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"Zero-Waste" Food Production System Supporting the Synergic Interaction between Aquaculture and Horticulture

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Abstract: Inadequate production practices are widely used in aquaculture management, causing excessive water and energy usage, as well as ecological damage. New approaches to sustainable aquaculture attempt to increase production efficiency, while reducing the quantities generated of wastewater and sludge. The sustainable operating techniques are often ineffective, expensive, and difficult to implement. The present article proposes a zero-waste production system, designed for growing fish and vegetables, using a new circular operational concept that creates synergies between fish farming and horticulture. In order to optimize the operational flows with resources, products, and wastes in an integrated zero-waste food production cluster, a business model was designed associating three ecological production practices: a closed fishing pond, a technology for growing vegetables in straw bales, and a composting system. The design had the role to assist the transition toward multiple circular material flows, where the waste can be fully reintegrated into the production processes. A comparative evaluation was conducted in three alternative growing environments, namely, a soilless culture established in straw bales, a culture grown in soil that had received compost fertilizer, and the conventional farming technique. When compared to conventional methods, experiments showed a significant increase in the cluster's cumulative productivity, resulting in a 12% improvement in energy efficiency, 18% increase in food production, and 25% decrease in operating expenses.

Keywords: zero-waste food production; organic farming; straw bales vegetables; sustainable aquaculture

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1. Introduction

Sustainable exploitation of fisheries and water resources is an approach that calls for a collective effort to preserve the aquatic environment, one of the primary drivers for global development [1]. Effective fish waste valorization is a circular economy key goal that promises to provide new and sustainable alternatives to minimize pollution from aquaculture management. The demand for fish products has increased significantly in the last years [2]. As a result, this sector registers a constant growth for the natural resources needed for aquaculture development, as well as an intensification of the inputs being used (particularly feeder), which automatically leads to an exponential increase in the amount of generated waste [3].

The goal of the present research is to provide farmers with an efficient tool for producing fish and ecological vegetables in a sustainable and efficient manner, without generating waste in the process. In contrast to the present polluting fish-farming technologies, a zero-waste approach will both positively contribute to the full use of waste in complementary production chains and improve the productivity and profitability of the business. Designing and developing agricultural production clusters is crucial because they promote the circular economy by optimizing resource and waste usage, creating valuable secondary products, protecting the ecosystem and improving farmer working conditions.

Under the current global crop production systems, achieving the sustainable development goals related to agriculture, nutrition levels, and food security is challenging, because raising crop yields creates detrimental effect on the environment. It is, therefore, critical to design and implement the best soil-improving cropping strategies that will enable fishing industry to balance these vulnerabilities [4]. Organic farming has demonstrated over time a positive impact on the environment, promoting nutrient recycling, enabling the soil–plant system's fertility to be maintained exclusively by organic matter, and reducing the quantity of synthetic fertilizers delivered to the farm. Even though the market for organic goods is growing both locally and globally, and the demand is expected to rise in the coming years, the associated cost of producing high-quality nutrients from organic waste is still quite expensive [5].

The zero-waste concept is a collection of waste prevention guidelines that encourages redesigning resource lifecycles to ensure that every production output is being reused. In order to improve the waste management practices, a number of original ideas are provided from various fields. For instance, the textile industry rising demand for raw materials requires adoption of innovative approaches, to change the current linear economy into a circular model, which has a reduced environmental impact [6]. The major objective is to valorize post-consumer waste by recycling or by recovering some of the energy and materials used in the production chain. Food production industry is oriented toward several operational plans that lean toward the zero-waste approach. Here, the expenditures are substantially larger since they require measures such as the installation of hybrid co-digestion systems for organic waste and wastewater that would enable water treatment while also producing biogas, which could then be consumed as an energy source [7].

An innovative tool has been developed to assess waste management performance and material substitution of waste management systems in cities [8]. The "zero-waste index" forecasts the amount of virgin materials, energy, water, and greenhouse gas emissions substituted by the resources that are recovered from waste streams [9].

1.1. Increasing Concerns Related to Conventional Aquaculture Waste Management Practices

Aquaculture is one of the agricultural production sectors where environmental impacts are growing more severe as output rises to satisfy rising global demand. Aquaculture effluents are typically loaded with organic and inorganic compounds that disturb the natural balance of aquatic ecosystems, causing their release into natural water bodies unsustainable [10]. Fish sludge is a residue produced by fish farming, which is composed of excrements and undigested excessive feed. Compared to other types of animal husbandry sludge, fish effluents are highly rich in phosphorus (P) (2–3% of total solids) and nitrogen (N) (4–11% of total solids). The easiest method for managing fish waste and addressing the environmental issue is composting, since the process reduces disease-causing microorganisms and fly larvae in a safe and natural manner. Compared to other disposal options, composting is an inexpensive process for improving soil nutrients, controlling some plant diseases, lowering parasite populations, and disposing the weed seeds.

Research have been conducted on composting initiatives that employ aquaculture derived fish waste as an alternate and viable approach for converting sludge into valuable agricultural products. A study conducted to assess co-composting of seaweeds and fish wastes with lignocellulosic material [11] showed that the technology may be practical to recycle organic byproducts and wastes in order to create a high-quality organic fertilizer.

