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SUPERIOR CAPITALIZATION OF VEGETABLE WASTE AND NATURAL AGRO-INDUSTRIAL BY-PRODUCTS BY CREATING INNOVATIVE PRODUCTS FOR CONSTRUCTION. SOCIO-ECONOMIC PREDICTIVE ANALYSES

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Abstract

To ensure environmental preservation, it is increasingly necessary to capitalize on waste, both from agriculture and related industries. There is currently research at the worldwide level on the capitalizing of vegetable waste and natural agro-industrial by-products in the field of construction, to obtain innovative materials, which can replace traditional materials. The capitalization of waste ensures not only the reduction of the impact on the environment due to their recovery but also the possibility of cost efficiency compared to the use of traditional materials. Waste recovery is a priority component of sustainable development, aiming to create the conditions for ensuring the well-being of countries and their citizens and implementing global measures to manage natural resources. In this context, our studies focused on determining the economic efficiency of innovative materials, obtained by capitalization of some types of vegetal waste, being necessary to perform a comparative cost analysis. The acquisition costs related to innovative, environmentally friendly materials and those traditionally used in construction were considered, as well as the costs during their use, respectively the maintenance and repair costs.

Key words: *agro-industrial by-products, predictive analyses, sustainable development, waste capitalization.*

INTRODUCTION

The construction industry, one of the largest consumers of raw materials and energy worldwide and one of the significant sources of global greenhouse gas emissions and waste generation, has led to an increase in demand for new sustainable and environmentally friendly construction solutions. As a result, there is an increasing interest in exploring alternative materials and methods, aiming for the sustainable development of the built environment, while maintaining its structural integrity and functionality, under the conditions of reducing the ecological footprint specific to the field. Also, the negative impact on the environment is recognized because of the improper disposal of waste and even of the agro-industrial by-products.

These aspects end up representing a risk to the ecosystem and human health, causing air and water pollution, soil degradation, loss of biodiversity, and finally the irrational use of resources, given the fact that the respective materials often contain nutrients and valuable materials that could be reused or recycled. Thus, in general, the improper disposal of waste and agro-industrial by-products has become a waste of resources and a missed opportunity to use them for alternative, value-generating purposes, such as energy production or the creation of new, sustainable construction materials/products (Bakatovich et al., 2018; Binici et al., 2020; Cintura et al., 2021; Fuentes et al., 2021; Yaashikaa et al., 2022).

In this approach, vegetable waste and natural agro-industrial by-products (Popa et al., 2023) represent a notable category in terms of the benefits resulting from their superior valorization. Natural materials like straw, cereal husks, hemp, and low-quality sheep wool are often underutilized waste products from agricultural and industrial processes. By harnessing the potential of these materials for sustainable construction applications it is possible to avoid sending waste to landfills, reduce emissions associated with traditional construction materials and thus contributing to the development of the circular economy (Cintura et al., 2021).

Current research trends in the field of sustainable construction emphasize the use of natural materials in the development of environmentally friendly construction products. These types of materials offer numerous advantages, including low environmental impact, low energy demand, cost-effectiveness, large-scale availability, biodegradability, low density, and good thermal insulating and mechanical properties (Faruk et al., 2012; Berardi & Iannace, 2015; Sanjay et al., 2018, Nguyen et al., 2020; Popa et al., 2020).

The agricultural and industrial sectors generate large amounts of biodegradable waste which, in the absence of an effective management and without reducing waste production (Bonciu et al., 2021), if not properly collected and utilized, can cause significant damage to the environment and the health of the population. Although currently a way of recycling waste from the two sectors is represented by using it as organic fertilizers, in the short and medium term, the main option for managing biodegradable waste will be the storage, the objective being to promote ways of higher recovery, for example in the construction sector (Șalaru et al., 2013).

