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Waste Feathers Processing to Liquid Fertilizers for Sustainable Agriculture—LCA, Economic Evaluation, and Case Study

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Abstract: The poultry meat industry generates about 60 million tons of waste annually. However, such waste can serve as a cheap material source for sustainable liquid fertilizers or biostimulant production. Moreover, its practical potential associated with the circular economy is evident. One of the options for waste feather reprocessing is to use a hydrolysis process, whose operating parameters vary depending on the waste material used. The better the quality of the waste feathers, the less energy is needed; moreover, a higher yield of amino acids and peptides can be achieved. These are the main operational parameters that influence the overall environmental and economic performance of the hydrolysis process. The assessment of process operational environmental aspects confirmed that the environmental impacts of hydrolysate production are highly dependent on the amount of electricity required and its sources. This fact influences the midpoint and the endpoint impacts on the observed environmental impact categories. It also minimizes the pressure associated with fossil resource scarcity and the related impact on climate change. During an economic evaluation of the process, it was found that the option of processing more fine waste, such as CGF, provided a 5% saving in energy costs related to the reduction in the cost per liter of hydrolysate of 4.5%. Finally, a case study experiment confirmed the fertilizing effect of the hydrolysate on pepper plants (biometric parameters, yield). Thus, the hydrolysate produced from the waste feathers can serve as a substitute for nitrate fertilizing, which is commonly drawn from raw fossil materials.

Keywords: hydrolysate; poultry; life cycle; environmental; economic; assessment; nitrate substitute; cayenne pepper

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1. Introduction

The poultry meat industry generates not only a large number of products but also large volumes of by-products, such as feathers, blood, bones, meat scraps, skin, fatty tissues, feet, skulls, and viscera. The poultry industry produces approximately 60 million tons of by-products annually. A significant component is feathers, which is a protein containing 80–90% keratin [1]. In chicken slaughter processing, feather waste represents about 5–7% of its total body weight. According to the periodic report published by the US Department of Agriculture in April 2021, over 13.5 billion tons of chickens were slaughtered in the USA, which annually results in about 270 million kilos of problematic feather waste [2], and for comparison, worldwide, it is around 9 million tons of poultry feathers annually [3]. Thus, regarding the circular economy, the use of waste feathers would be beneficial from both economic and environmental points of view [4].

There is a massive opportunity to make economic and ecological use of these poultry leftovers, especially from chickens. The production of poultry products has been continually growing throughout the world, leading to the generation of thousands of tons of organic by-products, which may be important sources of bioactive peptides and amino acids [5]. Proteins present in poultry by-products are reduced to peptides via hydrolysis. Moreover, bioactive peptides derived from animal proteins are recognized for their biological activity and positive effects on plants [6].

In 2018, the global synthetic fertilizer N use reached almost 109 Tg N/year [7]. Feathers contain around 15% (*w*/*w*) of N [8]. Thus, nitrogen from feather hydrolysate cannot replace traditional synthetic nitrogen fertilizers. It can only partially substitute them; however, it brings a new perspective to the fertilization system, such as a new type of fertilizer with specific effects on plants. Moreover, it is free of heavy metals, which are typical for NPK, as well as emerging pollutants, antibiotics, and hormones compared with manure.

In contrast, the presence of amino acids, soluble proteins, and peptides in hydrolysate facilitates the growth of microbes in the rhizosphere that promotes the uptake and utilization of nutrients from the soil. The application of hydrolysate enhances the water-holding capacity, C/N ratio, and mineral content of soil [9]. The plant-growth-promoting activities of hydrolysate potentiate its possible use in organic farming and improve both the soil ecosystem and microbiota. The tea plant height (+98%), leaf number (+61%), shoot dry biomass (+128%), root length (+94%), root surface area (+15%), and root dry biomass (+152%) were significantly increased by the application of chicken feather protein hydrolysate (CFPH; 2 g/L dose) compared with a control [10]. Treating plants with CFPH stimulated plants and increased the root and shoot lengths, fresh and dry weights of the seedlings, and photosynthetic pigment content [11]. It was also confirmed that the application of hydrolysate has a significant effect on different qualitative and quantitative parameters of plants and crops, including prolonging seed growth and germination [12], earlier flowering, subsequent fruit set (yield improvement) [13], and mitigating effects on abiotic stress (esp. salinity) [14,15].