In most countries, there are strict regulations or guidelines that set limitations on the quantity of pathogens, heavy metals, and other pollutants, as well as the rates of land application for various products and organic wastes used to fertilize farmlands. To avoid exceeding the limits or causing groundwater pollution, application rates must be dependent on nutrient composition, soil type, and plant fertilizer absorption characteristics [12]. Land-use restrictions due to odor concerns may also apply in urbanized regions. Because thickened sludge contains more than 90% water, transporting it from the plant to a different location for disposal or processing may be responsible for a large rate of the costs associated with waste management [13].

Efforts to processing fish waste have been made across the world in order to find more practical and effective methods for transforming fish waste into usable agricultural products. Composting is a biological process that occurs under aerobic conditions and an adequate moisture and temperature, which transforms organic waste into stable, homogeneous and plant available minerals [14,15]. The process is driven by the action of microorganisms including fungi, bacteria, and corresponding enzyme, which play a significant role in decaying recalcitrant molecules such as cellulose and lignocellulose, resulting in a product that can be used as a plant fertilizer or as a soil conditioner [16,17].

Fish sludge is a mixture of solid feces, aquatic plants and uneaten feed, and it typically includes 7–10% of the fish feed inputs [18]. Without proper treatment, aquaculture sludge can accumulate and result in increased oxygen consumption, generating toxins, eutrophication, and infrastructure blockages [19]. Waste generation is influenced by various parameters, including species, variety, animal size, diet mix, nutrient availability, and husbandry practices [20]. Present fish farming technologies are typically unsustainable, considering that water and sludge generated from technological processes are usually discharged into rivers. Only newly constructed on-land hatcheries are currently required to collect fish waste before releasing water into the effluent. Maintaining costs to a minimum has always been more important to the development of innovative fish waste-processing technologies than minimizing their impact. Dried fish sludge without a prior treatment was shown to have 50–90% of the effect of mineral fertilizer when tested in pot trials using nutrient-deficient soils [21].

The current research is approaching aquaculture sludge as an agricultural byproduct rather than a liability since it can be utilized to fertilize land and support agricultural crops, increasing the sustainability of the business as a whole.

1.2. Evaluation of Existing Options for Managing Aquaculture Waste

There are three main approaches for managing sludge from fishponds: land application, composting, and anaerobic digestion. Field application is the simplest to achieve, but usually presents the highest operating costs due to the high-water content of the sludge ($\geq$99.76%) [22]. In addition, a large rate of the nutrients is being lost, while the risk of accidental pollution is extremely high.

Anaerobic digestion uses anaerobic bacteria to break down organic material, producing biogas as an energy source, while recovering various nutrients such as phosphate and ammonia from the liquid phase. It is also possible to stabilize the residual digested sludge and use it as fertilizer. The technique drawbacks, however, include a relative high complexity, the need for specialized installations, and the possibility of producing bad odors. Anaerobic digestion presents a lower availability of nutrients in the byproducts than composting, and if it is not carried out on a large scale with advanced equipment, the process may be unpredictable [23]. The organic N found in digestate derived from fish sludge does not mineralize fast enough to provide crops with enough N [24]. Therefore, any organic N that is still present in the digestate is likely to be present in stable, resistant compounds and will not lead to the desired total mineralization, while carbon is lost in the production of biogas.

Studies have shown that the process of composting sludge from fish farming brings superior results to anaerobic digestion. Composting has been accepted as the most suitable method of stabilizing solid waste, especially when the products are intended to be used in agriculture. It converts the sludge into humic compounds, resulting in a significant volume reduction, while the stabilized end product can be utilized as a solid fertilizer or soil conditioner. The drawbacks include a lengthy processing time and air pollution with some volatile organic compounds.

Previous research illustrating comparative analyses of composting and anaerobic digestion that aerobic processing leads to improved mineralization for P, Ca, Mg, B, Cu, Zn, Mg, and Na [25], as well as better volume reduction [26]. The main drawbacks of aerobic digestion include the high energy consumption carried out especially by constant aeration, the complexity of the management process, and the high system capital expenditures according to technical considerations and the fishing pond capacity [27].

1.3. Growing Vegetables in Straw Bales, as a Regenerative Technology for Establishing Soilless Cultures

Straw bale gardening is a specialized soilless agricultural technique that involves using agricultural waste as a growth medium for different crops, offering the benefit of maintaining relatively low costs while maximizing production [28]. It significantly reduces the associated labor costs, with plant seeds being established in different types of bales, which could be both the garden bed and the growing medium. Straw bales are usually wastes generated from agriculture that will decompose over time, becoming nutrient for plants. Straw bale gardening is particularly effective in regions with challenging soil conditions or in contaminated areas with salts or heavy metals. The straw bale creates an environment that maintains moisture and feeds the plants with nutrients as decomposes [29]. These could be an excellent option to grow crops in urban areas, where appropriate soil and space are not easily accessible. Instead of producing crops directly in the soil, in raised beds mixed with soil amendment, or in any other growth media, straw bales can provide a safer growing environment, without weed seeds, without contaminants, and without pathogenic elements [30]. Furthermore, it is an excellent strategy to reduce the effect on the sensitive soil ecosystem. Fewer pesticides are required since there are fewer pest and disease issues, and because the decomposition of straw bales protects plant roots from cold weather [31].

Before the plantation is established, the bales are either treated using a process similar to composting or used unprocessed, by adding a substrate of nutritious material in the area where the roots of the plants will grow. Comparing to plants grown in soil, the bales aid in water saving and drainage, and they may increase the production yields [32].

Replacing the soil with composted organic materials is becoming more popular since it stimulates the plants and helps the root system grow healthily. The organic compounds produced by composting, vermicomposting, or other similar processes have high aeration, good structure, water retention capacity, and the ability to better control the substrate temperature.