Considering the fact that the prevention of waste formation as well as the negative effects caused to the environment and health is much more effective than removing the consequences after they have occurred, by ensuring alignment with European practices of avoiding as much as possible final disposal solutions through storage or incineration, in the long term, the general objective is to find new ways of superior valorizing agro-industrial waste and to replace the permanent storage with a temporary one (Şalaru et al., 2013).

The recycling of agricultural waste can be viewed in terms of three large categories of benefits: social, economic and ecological (Yazid et al., 2020).

The socio-economic (Nath, 2022) and environmental benefits (Omer, 2010) generated by the superior valorization of vegetable waste and natural agro-industrial by-products are multiple:

- The most important benefit is represented by the reduction of the quantity in which these materials are generated and/or stored. When they are used, they are considered and thus transformed into raw materials for local industries, also raising the degree of local employment (Omer, 2010). By reintegrating them into the economic circuit, a reduction in the consumption of traditional raw materials is achieved, which leads to the conservation of natural resources necessary for production processes, resources obtained by using large amounts of energy. Therefore, recycling reduces energy consumption (Lamma, 2021) and negative effects that occur on the environment integrity (Omer, 2010) and society strong health (Lamma, 2021).
- Waste recycling decreases the need for new raw materials, saving a significant amount of energy in this way. By recycling waste, the energy-consuming industrial activities (Bonciu et al., 2021), the emission of greenhouse gases are mitigated, thus contributing to the reduction of global warming (Lamma, 2021);
- As an essential part of the circular economy, waste recycling leads to the promotion of new industrial processes and ecological products (Nath, 2022), determining the development of new companies, implicitly increasing and diversifying employment opportunities.
- Waste recycling aims to reduce the need for waste deposits and directly lower their volume (Mubaslat, 2021), with beneficial effects on the environmental costs (Halcos & Petrou, 2016) and the health of the population. As a result, on the one hand, it ensures the reduction of costs associated with the uncontrolled disposal of waste (Halcos & Petrou, 2016) and on the other hand, an increased availability of free land is obtained, land that can be used for economic purposes with benefits at the level of entire society (Mubaslat, 2021).

From an ecological and social point of view, an important benefit of recycling is represented by the reduction of the amount of waste sent for incineration, a process that affects the quality of the surrounding air. Referring to the use of vegetable waste and natural agro-industrial by-products by integrating them into different materials/innovative products for constructions, it is becoming increasingly recognized that this approach brings substantial benefits resulting from the specific properties of each natural material.

Agricultural activities generate substantial amounts of valuable waste/by-products, from various sectors:
- The crop sector - such as straw, husks, different types of fibers, substrates in the case of mushroom farms, etc.;
- The livestock sector - such as manure and low-quality wool;
- The agro-industrial processes - such as sunflower seed husks from the edible oil industry, rice husks (RH) from the food industry, etc.

Thus, for example, the use of agro-industrial waste such as rice husks can lead to obtaining new construction materials with good thermal insulation capacity, low moisture content and high thermal power.

The socio-economic benefits of using rice husks are obtained by integrating this material into concrete products, as well as by generating additional income from the sale of rice husk ash and its use as fuel in thermoelectric plants (Nwofoke & Udu, 2019). Also, agro-industrial waste from rice husks can be used in the production of building materials for partitions, such as bricks, ecological products with phono-thermo insulating properties, low weight, low transport costs due to reduced weight of products etc. (Chukwudebelu et al., 2015).

In another example, it is shown that ecological building materials, obtained by integrating vegetable waste generated by industrial hemp crops, offer more benefits than traditional materials: durability and light weight, fire resistance, impermeability, moisture, strength, self-insulation, pest resistance and low production costs.

In addition, building materials obtained from hemp (Crini et al., 2020) can capture carbon dioxide, leading to the reduction of carbon emissions (Mausum, 2022), being ideal for protecting the environment.

The increase in the production and consumption of bio-waste worldwide represents a significant challenge for waste management and resource use. In general, but especially for the field of construction materials/products, this challenge also offers an opportunity to transform vegetable waste and natural agro-industrial by-products into valuable resources to produce natural composites.