Nowadays, agriculture is constantly facing challenges to produce more and better food for the growing population under the effects of a changing climate. To respond to this demand, new agents were proposed related to sustainable agriculture. These agents, defined as biostimulants, appear to improve plant nutrition, quality, yield, and abiotic tolerance in different crops. In particular, the use of protein hydrolysates, including feather hydrolysate, as biostimulants offer promising results concerning the reduction of the use of agrochemicals and improvement of productivity parameters in a variety of cultivars, which corresponds to the modern agricultural production challenges [6].

Other advantages of hydrolysate seem to be indisputable. Field experiments were conducted to measure the yield response of Cantaloupe (*Cucumis melo*), pepper (*Capsicum annuum*), and tomato (*Lycopersicon esculentum*) to an organic fertilizer derived from hydrolyzed feathers. This study demonstrated that organic fertilizers can provide multiple benefits for specific vegetable production systems, including fertility improvement, an increase in soil microbial populations, and a reduction in the incidence of soilborne disease [16]. Similarly, foliar fertilization using a biostimulant obtained via hydrolysis of chicken feathers was tested on the productivity and stand quality of maize, which significantly increased the leaf macro- and micronutrient concentrations, while the grain protein content and yield increased by 26% and 14%, respectively. These results suggested that the foliar application of this biostimulant could be of great interest to farmers to improve the yield and quality of maize [17]. The result of the study by Adetunji et al. [18] indicated that feathers, which are cheap, readily available, and environmentally friendly, offer a promising prospect in agriculture, both as an organic fertilizer and in association with the control of cowpea diseases if applied at recommended rates and times.

Moreover, crops could be expected to be less prone to insect pests and diseases where organic soil amendments are used since these amendments usually result in lower concentrations of soluble nitrogen in plant tissue. Indeed, most studies documenting fewer insect pests in organic systems have partially attributed these reductions to the lower nitrogen content in the crop [19], which would be a major advantage of feather hydrolysates over synthetic nitrogen fertilizers (restrictions on the application of pesticides) [6].

These new biostimulants bring interesting results; unfortunately, the increase in costs during their application is not known given that their price, which depends not only on the waste used but also on the technology, is not known either. Regrettably, valorization options for the livestock sector and poultry industry waste streams have received relatively little attention compared with other sectors [20]. Nevertheless, economic evaluation and an LCA study are inevitable for any new technology [21]. Without them, it is impossible to realistically consider the possible market launch of a new biostimulant or to estimate the environmental costs of this technology.

Life cycle assessment (LCA), which assesses the environmental impacts and resources used throughout a product life cycle [22], has been broadly applied in practice since the 1990s. Currently, the LCA methodology is covered in the ISO standards 14040:2006 and 14044:2006 and their latest amendments from the years 2017 and 2020 [23,24]. Moreover, it gained more importance due to the new Circular Economy Action Plan (CEAP) adopted by the European Commission in March 2020 as one of the main building blocks of the European Green Deal (EGD) [25]. An LCA itself is a powerful method that is aimed at understanding the environmental impacts and flows of various systems [26]. A comparative LCA is often performed to evaluate and determine which is the better process, product, or system among several options. When such an LCA study is carried out, it is very important to apply coherent rules (e.g., system boundaries, source and quality of metadata), as the comparative study can be easily changed in favor of one product, system, or process over another [27]. Especially in the comparative context, the question *'Is product A better than product B?'* still evokes long and sometimes fierce debates [28,29]. Nevertheless, it is primarily a powerful tool for comparing the environmental impacts of two or more similar systems at different stages of their life cycle.