1.4. Circular Production Models in Aquaculture and Horticulture

Circular economies require new business models that substantially decrease environmental impact, reduce resource pressures, and produce a beneficial influence on society and the environment. Due to the necessity to change the essential components of the business and diverge from dominant business concepts, new circular business models are not yet widely used in practice [33,34]. It is generally accepted that the innovation process needs guidelines and a solid structure to define and focus ideas in order to help the business model design [35–37]. A wide range of techniques and tools have been created to offer direction in the circular business model innovation process and assist companies in overcoming the difficulties encountered when building and innovating business models towards circularity. Business model innovation is best defined as an iterative process with various stages (such as conception, implementation, and assessment) [38] and varying degrees of detail (such as modifications at the conceptual level to changes in operational processes) [39]. The new sustainable models that are developed must go beyond sustainability and achieve sustainable income, based on an adjustment of the traditional growth framework, which can be used to restore natural resources while also being economically viable [40,41]. Aquaculture wastes and byproducts need to be reused to maximize their output, in order to create a production system that is more profitable and complies with

European regulations [42]. This strategy will increase their productive capacity while decreasing their emissions and protecting the environment and public health [43].

1.5. Research Approach and Key Considerations for the Zero-Waste Food Production System

Our primary objective is to have a real contribution in accelerating in the transition toward a circular economy in aquaculture, with a particular focus on creating a functional approach where wastes and secondary raw materials are continuously reintegrated into the process, rather than being landfilled or disposed into water effluents. The proposed circular business model is designed to increase revenues, lower expenses, and strengthen resilience by identifying several practical solutions to the most frequent challenges faced by farmers in aquaculture.

The three subsystems of the circular business model (Figure 1) are (A) the fishing pond used for raising fish in a closed regime, (B) the open composting pile, (C) the system for growing ecological vegetables in soilless substrates (straw bales and compost).

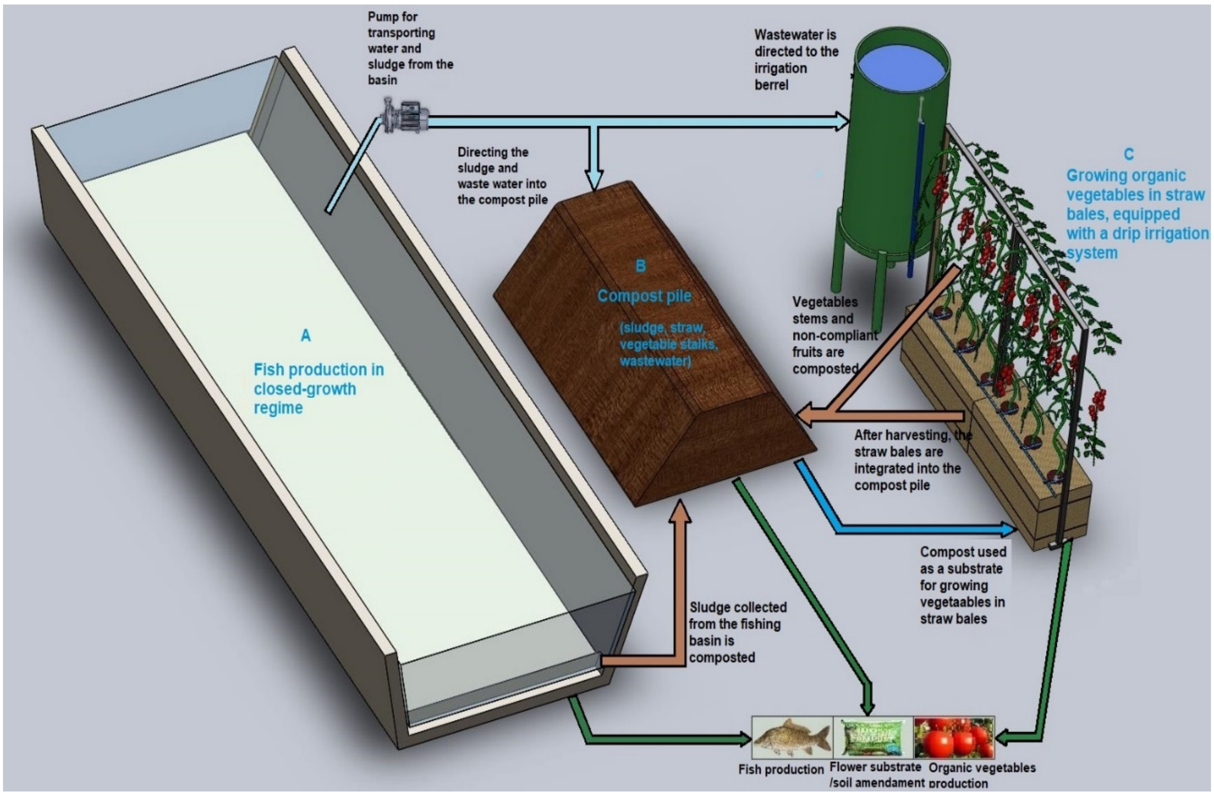


Figure 1. Research approach: optimizing the operational flows with materials, products, and wastes in an integrated zero-waste food production system.

The proposed circular business model aims to be zero-waste (all the waste generated by the three systems is reintegrated into other production fluxes), it has a low impact on the environment, and the obtained products are grown ecologically (lowering the risk of contracting soil-borne diseases, while also decreasing the use of chemical treatments), while productivity yields are maintained at high levels.

