Adv.* **2025**, *18*, 100667, <https://doi.org/10.1016/j.hazadv.2025.100667>.
- [2] Pilapitiya, P.G.C.N.N.T.; Ratnayake, A.S. The world of plastic waste: A review. *Clean. Mater.* **2024**, *11*, 100220, <https://doi.org/10.1016/j.clema.2024.100220>.
- [3] Ririe, A.K.; Fatema, N.; Dina, T.J.; Kuchipudi, J.D.; Tamanna, P.; Libriansyah, L.; Akter, T.; Kaderi, N. Impact of microplastic exposure on human health: A systematic review of mechanisms, biomarkers, and clinical outcomes. *Cureus* **2025**, *17*, e100295, <https://doi.org/10.7759/cureus.100295>.
- [4] Aditya, M.R.; Muhammad, A.R.; Adriansyah, V.; Samsu, N.; Sulistomo, H.W. Microplastic exposure and its consequences for renal and urinary health: Systematic review of in vivo studies. *All Life* **2025**, *18*, 2457760, <https://doi.org/10.1080/26895293.2025.2457760>.
- [5] Abazari, M.; Momeni Badeleh, S.; Barkhordari, S.; Salih Mohammed, S.; Mahmood Ahmed, M.; Sheet Mohammed Ameen, M.; Abdollahi, H. Preparation and characterization of polyvinyl

- alcohol thin films: Rheological, physicochemical and functional properties. *Heliyon* **2025**, *11*, e43604, <https://doi.org/10.1016/j.heliyon.2025.e43604>.
- [6] Chousidis, N. Polyvinyl alcohol (PVA)-based films: Insights from crosslinking and plasticizer incorporation. *Eng. Res. Express* **2024**, *6*, 025010, <https://doi.org/10.1088/2631-8695/ad4cb4>.
- [7] Sau, S.; Pandit, S.; Kundu, S. Crosslinked poly(vinyl alcohol): Structural, optical and mechanical properties. *Surf. Interfaces* **2021**, *25*, 101198, <https://doi.org/10.1016/j.surf.2021.101198>.
- [8] Ganesan, K.; Xu, B. A critical review on phytochemical profile and health promoting effects of mung bean (*Vigna radiata*). *Food Sci. Hum. Wellness* **2018**, *7*, 11–33, <https://doi.org/10.1016/j.fshw.2017.11.002>.
- [9] Sehwat, N.; Yadav, M.; Kumar, S.; Upadhyay, S.K.; Singh, M.; Sharma, A.K. Review on health promoting biological activities of mungbean: A potent functional food of medicinal importance. *Plant Arch.* **2020**, *20*, 2969–2975.
- [10] Karami, Z.; Changsiripun, C.; Duangmal, K.; Chotechuang, N. Health Benefits and Challenges of Mung Bean Bioactive Compounds: A Systematic Review of In Vivo Evidence for Functional Food Applications. *Food Rev. Int.* **2025**, *41*, 1681–1708, <https://doi.org/10.1080/87559129.2025.2452240>.
- [11] Hou, D.; Yousaf, L.; Xue, Y.; Hu, J.; Hu, X.; Feng, N.; Shen, Q. Mung bean (*Vigna radiata* L.): Bioactive polyphenols, polysaccharides, peptides, and health benefits. *Nutrients* **2019**, *11*, 1238, <https://doi.org/10.3390/nu11061238>.
- [12] Liang, X.; Feng, S.; Ahmed, S.; Qin, W.; Liu, Y. Effect of potassium sorbate and ultrasonic treatment on the properties of fish scale collagen/polyvinyl alcohol composite film. *Molecules* **2019**, *24*, 2363, <https://doi.org/10.3390/molecules24132363>.
- [13] Kowalczyk, D.; Kordowska-Wiater, M.; Sołowiej, B.; Baraniak, B. Physicochemical and antimicrobial properties of biopolymer-candelilla wax emulsion films containing potassium sorbate – a comparative study. *Food Bioprocess Technol.* **2015**, *8*, 567–579, <https://doi.org/10.1007/s11947-014-1423-6>.
- [14] Kowalczyk, D.; Skrzypek, T.; Basiura-Cembala, M.; Łupina, K.; Mężyńska, M. The effect of potassium sorbate on the physicochemical properties of edible films based on pullulan, gelatin and their blends. *Food Hydrocoll.* **2020**, *105*, 105837, <https://doi.org/10.1016/j.foodhyd.2020.105837>.
- [15] Jain, N.; Singh, V.K.; Chauhan, S. A review on mechanical and water absorption properties of polyvinyl alcohol based composites/films. *J. Mech. Behav. Mater.* **2017**, *26*, 213–222, <https://doi.org/10.1515/jmbm-2017-0027>.
- [16] Ben, J.; Song, Z.; Liu, X.; Lü, W.; Li, X. Fabrication and electrochemical performance of PVA/CNT/PANI flexible films as electrodes for supercapacitors. *Nanoscale Res. Lett.* **2020**, *15*, 151, <https://doi.org/10.1186/s11671-020-03379-w>.