In addition to an LCA analysis, it is also necessary to provide an economic analysis, without which the process cannot be implemented. Direct costs associated with the proposed hydrolysis technology, i.e., the investment costs and the direct operating costs of the related technology, belong among the most important information used to assess the effectiveness of a technology.

For these reasons, this study was focused on an LCA and the economic evaluation of a newly designed technology [30,31], which was based on an environmentally friendly method of physicochemical hydrolysis of waste feathers initiated by malic acid. This study compared the economic evaluation of two hydrolysates (biostimulants) prepared from different, albeit similar, raw materials: chicken feathers, which is a by-product of the poultry meat industry, and the waste material created after cleaning goose feathers from blankets. Simultaneously, LCA studies were carried out for both types of waste, which evaluated not only the potential impacts of the technology on the environment but also the environmental costs. The article also contains a case study focused on the fertilization of cayenne pepper by hydrolysate from chicken feathers.

2. Technology of a Hydrolysate Preparation

According to Hanika et al. [32], the hydrolysis of both materials—chicken feathers (CF) and waste material created after cleaning goose feathers (CGF)—initiated by malic acid was performed in an 8000 L batch-stirred reactor with a radial flow agitator (15 rpm). The batch of the reactor contained 2500 L of water, 18 kg of malic acid, and 340 kg of CF or CGF. Initially, the reactor was flushed with pressurized steam and the batch was heated to the temperature of 115–139 °C and pressurized up to 2.5 bars. The working time for the operational reactor consisted of two periods: the heating period lasted for 6 h for CF and 5 h for CGF. Finally, the cooling period, reaching 100 °C for both materials, took 10 h. The hydrolysis reaction took place during both periods; thus, the total reaction time was 16, eventually 15 h.

The resulting products contained a liquid hydrolysate, as well as a solid residue, which was about 5% for chicken feathers and 3% for waste material created after cleaning the goose feathers. However, the results related to protein and peptide analyses showed greater differences between both waste materials. The sums of amino acids and peptides were, respectively, 36.9 g/L and 22.7 g/L for CF and 46.3 g/L and 52.7 g/L for CFG. However, the results of the elemental analysis for both types of input raw materials, which are shown in Table 1, were nearly the same. The fact that the chicken feathers and the waste material created after cleaning goose feathers contained no heavy metals, neither in the hydrolysate nor in the cake, is really important for the utilization of these waste materials.

Table 1. Elemental analysis (wt. %) of hydrolysates and filtration cakes for both types of materials.

Product/Element	Material *	C	N	O	Na	P	S	Cl	K	Ca
Hydrolysate	CF	44.0	14.2	39.1	0.2	0.2	1.5	0.3	0.2	0.3
	CGF	43.6	15.3	38.7	0.3	0.0	1.8	0.3	0.10	0.23
Filtration cake	CF	52.9	14.2	30.3	0.1	0.2	2.1	0.1	0.0	0.1
	CGF	51.5	14.9	30.8	0.0	0.5	2.6	0.1	0.0	0.1

Note: * CF—chicken feathers; CGF—cleaning goose feathers.

3. Life Cycle Assessment

The LCA study was aimed at the comparison of the environmental impacts of liquid hydrolysate produced from two types of waste: chicken feathers (CF) and the material after cleaning goose feathers (CGF). The technological process of both hydrolysates is described above in the section titled Technology of Hydrolysate Preparation. The main difference regarding the use of the two wastes lies in the character of these materials. While CGF are a fine material without any quill compared with CF, its processing is less time- and energy-consuming and, at the same time, has a higher liquid hydrolysate yield.