Closed fishponds present the benefit of having a low environmental impact, because they do not discharge the wastewater into the effluent. However, they generate a large amount of wastewater and sludge, both of which are rich in nutrients. The immediate use of residues directly in agriculture can generate some risks for crops, and the maximum nutritional potential is not fully exploited in this way.

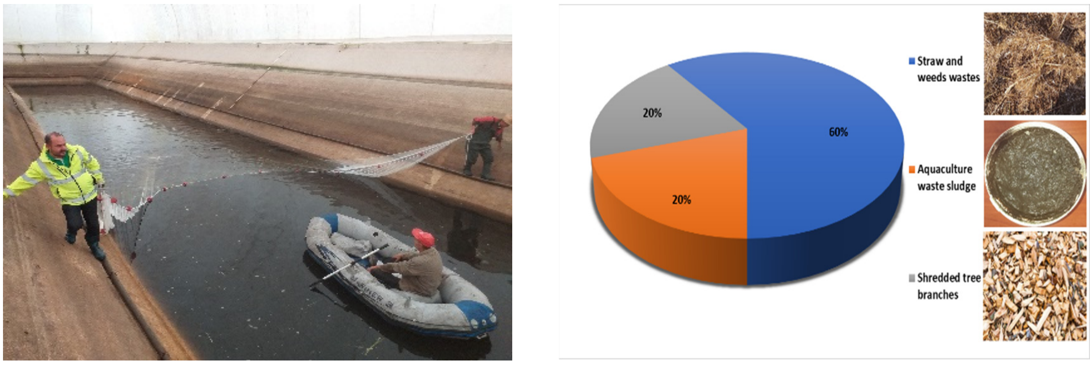
For an efficient integration of waste in the production process, the sludge generated from the fishing pond is sent to composting, while the water is used to irrigate the crops established on straw bales. The compost is further used to create the nutrient substrate for the vegetables planted in the bales, and the waste resulting from vegetable cultivation (vegetable stems and degraded straw bales) returns to the composting process. The main products obtained from the zero-waste circular system are: fish, flower substrate/soil amendments, and organic vegetable products (tomato, long peppers, and eggplant).

2. Materials and Methods

The strategic objective of the current research was to develop a new ecological business model that aim to replace the conventional linear production lifecycles, where synergistic interactions are made between various productive chains. The objective was, therefore, to design an agricultural production cluster, which is a convergence of three different agricultural systems (aquaculture, horticulture, and composting), combined to express effective synergies among residues and raw materials needed in other production flows, allowing us to reach the goal of zero-waste.

2.1. Development of Fish-Sludge Composting Processes

The solid waste used in the composting process was generated from the experimental plantations established within the research institute (the National Institute of Research—Development for Machines and Installations Designed for Agriculture and Food Industry) involved in the current work (greenhouses and orchards), while the sludge resulted from a 400 m^3 fishing pond, used for raising cyprinids in a polyculture system (Figure 2a). The sludge is extracted from the pond once a year, after harvesting the fish, leaving a concentration of approximately 10% sludge.



(**a**) (**b**)

Figure 2. Management of wastewater and sludge from closed aquaculture ponds: (**a**) basin preparation for pumping the sludge towards the composting station; (**b**) establishment of a compost recipe considering the characteristics of the sludge in order to produce an appropriate fertilizing substrate.

The fastest and most inexpensive approach to address the sludge was to extract it with the pump while it was in the liquid phase and move it straight to the composting platform. To counterbalance the high moisture level of the sludge and regulate the C–N ratio for the composting process, the recipe used consisted of 20% aquaculture sludge, 20% shredded pomiculture waste (branches), and 60% straw and weeds (generated from production processes in greenhouses), as depicted in Figure 2b. The optimal dosage of wastes in the composting mix was determined in previous research studies, considering several factors such as the moisture level of the sludge extracted from the fishing pond, the carbon–nitrogen content of the mixture and the aeration potential provided by shredded branches and straw. In terms of plant-available N and P and the ratio of micronutrients, fish sludge offers several benefits. Fishing sludge is accepted as a safer fertilizer when comparing to other sludge types since it originates from a single source and contains no micropollutants or microplastics.

For this experiment, the technology of composting in trapezoidal piles was used (the pile measuring a height of 0.6 m, a width of 3.5 m, and length of 30 m), with the composting station being located in the south of Romania. The average daily temperature during composting was 21 °C during the daytime and 13 °C during the night. A windrow turner was used for mixing and aeration (Figure 2), the total duration of the composting process was 4 months. Compost from a previous batch was used for inoculation, and the composting parameters were monitored every 2 days to ensure the process had been operating properly. The pile was placed on an impermeable foundation to prevent lixiviation and nutrient washout (Figure 3).

Figure 3. Compost processing phase, using a mechanical aeration and mixing equipment.

The compost pile was turned once every week for the first 2 months and once every 15 days for the final 2 months. When the compost was considered to be adequate, it was sieved through a 20 mm mesh screen and was transferred to the application location, where it was dosed using a 7 dm^3 graded cylinder.