MATERIALS AND METHODS

The previously specified socio-economic and ecological benefits from a theoretical point of view, regarding the valorization of natural waste and natural agro-industrial by-products in construction, as well as the analysis and quantification of the economic benefits of the valorization of hemp and rice husk waste are presented below.

Determining the economic efficiency of the innovative products, obtained by capitalizing on some types of vegetable waste, requires a comparative analysis of costs. Cost analyses related to construction materials must be carried out in the initial phases of product development so that, during the design of the material, certain changes can be made to obtain an optimal cost.

Starting from the existing regulations in the field of cost estimation for construction works (GD no.907/2016; P91/1-02), after assimilating them from a methodological point of view for determining the economic efficiency of an innovative construction product, the cost estimate for its production can be determined by going through the following stages:
- Estimation of the necessary resources (materials, labor, machinery, transport) for the creation of innovative eco-sustainable products;
- Determination of specific consumption for each considered resource;
- Collection of unit prices at the level of component resources;
- Estimating the cost of the innovative product by aggregating the costs based on multiplying the unit prices with the specific consumptions;
- Carrying out a comparative cost analysis between the innovative product and the traditional product.

Similarly, by extrapolating the Life Cycle Cost (LCC) methodology for estimating the costs during the lifetime of constructions (COSTCONS), it was considered that the cost efficiency of the ecological product can also be quantified through the life cycle cost analysis of the resulting product, to determine its feasibility.

The analysis involved the treatment of cost aspects considering the whole lifetime of the innovative product, the results being determined mainly by the properties of the component materials considered, the durability of the resulting product and the related costs for manufacturing/repairs/replacements.

The costs involved during the lifetime of the innovative product can be defined as follows:

- The initial acquisition costs - the costs related to the raw materials necessary for the creation of the innovative product;
- Costs for manufacturing the innovative product (e.g. labor, machinery, transport);
- Installing costs - the costs of putting the product into place, estimated on the basis of similar works or by own estimates; if the commissioning allows a selection of the technology based on cost efficiency, the cost optimization will be pursued by ensuring the quality of the works;
- Operating costs - all the costs related to checking and maintaining the product during its use (current and capital repairs);
- Replacement costs - costs resulting from replacing the product.

The lifetime cost expresses the totality of the costs that occur during the use of the analyzed innovative product. Different values of this type of cost for the resulting products, depending on the substitute materials analyzed, can lead to decisions regarding the optimization of costs during the lifetime of use, by selecting the products that present a minimum cost of use during the lifetime.

By summing up the costs related to the acquisition, manufacturing, installation, operation, repair and replacement activities, the total cost over the lifetime of the considered innovative product will be obtained.

RESULTS AND DISCUSSIONS

There is a worldwide interest of the researchers to create, study and promote construction materials/products characterized by comparable properties with those made up of traditional materials, based on synthetic raw materials.

At the international level, many technologies and processes are currently being explored for the valorization of vegetable waste and natural agro-industrial by-products and there are still in the research and development stage.

Considering a first example of the utilization of rice husks in construction, by integrating them into the composition of ecological concrete mixtures (Winarno, 2019), it is found that the strength of the ecological concrete blocks and the resulting costs vary with the proportions of the components of the mixtures, especially with the proportions of cement/rice husks related to the variants of the mixes (Table 1).

Table 1. Overall cost (Indonesian Rupiah, R_p) for 1 m^3 of concrete mixture

Mix	% RH to PC	Proportions by weight, kg			Strength kg/cm^2	Cost of 1 m^3 of mix, Rp
		PC	Filler	RH		
V1	67	637	159.25	425.35	19.44	784.40
V2	89	528	132.00	470.09	19.02	662.10
V3	110	451	112.75	501.92	18.61	575.71
V4	134	394	98.50	526.18	17.59	511.81
V5	156	349	87.25	543.76	14.38	461.26
V6	178	314	78.50	559.12	11.51	422.05

Analyzing the data in Table 1 for each of the 6 variants of mixtures V1 to V6, can be noted that, by using the rice husks (RH), the cost of the obtained materials decreased, compared to the initial cost (890 R_p/m^3). The cost reductions are between 11.86% and 52.58% depending on the percentage content of husks in the composition of the concrete blocks.