The comparative analysis was performed in the openLCA software v1.10.3 (GreenDelta, Germany, 2020) using the ecoinvent database v3.8 (Ecoinvent, Switzerland, 2021). The APOS unit model was chosen for use as it follows the attributional approach in which burdens are attributed proportionally to specific processes. For the impact assessment, the ReCiPe LCIA method—which was developed by the Dutch National Institute for Public Health and the Environment (RIVM), the Radboud University Nijmegen, and the PRé Sustainability (all the Netherlands), together with the Norwegian University of Science and Technology (Norway) in 2008 and later updated in 2016—was chosen, as this method is comprehensive and combines two widely used LCIA methods, i.e., Eco-Indicator 99 (a damage-oriented LCIA approach) and the CML baseline/no-baseline (the most commonly used method in LCA) [33,34]. Moreover, ReCiPe distinguishes two levels of indicators, the midpoint (*'immediate'*), as well as the endpoint (*'intermediate'*). Thus, it covers all important midpoint impact categories, such as resource depletion, climate change, human toxicity, marine, freshwater and terrestrial ecotoxicity, acidification, and eutrophication as relevant endpoint categories, which are expressed as damage to human health, ecosystems, and resource availability [34,35]. The ReCiPe approach also distinguishes between three different cultural perspectives: (H) hierarchist (default), (I) individualist, and (E) egalitarian [34], which makes this LCIA method even more powerful. These perspectives represent a set of choices related to the issues connected with time or expectations that proper management or future technology development can avoid future damage. While the hierarchist perspective involves a consensus model, as is often encountered in scientific models, the individualist perspective represents a short-term optimism that the technology can avoid many problems in the future. Additionally, the egalitarian perspective is a long-term model based on precautionary principle thinking [36]. In the conducted LCA study, the ReCiPe2016 method v.1.1 was used in the hierarchical (H) perspective for both levels of indicators (midpoint and endpoint). The ReCiPe2016 used for the calculation was provided within the openLCA LCIA methods package v2.1.2 (GreenDelta, Germany, 2021), which is compatible with the used ecoinvent v3.8.

The functional unit (FU) of the comparative LCA was set to the production of 1 L of hydrolysate. Therefore, the operational inputs and outputs to process CF or CGF were recalculated to the FU. It is necessary to mention that only the own production of liquid hydrolysate was assessed in the LCA study. The analysis of the operational phase of the hydrolysate production covered the input materials, such as the waste substrate, chemicals, and water, as well as the electricity needed (or natural gas considered as an alternative for reactor heating), and the outputs of hydrolysate and residual waste (i.e., filtration cake). The material and energy flows related to resources' extraction, reactor construction, and material and waste transportation were not included in the LCA study, as they are the same for processing both waste materials. The flows included in the LCA comparative study are reflected in Table 2. As can be seen, there were minimal deviations between the evaluated waste substrates. Overall, it was only the amount of electricity and natural gas that, to some extent, decreased.

Table 2. Inputs and outputs related to the production of 1 L of hydrolysate (FU).

Inputs	**Unit**	**CF_E**	**CF_G**	**CGF_E**	**CGF_G**
Chicken feathers	kg	0.125	0.125	-	-
Goose feathers	kg	-	-	0.123	0.123
Water	L	0.921	0.921	0.902	0.902
Malic acid	kg	0.007	0.007	0.006	0.006
Electricity	kWh	0.20	0.03	0.16	0.03
Natural gas	m^3	-	0.024	-	0.020
Outputs	**Unit**	**CF_E**	**CF_G**	**CGF_E**	**CGF_G**
Liquid hydrolysate	L	1	1	1	1
Solid filter cake (waste)	kg	0.053	0.053	0.031	0.031

Note: FU—functional unit; CF—chicken feathers; CGF—cleaned goose feathers; $_E$—electricity heating and steering; $_G$—gas heating and electricity steering.

Tables 3 and 4 show the LCIA results of the assessed production variants. Each selected LCIA category is displayed in the rows and the production variants are shown in the columns. The units presented in the tables are the units of the LCIA category as defined in the ReCiPe method.

Table 3. LCIA results of 1 L of hydrolysate production—ReCiPe2016 midpoint (H).