2.2. Characterization of Raw Material and Compost

Elemental analysis was performed for both the materials that enter the composting process and the obtained compost, for all three tested batches. The analyses were carried out with standardized measurement methods. The total carbon content and total nitrogen content were determined using dry combustion (Dumas method). UV/Vis spectrometry determination was used for total phosphorus content. Total potassium content was determined by calcination and determination by flame photometry. The Kjeldhal method was used for Kjeldhal nitrogen content. Metal contents (Cd, Cr, Cu, Ni, Zn, Pb, Hg, and As) were obtained via extraction in regal water and determination by atomic absorption spectrometry. For the determination of total Kjeldahl nitrogen, the following standardized methods were used: EN 13342 (characterization of sludges—determination of Kjeldahl nitrogen) and EN 13654-1 (soil improvers and growing media—determination of nitrogen—modified Kjeldahl method).

2.3. Establishment of Vegetable Crops on Bales Using Compost Produced from Fishing Sludge as Nutrient Material

To increase control over the growing environment and remove uncertainties in the soil, water, and nutrient conditions, soilless cultivation is becoming more commonly used. Soilless farming practice is a key vector for preserving the ecosystem, but it might be challenging to grow high-quality vegetables without using a significant amount of chemicals. That is why the solutions targeted in this research are oriented toward not only the environment protection, but also the quality of the products, even if this may bring a negative impact on the generated quantities.

For the targeted experiment, straw bales and compost were used as growing medium. In order to properly use the straw bales, they have to be prepared using a preconditioning process, which is a form of composting. The bales will heat up during preconditioning, and the pH will vary as decomposition takes place. Before planting the vegetables into the bales, the initial straw processing is mandatory in order to prevent damage to the plants.

As soon as the straw bales are moistened, microorganisms start decomposing organic matter, bonding some of the nutrients such as nitrogen. Because of this, plants growing in a high-carbon environment, such as straw bales, may not receive the vital nutrients available for growth until the straw have adequately broken down. That is why a carbon-to-nitrogen ratio close to 30:1 must be maintained for appropriate composting, by adding liquid sludge, generated from fish farming. The carbon dioxide and the heat generated by composting process are beneficial for the growth of plants in greenhouses. The method proposed for conditioning straw bales is depicted in Figure 4.

Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Water application *[liters per day]*	25	20	20	0	0	2	2	0	2	2	0	2	2	0
Liquid sludge application *[liters per day]*	0	0	0	10	5	5	0	5	0	0	5	0	0	5

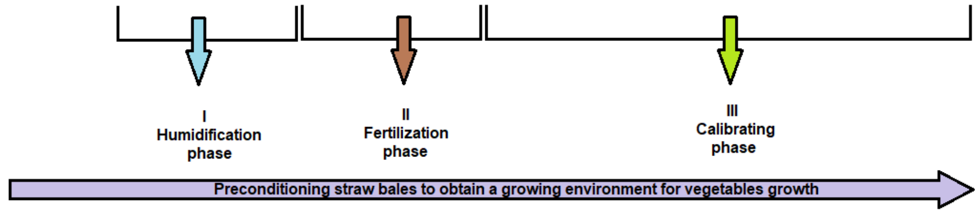


Figure 4. The 2 week approach used for preconditioning straw bales, in order to obtain the proper growing environment for vegetables.

During the 2 week period, the bales were kept highly moist; however, it is preferable to slowly apply water to each bale to reduce runoff and ensure that the surface-applied fertilizer is incorporated by the bales. Starting with the second week, a drip system was installed to maintain constant humidity and to prevent runoff. The preconditioning process was maintained for 2 weeks considering the long process of complete composting (up to 37 days) and because vegetables were planted in a layer of compost, and not straight into the bales. The experimental design presented in Figure 5 was built and tested.

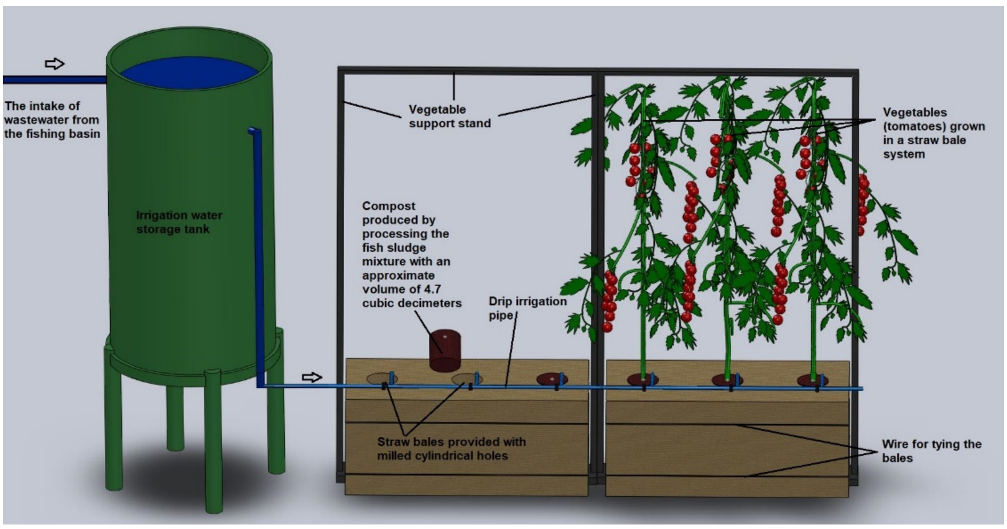


Figure 5. Design of a soilless vegetable production system using straw bales, compost, and wastewater.

Considering that the main objective was to evaluate the cultures established in bales compared to other cultures established in a classic or mixed regime, the comparative evaluation was performed in a protected space (a greenhouse). Plants were seeded at a distance of 40 cm, in a volume of compost of approximately 4.7 dm^3.

