WHEAT STRAW AND SEAWEED *FURCELLARIA LUMBRICALIS* – DERIVED CARRAGEENAN BIOCOMPOSITE CHARACTERISTICS: CASE STUDY

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Abstract. This study provides an in-depth analysis of the properties of a novel biocomposite synthesized from wheat straw and carrageenan obtained from the seaweed *Furcellaria lumbricalis*. Mainly focusing on the evaluation of the properties of this biocomposite, the study explores its possible applications in the field of biodegradable products. The combination of wheat straw and carrageenan is not only an environmentally friendly and sustainable alternative but also takes advantage of the unique properties of these natural materials. The investigation includes a comprehensive examination of the biocomposite structural, mechanical, and biodegradation properties, including moisture and UV effects. The structural integrity and mechanical strength of the material are evaluated to ensure its suitability for various applications. In addition, biodegradability properties are scrutinized to assess environmental impact and potential contribution to sustainability. The results of this study provide valuable insight into the promising applications of wheat straw and carrageenan biocomposite in the development of environmentally friendly products. As the world increasingly looks for sustainable alternatives, this research contributes to the development of the field of green materials. The use of abundant and renewable resources in biocomposite synthesis complies with circular economy principles and environmental responsibility. In conclusion, wheat straw and *Furcellaria lumbricalis*-derived carrageenan biocomposite is a promising candidate for use in biodegradable products, showing their potential to promote development of sustainable materials. A comprehensive study of its properties is the basis for further research and application in various industries committed to environmental stewardship.

Keywords: biocomposite, biodegradability, structural properties.

Introduction

The utilization of peat in agriculture, a widely adopted material in recent decades, has emerged as a significant point of discussion concerning its impact on climate change and sustainable resource management [1]. Peat, a popular choice for soil improvement and seedling cultivation, especially in the production of plant pots, is harvested from peatlands - ecosystems that act as substantial carbon dioxide (CO2) sinks. Its exploitation not only contributes to greenhouse gas emissions but also threatens biodiversity and ecosystem services vital to our planet's well-being [2].

The European Union (EU) has assumed a leadership role in the fight against climate change, adopting a suite of policies and targets aimed at reducing carbon emissions and promoting sustainable resource use. This includes initiatives and regulations that limit the use of peat in agriculture, encouraging the search and adoption of alternative materials that are more environmentally friendly [3-5].

This study aims to explore the necessity of reducing peat usage in agriculture, particularly in the production of plant pots, considering its impact on the carbon footprint and compliance with the EU policy directions. It will examine the potential of alternative peat materials, their economic, ecological, and social aspects, as well as investigate possible obstacles and challenges associated with their broader implementation in practice.

Recently, there have been studies on the development of seedling pots from cattle manure and wood residues [6], discarded textiles and paper waste [7], various biopolymers [8, 9], and other biodegradable materials [10]. The availability of local raw materials largely determines the study of processing and material composition, processing technologies and mechanisms to be used. The demand for energy resources plays an important role in ensuring the technological process.

The study emphasizes the application of admixtures of wheat straw and seaweed *Furcellaria lumbricalis* composite with or without waste paper in the development of seedling pots with a focus on biodegradation of the composite under the influence of moisture and UV radiation - the main degrading factors [11-13]. The availability of local renewable materials, processing technology, and the possibility of using existing equipment determine the sustainability of the solution and provide an opportunity to reduce the use of peat under EU requirements.

Materials and methods

For the experiments, two sets of samples comprising the prepared materials were generated: one set remained unirradiated, while the other underwent treatment in an ultraviolet ray chamber emitting near ultraviolet rays (NUV). Each set comprised straw-carrageenan composite material and straw-waste paper-carrageenan composite material, with five strips of each material. The thickness of all specimens was maintained at 3-5 mm, with a slight variation in the width ranging from 20-25 mm, and a length of approximately 100 mm. The UV processing step was vital as it served to simulate the effects of solar radiation on the materials, replicating real-world environmental conditions. Exposure to near ultraviolet rays (NUV) is known to induce chemical changes in certain materials, potentially altering their mechanical properties. Understanding these effects is crucial for assessing the durability and performance of the materials in outdoor or sunlight-exposed applications.

Mechanical testing involved subjecting the samples to tensile stress, with force measurement. Clamps were affixed to both ends of the samples: one end secured to a fixed wall while a dynamometer was attached to the other end for force measurement. Due to slight variations in the sample width, results were normalized to a standard width unit of one meter.

After the mechanical strength tests, the microscopic structure of the composition was investigated, both for the straw-carrageenan composite and for the material with added waste paper, which generally fills the fine gaps and increases the contact area. It was studied using scanning electron microscope (SEM) and optical microscope images, paying special attention to the contact angle created by the adhesive-carrageenan with the structuring material - straw, and the quality of the connection. As in the mechanical tests, a 22-day strong UV exposure was performed on the created composition (see the section "Mechanical strength tests"). In all cases, the microscopic material structure was compared with the macroscopic parameters in the optical microscope images and the visible properties of the product.