The most efficient variant is V4 (Winarno, 2019), for which optimal cost values are obtained, a 42.5% reduction compared to the traditional concrete block, respectively 890 R_p/m^3, with the fulfillment of the resistance standards (Figure 1).

Considering a second example of the valorization of rice husks, this time through the integration of rice husks ash in two road structures (Hossain et al., 2018), the economic efficiency of modified rigid and flexible road structures which contain RHA (rice hull ash) is presented, compared to conventional structure, efficiency assessed through a Life Cycle Cost Analysis (LCCA).

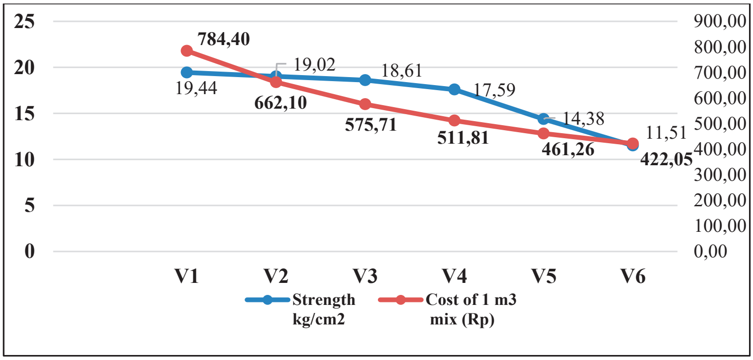


Figure 1. Compressive strength (at 28 days) and cost gained for different percentage of RH

The following scenarios were considered for the LCCA calculation:
- The use of unmodified conventional asphalt mixture (binder) for the realization of the flexible road structure;
- The use of RHA modified asphalt mixture (binder) for the realization of the flexible road structure;
- The use of ordinary unmodified concrete for the realization of the rigid road structure;
- The use of RHA modified concrete for the realization of the rigid road structure (Table 2).

In the analysis, the obtained results are detailed in percentage form (processing data from Hossain et al., 2018) for the four variants considered (Figure 2).

Table 2. Present cost ($/mile) for different pavements

	Initial cost	Resurfacing and structural overlays cost	Recurring maintenance cost	Total cost ($/mile)
Unmodified Asphalt binder	3,330,845	1,459,982	566,264	5,357,091
RHA-Modified Asphalt binder	3,330,845	918,405	436,605	4,685,855
Unmodified Rigid pavement	3,326,079	1,797,108	730,857	5,854,044
RHA-Modified Rigid pavement	3,150,079	1,042,860	365,428	4,558,367

The results indicated that, for the rigid road structure, the initial installing costs, in the case of using the eco-material, are reduced by 5%, the costs for capital repairs by 42%, and the costs for current repairs by 50%, the total cost for the duration of use being 22% lower compared to the traditional version.

For the flexible road structure, the initial installation costs do not show differences, the costs for capital repairs are reduced by 37% in the case of using the asphalt mixture containing RHA, and for current repairs, a lower cost was obtained by 23%. A 13% reduction was obtained for the total cost during the period of use.

Cost analysis is also presented for the materials used in the two constructive variants considered, rigid structure and flexible structure respectively (Hossain et al., 2018).