Impact Category—Midpoint (H)	**Unit**	**CF_E**	**CF_G**	**CGF_E**	**CGF_G**
Fine particulate matter formation	kg $PM_{2.5}$ eq.	1.97037×10^{-4}	6.55483×10^{-5}	1.59938×10^{-4}	5.95671×10^{-5}
Fossil resource scarcity	kg oil eq.	4.33827×10^{-2}	3.63203×10^{-2}	3.52691×10^{-2}	3.13496×10^{-2}
Freshwater ecotoxicity	kg 1,4-DCB	8.16800×10^{-3}	1.98375×10^{-3}	6.58594×10^{-3}	1.85838×10^{-3}
Freshwater eutrophication	kg P eq.	2.91942×10^{-4}	4.86002×10^{-5}	2.33895×10^{-4}	4.78191×10^{-5}
Global warming	kg CO_2 eq.	2.00330×10^{-1}	6.06150×10^{-2}	1.62084×10^{-1}	5.55210×10^{-2}
Human carcinogenic toxicity	kg 1,4-DCB	1.62818×10^{-2}	3.90897×10^{-3}	1.31405×10^{-2}	3.69261×10^{-3}
Human non-carcinogenic toxicity	kg 1,4-DCB	3.16769×10^{-1}	6.39434×10^{-2}	2.54535×10^{-1}	6.12314×10^{-2}
Marine ecotoxicity	kg 1,4-DCB	1.11944×10^{-2}	2.83172×10^{-3}	9.02387×10^{-3}	2.64113×10^{-3}
Marine eutrophication	kg N eq.	2.94723×10^{-5}	1.36556×10^{-5}	2.42005×10^{-5}	1.21062×10^{-5}
Mineral resource scarcity	kg Cu eq.	1.91403×10^{-4}	1.08147×10^{-4}	1.58311×10^{-4}	9.52245×10^{-5}
Ozone formation, human health	kg NO_x eq.	3.59839×10^{-4}	1.36390×10^{-4}	2.92523×10^{-4}	1.22648×10^{-4}
Ozone formation, terrestrial ecosystems	kg NO_x eq.	3.62744×10^{-4}	1.38648×10^{-4}	2.94945×10^{-4}	1.24602×10^{-4}
Terrestrial acidification	kg SO_2 eq.	6.03677×10^{-4}	1.96519×10^{-4}	4.89782×10^{-4}	1.78861×10^{-4}
Terrestrial ecotoxicity	kg 1,4-DCB	2.40481×10^{-1}	1.98403×10^{-1}	2.03304×10^{-1}	1.71247×10^{-1}

Note: PM—particulate matter; DCB—dichlorobenzene; CF—chicken feathers; CGF—cleaned goose feathers; $_E$—electricity heating and steering; $_G$—gas heating and electricity steering.

Figures 1 and 2 show the relative indicator results of the assessed variants of feather hydrolysate production. For each indicator, the maximum result was set to 100%, and the results of the other variants are displayed in relation to this result. Both the midpoint and the endpoint impact categories are shown.

Table 4. LCIA results of 1 L of hydrolysate production—ReCiPe2016 endpoint (H).