Results and discussion

Mechanical strength tests

The force dynamometer was used to measure the tearing force required for two distinct sets of materials. The first material consisted of a combination of wheat straw and carrageenan derived from *Furcellaria lumbricalis*. The second material was composed of paper pulp mixed with wheat straw and carrageenan extracted from *Furcellaria lumbricalis*.

Two sets of each sample were produced, the first set consisted of samples that had not been exposed to near-ultraviolet light (NUV) light and the second set that had been exposed to near-ultraviolet light at 405nm. From the first set, five samples were collected for each material mix. Following this, the dynamometer was securely fastened. A clamp was then attached to the end of the dynamometer to hold the prepared specimens. Their width varied from 23 mm to 33 mm; the breaking force was measured with a dynamometer. To ensure that the samples are pulled with equal tension, a secondary clamp is attached to the other end of the sample. Each measurement was repeated five times with a new sample each time, statistical calculations were performed, and the average result was normalized to the width of one unit (one meter). Thus, the results shown in Table 1 were obtained.

Table 1

Tensile forces applied to material samples, $N \cdot m^{-1}$, accuracy ± 4 $N \cdot m^{-1}$

No.	Force applied to wheat and carrageenan, $N \cdot m^{-1}$	Force applied to wheat and carrageenan exposed to NUV, $N \cdot m^{-1}$	Force applied to wheat/paper pulp and carrageenan, $N \cdot m^{-1}$	Force applied to wheat/paper pulp and carrageenan exposed to NUV, $N \cdot m^{-1}$
1.	183	240	260	227
2.	204	156	326	232
3.	296	203	292	178
4.	328	196	341	257
5.	228	153	280	133
average	**231,8**	**189,6**	**299,8**	**205,4**

In the table, a significant decrease in the mechanical strength of NUV-exposed samples can be observed. In the first group of tests (straw and carrageen mix) the difference is 22%, while in the second group (straw, waste paper and carrageen mix) the difference is 46%, which indicates biodegradation under the influence of NUV. Tensile tests provide a view of mechanical strength in general. It manifests itself in the material resistance to compression, bending, tilting and other deformation. In the case of finished products, they are the ability to maintain not only form and functionality, but also market appearance and suitability for sale under the influence of loading, transportation, storage and other logistics operations.

Study of biodegradability under the influence of near UV

Biodegradability under the influence of moisture and UV rays was chosen because they are the main methods of destructive influence of organic materials - the first in the soil (microbiological effects are not studied here), the second - sunlight, especially the near-UV spectrum in open air conditions. The microscopic properties of the material composite visible in the scanning electron microscope (SEM) images (Fig. 1-3, 5, 6) – sticking, adhesion, contact angle, and its changes after treatment with near-UV radiation – result in the macroscopic material (Fig. 4) – a seedling pot made according to the technology discussed in [14; 15].

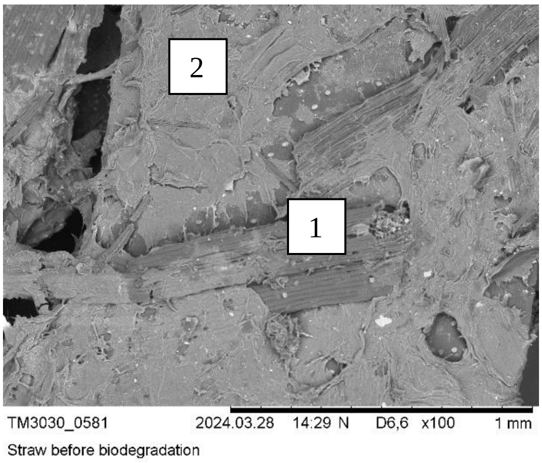

Fig. 1. **SEM image – straw glued with carrageenan before degradation:** 1 – wheat straw; 2 – carrageenan; magnification 100x, tabletop microscope HITACHI TM3030

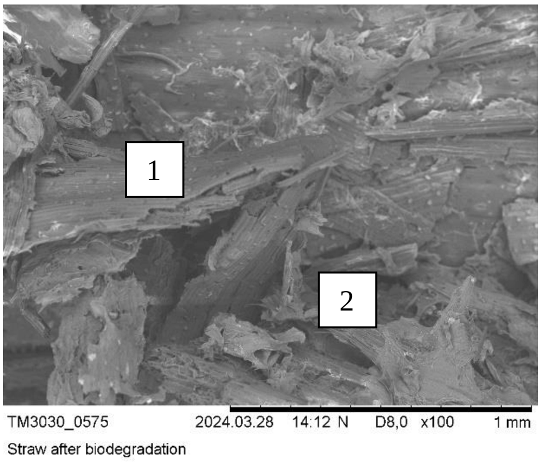

Fig. 2. **SEM image – straw with carrageenan after degradation by near-UV radiation (λ = 405 nm):** 1 – wheat straw with a damaged surface; 2 – carrageenan damaged and detached, magnification 100x, tabletop microscope HITACHI TM3030