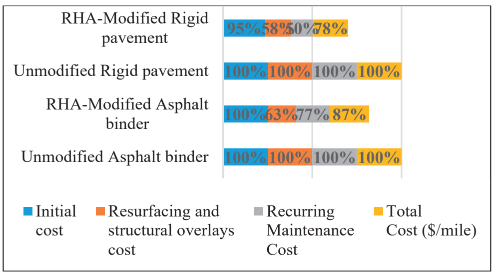


Figure 2. Comparative percentage analysis for the variants considered

For the version with a rigid structure, the cost of the eco-material is 10% lower compared to the use of the traditional product (Table 3), and for the flexible structure, the necessary costs of installing with the ecological material show a reduction of 46% (Table 4).

Table 3. Cost of cementitious material for 5-mile road construction

Types of Rigid Pavement	Required Cement (Ton)	Unit Price ($/Ton)	Total Cost ($)
Unmodified	4,921	113	556,073
RHA-modified	4,428	113	500,364

Table 4. Cost of asphalt binder for 5-mile road construction

Types of Flexible Pavement	Required Cement (Ton)	Unit Price ($/Ton)	Total Cost ($)
Unmodified	1,148	901	1,034,348
RHA-modified	1,148	485	556,780

Natural agro-industrial by-products can also be used for other purposes, such for example as solid fuel, in the form of fertilizer for agricultural land or in the livestock industry, the data presented below being the authors' estimates within the research.

If we refer to rice husks and industrial hemp, as natural by-products, in a comparative presentation of the total costs resulting from their recovery (Figure 3), a higher cost is noted for the recovery of the husk, of 561.87 lei/t, the lower cost being obtained for the valorization of the two natural by-products as fertilizers. Comparable costs were obtained to produce hemp-based briquettes, 455.35 lei/t and for the use of husks as bedding in the livestock industry, namely 418.39 lei/t.

Similarly, the total costs for the final disposal of vegetable waste (Figure 4) indicated that, for the final disposal by incineration, the costs are higher compared to the final disposal in ecological deposits, namely 299.50 lei/t compared to 237.13 lei/t.

For all cost categories, regarding the share of direct costs per resource category in the total cost, the highest values were obtained in the "Equipment" chapter, with shares between 50.48% and 88.83% in the total cost, and the lowest for the “Transport” chapter, with weights between 1.87% and 3.56% (Figure 5).

The presented analyzes aimed to estimate the costs regarding the valorization and disposal of vegetable waste and natural agro-industrial by-products. In this sense, the costs for the related resources (materials, labor, equipment, transport) were determined for each option.

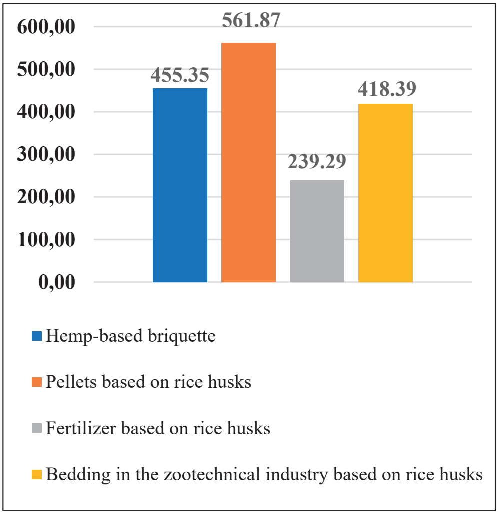


Figure 3. Total costs regarding the capitalization of natural agro-industrial by-products (lei/t)