Impact Category—Endpoint (H)	Unit	CF_E	CF_G	CGF_E	CGF_G
Fine particulate matter formation	DALY	1.23761×10^{-7}	4.11847×10^{-8}	1.00459×10^{-7}	3.74256×10^{-8}
Fossil resource scarcity	USD2013	5.11421×10^{-3}	1.14543×10^{-2}	4.29199×10^{-3}	9.67098×10^{-3}
Freshwater ecotoxicity	species.yr	5.65829×10^{-12}	1.37391×10^{-12}	4.56231×10^{-12}	1.28712×10^{-12}
Freshwater eutrophication	species.yr	1.95514×10^{-10}	3.25487×10^{-11}	1.56640×10^{-10}	3.20254×10^{-11}
Global warming, freshwater ecosystems	species.yr	1.53246×10^{-14}	4.63667×10^{-15}	1.23988×10^{-14}	4.24702×10^{-15}
Global warming, human health	DALY	1.85909×10^{-7}	5.62533×10^{-8}	1.50416×10^{-7}	5.15256×10^{-8}
Global warming, terrestrial ecosystems	species.yr	5.60955×10^{-10}	1.69739×10^{-10}	4.53859×10^{-10}	1.55474×10^{-10}
Human carcinogenic toxicity	DALY	5.40504×10^{-8}	1.29769×10^{-8}	4.36224×10^{-8}	1.22586×10^{-8}
Human non-carcinogenic toxicity	DALY	7.22232×10^{-8}	1.45792×10^{-8}	5.80340×10^{-8}	1.39608×10^{-8}
Marine ecotoxicity	species.yr	1.17604×10^{-12}	2.97527×10^{-13}	9.48016×10^{-13}	2.77497×10^{-13}
Marine eutrophication	species.yr	5.00794×10^{-14}	2.32071×10^{-14}	4.11218×10^{-14}	2.05738×10^{-14}
Mineral resource scarcity	USD2013	4.42486×10^{-5}	2.49979×10^{-5}	3.65981×10^{-5}	2.20109×10^{-5}
Ozone formation, human health	DALY	3.27457×10^{-10}	1.24118×10^{-10}	2.66199×10^{-10}	1.11612×10^{-10}
Ozone formation, terrestrial ecosystems	species.yr	4.67939×10^{-11}	1.78855×10^{-11}	3.80479×10^{-11}	1.60736×10^{-11}
Terrestrial acidification	species.yr	1.27981×10^{-10}	4.16676×10^{-11}	1.03836×10^{-10}	3.79231×10^{-11}
Terrestrial ecotoxicity	species.yr	2.74228×10^{-12}	2.26246×10^{-12}	2.31834×10^{-12}	1.95279×10^{-12}

Note: DALY—disability-adjusted life years; USD2013—US dollar reference year 2013; species.yr—damage to water and terrestrial species annually [37]; CF—chicken feathers; CGF—cleaned goose feathers; $_E$—electricity heating and steering; $_G$—gas heating and electricity steering.