Moreover, higher magnification images reveal intricate details of the straw and the binder-carrageenan composite structure. Following drying, carrageenan demonstrates strong adhesion to the straw, establishing a substantial surface contact area. Empirical evidence suggests that the drying mechanism remains consistent across both natural and forced drying scenarios. Initially, moisture separates from the outer surface, ensuring extensive contact with the straw fibers. This consistent drying process contributes to the cohesion and integrity of the composite materials. The binder carrageenan does not flow, but retains dry organic matter between the straw fibers, maintaining a large contact area, which results in good adhesion.

The contact angle of the compound in the places marked with an arrow (Fig. 3) is close to 180°. This is proof of good hydrophilic properties, which form high adhesion after drying. As a result, the developed material has high mechanical strength; things made of it, such as seedling pots, seedboxes, etc., can be safely stored, transported, and used in field and greenhouse conditions.

Reducing the contact angle of carrageenan and straw pulp and thus increasing the mechanical strength of the composite does not require surface-active substances, thus the cost of preparing the material and the presence of chemicals in the product do not increase. The maximum use of natural raw materials opens possibilities for the use of the product in agriculture.

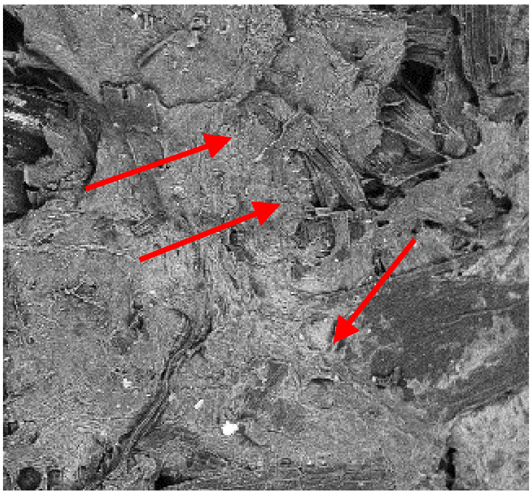

Fig. 3. **SEM image – straw glued with carrageenan before degradation. The contact angle of the composite joint in the arrowed locations is close to 0,** magnification 400x, tabletop microscope HITACHI TM3030

Fig. 4. **Finished product – seedling pot. A rough surface of the walls can be observed under the influence of moisture and visible light, the straw-carrageenan composite easily decomposes in contact with the soil**

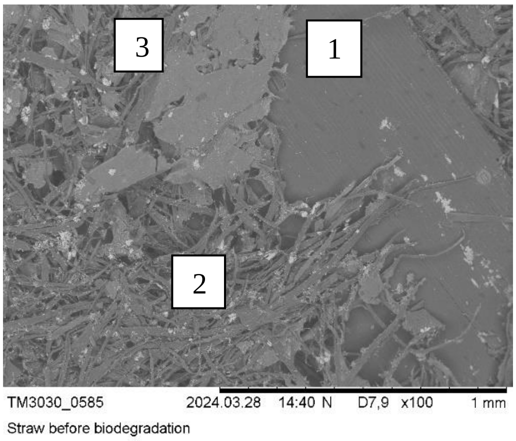

Fig. 5. **SEM image – straw and waste paper glued with carrageenan before degradation:** 1 – wheat straw; 2 – waste paper; 3 – carrageenan; magnification 100x, tabletop microscope HITACHI TM3030

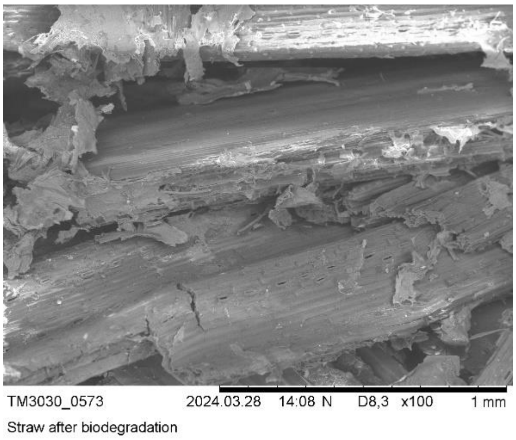

Fig. 6. **SEM image – damaged composite of straw, waste paper, and carrageenan after degradation by near-UV radiation (λ = 405 nm),** magnification 100x, tabletop microscope HITACHI TM3030