By creating a hole in the straw and filling it with compost, seeds may be planted the same way as in any regular soil or a raised bed. Bales were positioned in a row, and a supporting stand has been installed to offer additional holding for vegetables, because, when the bales decompose, their stability is reduced. If the greenhouse is already equipped with a plant palisade system, then the support is no longer mandatory.

Three testing areas were delimited in the greenhouse, each presenting different plant developing conditions: *Area no. 1:* soilless cultures established in straw bales and compost substrate, in an ecological system; *Area no. 2:* cultures established in the soil in an ecological system, fertilized with compost; *Area no. 3:* cultures established in soil, in the conventional growing system.

Three types of vegetables were planted: tomatoes (*Solanum lycopersicum*, Rila F1 hybrid, with indeterminate growth, for production in protected spaces and in the field), long peppers (*Capsicum annuum L.*, Kaptur F1 early hybrid, resistant to stress conditions and low temperatures), and eggplants (*Solanum melongena*, Kreola F1 hybrid). Planting was carried out on 15 May, for all evaluated culture media. In the case of ecological crops established in the soil, fertilization was accomplished with compost (7 kg/m^2), while, in the case of conventional culture, 7 $kg/100\ m^2$ of chemical amendments (superphosphate and potassium sulfate) were applied. The soil was mobilized at the depth of 28–30 cm, and weeding was performed manually when needed.

Utilizing a portable measuring tool (multiparameter water quality meter—HI98194), the amount of pollutant from the water was continuously monitored in order to ensure that the irrigation water supplied from the fishing pond would not have a negative impact on the plant's health.

3. Results

3.1. Compost Characteristics

The volumetric analysis on 10 m^3 of material showed that decomposition reduced the initial material by 57% after 4 months of processing. The compost was stable and adequate for use as organic fertilizer, particularly in regard to the NPK content. The average values of the physicochemical evaluation are presented in Table 1.

Table 1. General classification of the materials used in the compost pile, as well as the compost obtained [1].

Parameter	Tests Performed												
	C	N	P	K	Ca	Mg	Cd	Cu	Cr	Ni	Mn	Pb	Zn
	%	%	%	%	%	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
Fish sludge	12.11	2.84	2.95	0.12	3.8	0.5	0.7	19	3.2	2.6	125	0.11	286
Vegetable wastes and wheat straw	43.45	1.15	0.22	1.44	1.18	0.08	N.A.	5.5	11.5	7.8	17.2	3.78	17.4
Chopped wood material (garden waste)	39.99	0.45	0.08	0.37	0.61	0.08	N.A.	9.4	91.6	31.9	48.4	2.26	106
Compost (average value)	37	1.5	0.3	0.2	1.1	0.2	0.7	70	22	6	315	28.3	166

[1] Dried substance basis.

3.2. Vegetable Growth Yield

Three different vegetable types were grown in unheated greenhouses, using three different development environments; the first soilless environment was composed of straw bales and compost, the second environment tested was planting the vegetables on the soil in an ecological system (which was fertilized with the compost created by processing fish sludge), and the third was the conventional growing of vegetables in greenhouses (Figure 6).

Figure 6. Cultivation of vegetables in straw bales, images during the plant growing cycle.

The present study evaluated only the feasibility and applicability of using the cluster production system; therefore, the most relevant analyzed parameter was the productivity, which is depicted in Figure 7. The first stage of the study lasted 18 months, while the following stages will optimize the planting and operating conditions.

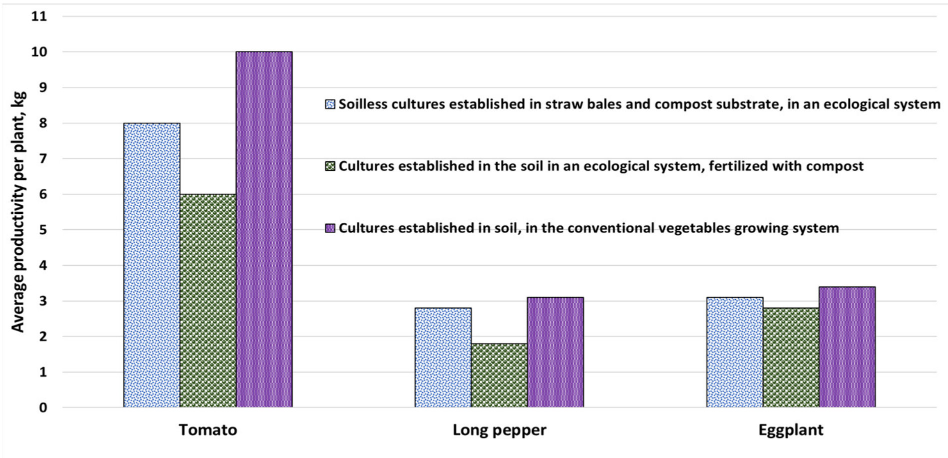


Figure 7. Productivity analysis for tomato, long pepper, and eggplant, grown in three growing environments.

4. Discussion

The residues and wastes produced from aquaculture and horticulture have a relative low value, being heterogeneous in composition, and challenging to incorporate into other production cycles. In addition, they may cause considerable environmental damages, contributing to degradation of air quality, land depletion, and water pollution, all converging to severe social and economic problems.

Our proposed circular solution aims to reconfigure the aquaculture and horticulture businesses, decreasing the negative impact that fish farming has on flowing waters and on the excessive eutrophication of rivers, as well as optimize the use of gardening waste by developing symbiotic relationships between these two agricultural sectors. The designed *zero-waste food production system aimed at supporting the synergic interaction between aquaculture and horticulture* is depicted in Figure 8.