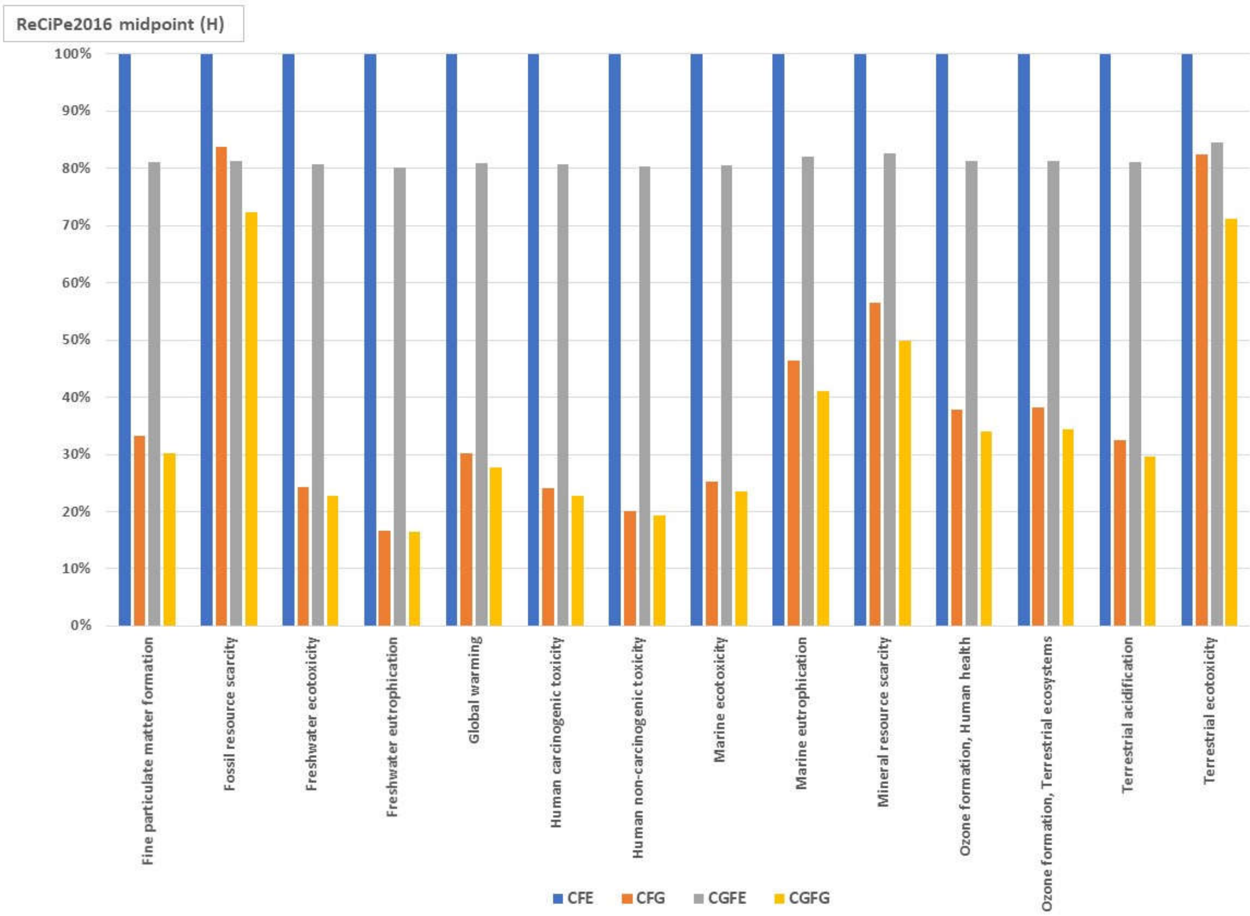

Figure 1. Relative indicator results of 1 L of hydrolysate production—midpoint indicators. Note: CFE—chicken feathers, electricity; CFG—chicken feathers, gas and electricity; CGFE—cleaned goose feathers, electricity; CGFG—cleaned goose feathers, gas and electricity.