The observed SEM images correlate well with the surface roughness assessment of the finished product before and after aging (degradation) procedures in UV rays. Small-sized (2 cm x 6 cm) samples of the straw-carrageenan and straw-carrageenan-paper composite were fabricated, and the surface roughness was compared by random measurements with a micrometer. The breakdown of carrageenan, the increase in the angle of contact with the straw, and structural damage after UV radiation (Fig. 5, 6) lead to the release of the glued straw sections and partial separations, which is facilitated by the flexibility of the straw material and the fractional size. After degradation, straw particles are easily separated because of external effects (friction, pressure, and other mechanical effects). The breakdown of carrageenan can be observed well in Fig. 6, where there is a decrease in the contact area and straw bonding.

The straw pulp was mixed with purified carrageenan derived from the seaweed *Furcellaria lumbricalis*, pressed into an appropriate matrix-poison system, and dried. The initially smooth surface (Fig. 7), after drying in natural/room/greenhouse conditions, acquired a roughness of 2-3 mm (Fig. 8) within 3-4 weeks, confirming the results of laboratory examinations.

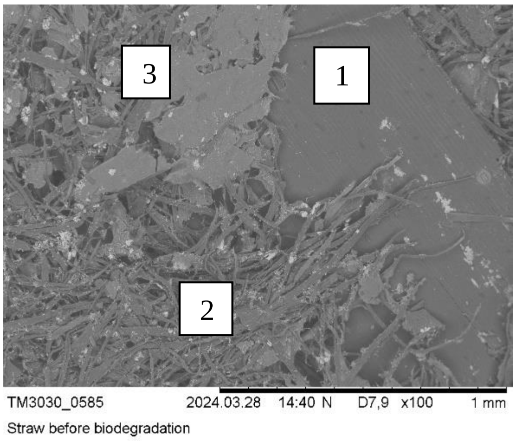

Fig. 5. **SEM image – straw and waste paper glued with carrageenan before degradation:** 1 – wheat straw; 2 – waste paper; 3 –carrageenan, magnification 100x, tabletop microscope HITACHI TM3030

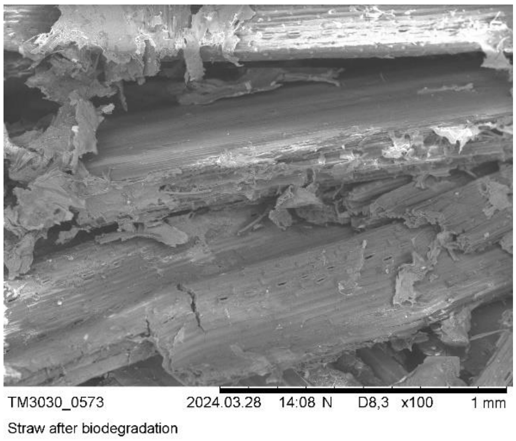

Fig. 6. **SEM image – damaged composite of straw, waste paper, and carrageenan after degradation by near-UV radiation (λ = 405 nm),** magnification 100x, tabletop microscope HITACHI TM3030

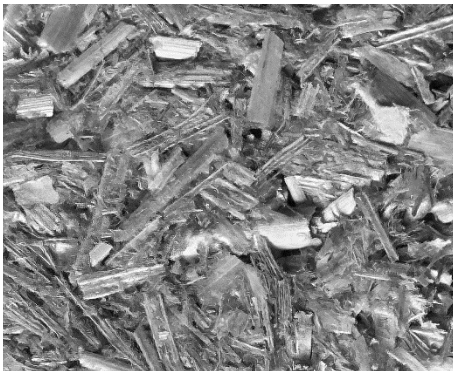

Fig. 7. **Optical microscope image – straw and carrageenan composite before degradation - surface roughness on average 1-1.5 mm, no significant voids between straws,** microscope ZEISS Primo Star, grayscale, magnification 20x

Fig. 8. **Optical microscope image – straw and carrageenan composite after degradation with near-UV radiation (λ = 405 nm): – surface roughness on average 2-3 mm, there are significant voids between the straws,** microscope ZEISS Primo Star, grayscale, magnification 20x

Conclusions

1. Straw-carrageenan composite is a good alternative to peat applications in the fabrication of seedling pots and other agriculturally useful products.
2. The straw-carrageenan composite has good mechanical strength properties that facilitate product logistics.
3. Straw-carrageenan composite easily degrades under the influence of moisture and UV radiation.

Author contributions

Conceptualization, U.Z.; methodology, S.O. and U.Z.; software, A.K.; validation, U.Z. and S.O; formal analysis, S.O writing – original draft preparation, U.Z. and A.K.; writing – review and editing, U.Z. and A.K.; visualization, U.Z.; project administration, U.Z. All authors have read and agreed to the published version of the manuscript.

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