- [17] Ren, M.; Frimmel, F.H.; Abbt-Braun, G. Multi-cycle photocatalytic degradation of bezafibrate by a cast polyvinyl alcohol/titanium dioxide (PVA/TiO₂) hybrid film. *J. Mol. Catal. A Chem.* **2015**, *400*, 42–48, <https://doi.org/10.1016/j.molcata.2015.02.004>.
- [18] Aslam, M.; Kalyar, M.A.; Raza, Z.A. Fabrication of nano-CuO-loaded PVA composite films with enhanced optomechanical properties. *Polym. Bull.* **2021**, *78*, 1551–1571, <https://doi.org/10.1007/s00289-020-03173-9>.
- [19] Dahiya, P.K.; Linnemann, A.R.; Van Boekel, M.A.J.S.; Khetarpaul, N.; Grewal, R.B.; Nout, M.J.R. Mung bean: Technological and nutritional potential. *Crit. Rev. Food Sci. Nutr.* **2015**, *55*, 670–688, <https://doi.org/10.1080/10408398.2012.671202>.
- [20] Enyiukwu, D.N.; Chukwu, L.A.; Bassey, I.N. Nutrient and anti-nutrient compositions of cowpea (*Vigna unguiculata*) and mung bean (*Vigna radiata*) seeds grown in humid Southeast Nigeria: A comparison. *Trop. Drylands* **2020**, *4*, 41–45, <https://doi.org/10.13057/tropdrylands/t040202>.

- [21] Chozhanathmisra, M.; Murugesan, L.; Murugesan, A.; Palanisamy, G.; Rajavel, R. Enhancement on physical, chemical, and biological properties of HNT-PVA-ALG-HAp biocomposite coating on implant substrate for biomedical application. *Ceram. Int.* **2022**, *48*, 16868–16876, <https://doi.org/10.1016/j.ceramint.2022.02.241>.
- [22] Zhang, Y.; Dai, Y.; Yu, K.; Wang, L.; Ding, X.; Hou, H.; Wang, W.; Zhang, H.; Li, X.; Dong, H. Mechanochemical effects of ultrasound on mung bean starch and its octenyl succinic anhydride modified starch. *J. Food Meas. Charact.* **2020**, *14*, 1261–1272, <https://doi.org/10.1007/s11694-020-00374-8>.
- [23] Zhang, X.; Tang, N.; Jia, X.; Geng, D.; Cheng, Y. Multi-Scale Comparison of Physicochemical Properties, Refined Structures, and Gel Characteristics of a Novel Native Wild Pea Starch with Commercial Pea and Mung Bean Starch. *Foods* **2023**, *12*, 2513, <https://doi.org/10.3390/foods12132513>.
- [24] Harpaz, D.; Axelrod, T.; Yitian, A.L.; Eltzov, E.; Marks, R.S.; Tok, A.I.Y. Dissolvable Polyvinyl-Alcohol Film, a Time-Barrier to Modulate Sample Flow in a 3D-Printed Holder for Capillary Flow Paper Diagnostics. *Materials* **2019**, *12*, 343, <https://doi.org/10.3390/ma12030343>.
- [25] Tsiptsias, C.; Fardis, D.; Ntampou, X.; Tsivintzelis, I.; Panayiotou, C. Thermal Behavior of Poly(vinyl alcohol) in the Form of Physically Crosslinked Film. *Polymers* **2023**, *15*, 1843, <https://doi.org/10.3390/polym15081843>.
- [26] Asy-Syifa, N.; Kusjuriansah; Waresindo, W.X.; Edikresnha, D.; Suciati, T.; Khairurrijal. The Study of the Swelling Degree of the PVA Hydrogel with varying concentrations of PVA. *J. Phys.: Conf. Ser.* **2022**, *2243*, 012053, <https://doi.org/10.1088/1742-6596/2243/1/012053>.
- [27] El-Hefian, E.A.; Nasef, M.M.; Yahaya, A.H. The preparation and characterization of Chitosan/Poly(Vinyl Alcohol) blended films. *J. Chem.* **2010**, *7*, 626235, <https://doi.org/10.1155/2010/626235>.
- [28] Pop, L.M.; Mihaly Cozmuta, A.; Nicula, C.; Mihaly Cozmuta, L.; Peter, A. Attempts to Obtain Material Based on Polyvinyl Alcohol with Barrier Properties against Water Vapor. *Appl. Sci.* **2024**, *14*, 4310, <https://doi.org/10.3390/app14104310>.
- [29] Ma, L.; Zhu, Y.; Huang, Y.; Zhang, L.; Wang, Z. Strong water-resistant, UV-blocking cellulose/glucomannan/lignin composite films inspired by natural LCC bonds. *Carbohydr. Polym.* **2022**, *281*, 119083, <https://doi.org/10.1016/j.carbpol.2021.119083>.
- [30] Liu, Y.; Zhu, X.; Liu, S.; Cheng, H.; Ji, W.; Lin, B.; Yi, C. Physico-chemical properties, adsorption capacity and anti-oxidization of lignin and cellulose separated from mung bean skin by deep eutectic solvent treatment. *J. Sci. Food Agric.* **2025**, *105*, 8836–8843, <https://doi.org/10.1002/jsfa.70123>.