The fundament of the zero-waste food production system is the concept that economic growth can be partially separated by the resource consumption using clustered agricultural practices. This approach involves improving resource utilization through new business models, which can increase production efficiency, to conserve materials and to fully recycle the waste generated in the production flows. By combining three agricultural production systems (aquatic system for raising fish in a closed regime, composting system, and system for growing organic vegetables in straw bales) an industrial flow that is regenerative by design was created, managing to transform non-value residues (that usually go to landfills or in the water emissary) into valuable nutrients capable of generating products with higher values.

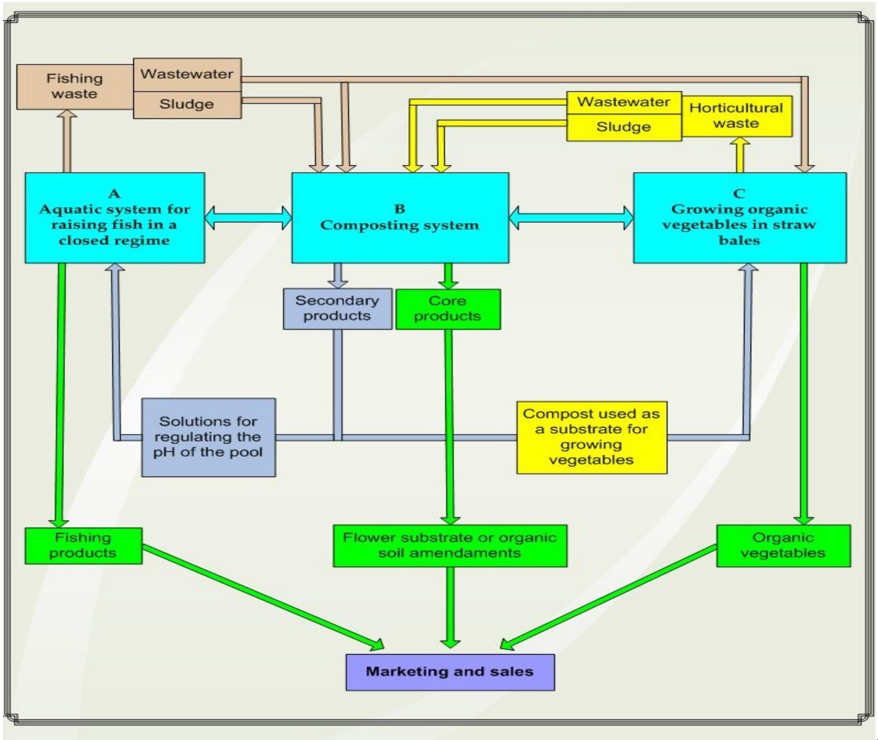


Figure 8. Zero-waste food production system aimed at supporting the synergic interaction between aquaculture and horticulture.

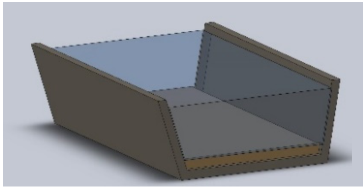
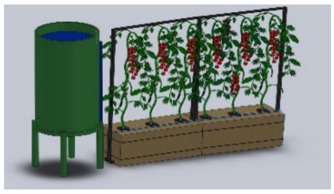
The proposed zero-waste production system is based on the circular economy approach. It operates as an organizational system, is designed to be regenerative, and converts low-value waste into high-value resources. The interconnections between production lines are designed to sustain the industrial symbiosis, involving the direct exchange of energy, materials, wastewater, sludge, and plant wastes from all agricultural activities.

Consequently, productivity cycles close the loop of both economic and environmental synergies. The relationships between production systems are referenced as industrial symbiosis, since three agricultural structures are combined with the circular economy dynamics. A number of benefits were identified for the zero-waste food production system; the most important ones are summarized in Table 2.

Straw bale gardening is significantly less labor-intensive because it does not require tillage, weeding, or carrying out difficult tasks to adjust the characteristics of the soil. At the beginning of the process, the straw bale is basically sterile (which is advantageous because it reduces the risks of contamination and the presence of pathogens is also reduced); however, as time passes, it changes into partially decomposed organic matter, which is microbiologically regulated. After the vegetables are harvested, the straw bales serve an additional beneficial purpose, being integrated into the compost pile.

Straw bale gardening associated with other production chains can be an efficient technique for growing vegetables, particularly in regions with poor soil conditions that are difficult to correct. Alkaline and saline soils, as well as typical urban soil pollutants such as heavy metals can, therefore, be avoided, making the transition to organic agriculture easier. The roots of plants cultivated in straw bales are also physically separated from soil-borne illnesses and pests, especially because the composting process destroys all pathogenic elements. The straw bale offers an environment that retains moisture and supplies the plants with nutrients as it decomposes.

Table 2. Evaluation of the main advantages brought by the synergistic production approach.