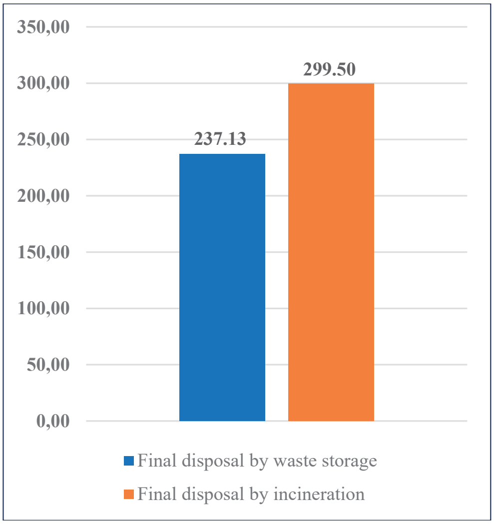
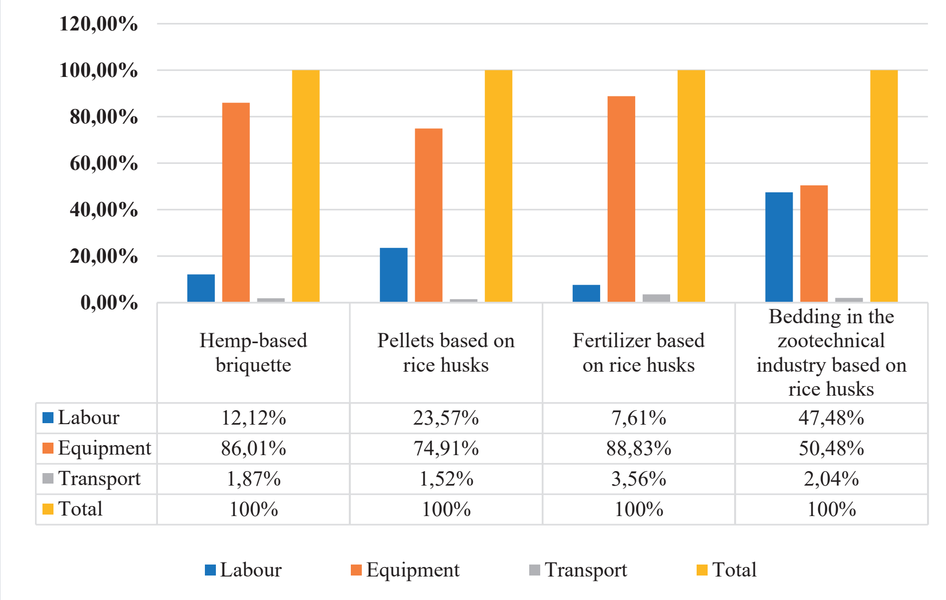


Figure 4. Total costs regarding the final disposal of vegetable waste (lei/t)



	Hemp-based briquette	Pellets based on rice husks	Fertilizer based on rice husks	Bedding in the zootechnical industry based on rice husks
Labour	12,12%	23,57%	7,61%	47,48%
Equipment	86,01%	74,91%	88,83%	50,48%
Transport	1,87%	1,52%	3,56%	2,04%
Total	100%	100%	100%	100%

Figure 5. Analysis of direct costs for resources used regarding the capitalization of natural agro-industrial by-products (%)

Based on the results of the analysis, the necessity and opportunity of vegetable waste and natural agro-industrial by-products recovery can be confirmed. This is a process that presents benefits not only from a social but also from an economic point of view compared to disposal processes.

CONCLUSIONS

Generally, the main objectives regarding de management of agro-industrial solid wastes are to protect the health of the population, the environment and to conserve natural resources through waste reduction policies, i.e recycling, valorization, or composting.
Capitalizing vegetable wastes and natural agro-industrial by-products offers a promising path for sustainable development, transforming potential waste into valuable resources by respecting the principles of the circular economy.
Minimizing the generation of agro-industrial waste implies reducing their quantities, regardless of the source of production and the type of waste.
Preventing the formation of waste and the negative effects caused to the environment and health is much more effective than removing the consequences after they have occurred.
The recycling of vegetable waste and natural agro-industrial by-products can generate numerous benefits, social, economic, and ecological ones.
The capitalization of waste and natural agro-industrial by-products in the construction sector contributes to the reduction or even to the substitution of the energy-consuming and polluting production of traditional construction materials, having a significant impact in reducing the negative effects on the environment, the innovative products obtained within the circular economy contributing to sustainable development of the built environment.

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