		
A. Aquatic system for raising fish in a closed system	B. Composting system	C. Growing organic vegetables in straw bales
Most important benefits identified for each of the three subsystems operating in the synergistic production model		
✓ Closed aquatic farming systems do not discharge sludge and wastewater into the effluent, having a reduced impact on the contamination of rivers and the aquifer. ✓ The water from the pond has superior quality, being provided from underground sources. ✓ Simplicity of handling the sludge, which can be easily pumped to the composting system. The sludge no longer undergoes drying/dehydration processes, avoiding management costs, generation of unpleasant odors, sophisticated auxiliary equipment. ✓ Ease in obtaining legal permits and operating authorizations due to the closed operating system.	✓ The compost meets the requirements regarding the carbon–nitrogen proportions, considering the very varied waste mix: fishing sludge, straw, and plant stems. ✓ The water used to maintain the humidity level for compost piles contains bacteria and nutrients, which help the composting process. ✓ Reduction in operating and maintenance costs for compost piles. ✓ Large quantities of the produced compost can be used directly in another productive cycle (substrate for growing vegetables), thus reducing costs associated with commercialization.	✓ Planting vegetables in straw bales reduces the risk of acquiring diseases from the soil, accidental contamination, and weed infestation. ✓ Straw baling systems may be installed everywhere, including metropolitan areas (on concrete), infertile soil regions, flooded regions, and desert areas. ✓ Plantations on straw ensure better heat for plant roots, especially in early spring due to the isolation provided by straw and as a result of organic matter degradation (exothermic process). ✓ The water used to water the vegetables is wastewater from fish farming, which contains a high level of nutrients and beneficial bacteria.
The influence on the productivity of each production system caused by the synergistic action		
Since both sludge and wastewater are fully utilized in the other two systems, without harming the environment, the pond water is replaced with fresh water from deep wells. The better quality of this water, as well as the lower temperature during the summer compared to surface water, improves the health of the fish and can increase productivity by up to 18%.	The sludge from fish farming has constant characteristics; it contains microorganisms that improve the process, shortening the composting time and improving the amount of nutrients such as phosphorus.	Providing, at any time and free of charge, qualitative fertilizers (compost), irrigation water (wastewater from the basin), and an efficient management scheme for waste has been addressed as the most frequent challenges encountered by farmers. By optimizing the cultivation practices and the hybrids employed, a significant increase in production can be achieved for ecological and regenerative agriculture.

Establishing vegetables in straw bales in greenhouse environment showed some advantages compared to other systems. First of all, it has a high level of versatility regarding the positioning of the crop, being able to grow vegetables in places with inappropriate soils. Therefore, the system can be extended to several restrictive areas including deserts and cities. Weed reduction was achieved by more than 90% in the strow bales, and a higher planting bed offer easier working conditions. Planting on straw bales lowers the associated work because no plowing is required.

In the analyzed period, the increase in temperature only as a result of using the straw bale planting technology was not significant. The effect could be more significant for heated greenhouses or for early crop establishment.

The experiment showed that plants grown in straw bales and composted fish sludge might be up to 25% more productive than plants grown in ecological soil growing systems, but 20% smaller than plants grown in conventional soil growing systems.

The straw preconditioning techniques can be designed to maximize heat generation, oriented toward more sensitive crops to temperature variations.

Several authors recommend consistent bale conditioning before planting since the composting process could deprive the plants of easily accessible nutrients. However, adding 7 dm^3 of compost reduces this need because the plant has room to develop its roots until the bale degrades.

The proposed system successfully addressed the highly energy-consuming and expensive operations of dehydration and final removal of the sludge from the fishing pond. As a result, the expense with the dehydration equipment is mostly saved. If the sludge is not treated, it usually ends up in landfills, since it is difficult to employ in agriculture, and final disposal involves additional management costs. There were, however, several supplemental costs associated with the proposed system, represented by the purchase of straw bales, the analysis of the characteristics of the compost, the aeration and mixing of compost piles, and the more frequent pumping of wastewater. The extra compost not used in the processes was not capitalized by sale, but was applied to other experimental crops as fertilizer.

No optimization techniques were carried out at this point because the experiment's primary goals were to evaluate the system's functionality and confirm that it can operate without generating waste. Even under early evaluation conditions, productivity in the cluster increased, recording a 12% improvement in energy efficiency, an 18% increase in food production (fish and vegetables), and a 25% decrease in operating expenses.

5. Conclusions

- The study successfully proved the system functionality and usefulness, especially in terms of managing to create a circular management of resources and wastes, even though the research is in its early stages.
- The main management issue reported by the aquaculture sector, related to the evacuation of the sludge without going through the expensive and time-consuming processes of dehydration, was addressed by composting in a mix with other vegetable waste. In this way, expenses and time allocated with labor force and energy consumption were reduced.
- The zero-waste approach brings significant benefits to environmental sustainability, allowing the reintegration of sludge and water into the production circuit (which would otherwise have ended up in rivers and landfills), as well as the maximum efficiency of using agricultural waste (straw and shredded branches). In addition, the excess of compost being produced has high quality and can be used outside the production cluster for soil reconditioning or can be sold to local farmers.
- Ecological agriculture involves a series of risks; therefore, the establishment in protected space has proven very important in order to protect against pests. However, the quantities achieved using straw bales as substrate were lower than those obtained with conventional farming. In order to assess if the greenhouse's space is adequately utilized and which plants are more appropriate for the technology, a feasibility study would be required.
- The designed zero-waste food production system supported the symbiotic connection among the three subsystems (aquaculture, horticulture and composting), and showed effective functioning, while reducing operating costs and increasing productivity. However, the improvements were not constant; therefore, the production quantities and the mode of operation must be optimized. In the conducted study, too large amounts of compost resulted (correlated to the amount of waste generated), while the production of vegetables was constrained by the limited space of the greenhouse.

- The quantitative influence on the productivity produced by the synergistic action of the new system has to be further tested in association with several small-sized farms, considering that production may involve some management challenges.

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