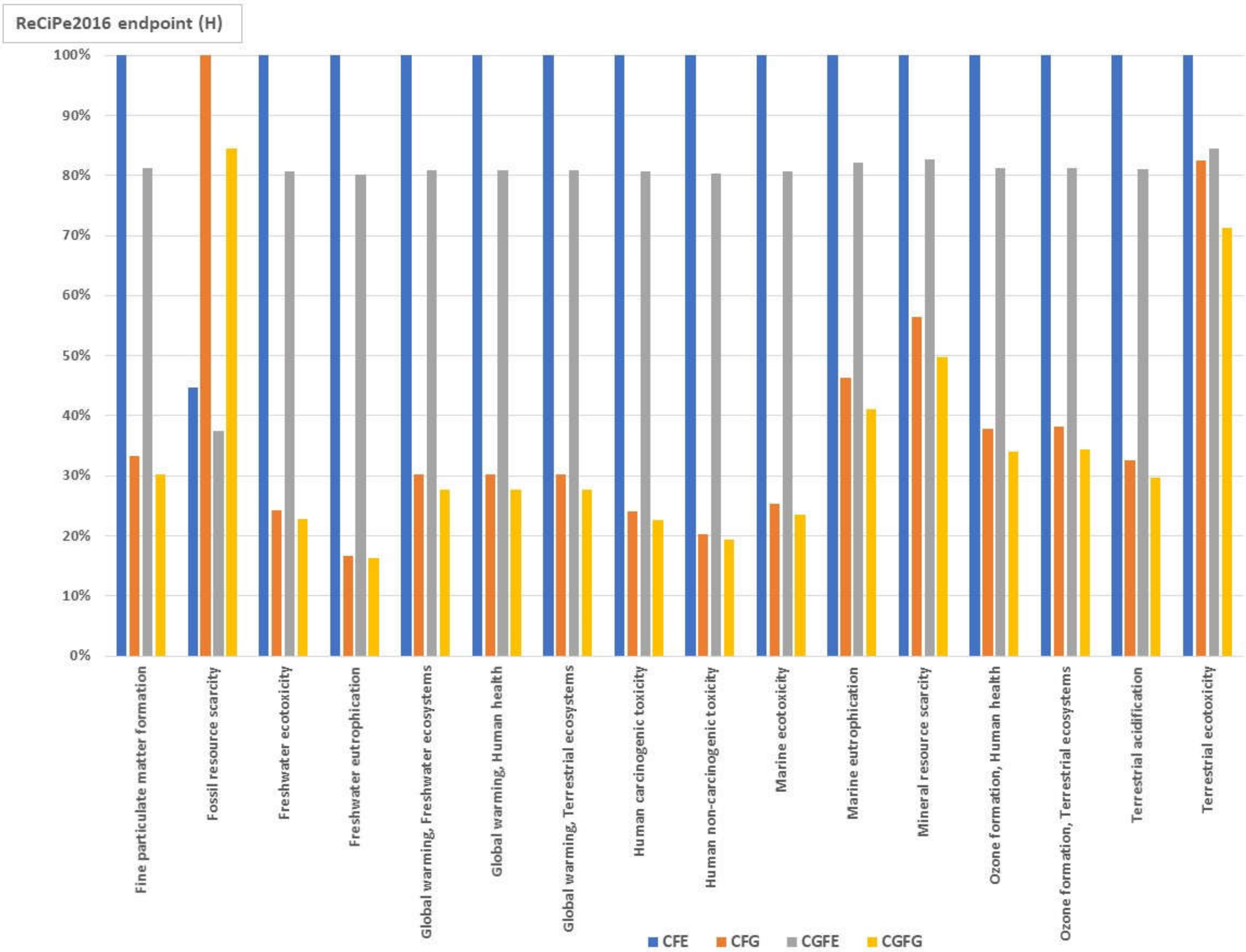

Figure 2. Relative indicator results of 1 L of hydrolysate production—endpoint indicators. Note: CFE—chicken feathers, electricity; CFG—chicken feathers, gas and electricity; CGFE—cleaned goose feathers, electricity; CGFG—cleaned goose feathers, gas and electricity.

Finally, the endpoint impacts were united into three damage categories concerning (1) humans, reflecting the disability-adjusted life years lost in the human population; (2) ecosystems, as the number of species lost integrated over a period; and (3) resources, pointing out their scarcity and potential exhaustion. However, it should be mentioned that fossil resource scarcity was in the midpoint category, which did not have a constant midpoint related to the endpoint factor [37]. Details are given in Table 5 and Figure 3.

Table 5. Sum of the damage of 1 L of hydrolysate production—ReCiPe2016 endpoint (H).

Damage to	Unit	CF_E	CF_G	CGF_E	CGF_G
Ecosystems	species.yr	9.40886×10^{-10}	2.65803×10^{-10}	7.60265×10^{-10}	2.45038×10^{-10}
Human	DALY	4.36271×10^{-7}	1.25118×10^{-7}	3.52798×10^{-7}	1.15282×10^{-7}
Resources	USD2013	5.15846×10^{-3}	1.14793×10^{-2}	4.32859×10^{-3}	9.69299×10^{-3}

Note: DALY—disability-adjusted life years; USD2013—US dollar reference year 2013; species.yr—damage to water and terrestrial species annually [37]; CF—chicken feathers; CGF—cleaned goose feathers; $_E$—electricity heating and steering; $_G$—gas heating and electricity steering.

Based on the presented results, it is evident that the main impacts of both waste materials on the environment differed only slightly. The finest material, namely, cleaned goose feather (CGF), and its lower electricity and gas requirement for the process heating reduced the midpoint as endpoint impacts by an average of 10–20% for electrical heating and 5–10% for its combination with gas. In general, the combined electric and gas heating showed a significantly lower impact in most observed categories on both levels, with the exception of the endpoint category of fossil resource scarcity, which was directly related to gas extraction and its supply. The highest impact on resources was also confirmed by the grouping into related damage categories, where 99.9% of the total burden fell on resource depletion. From the point of view of individual environmental indicators, the depletion of abiotic sources (fossil fuels consumption) and climate change contributed the most out of all the assessed variants of the feather hydrolysis processes, which were again related to the electricity and gas used.

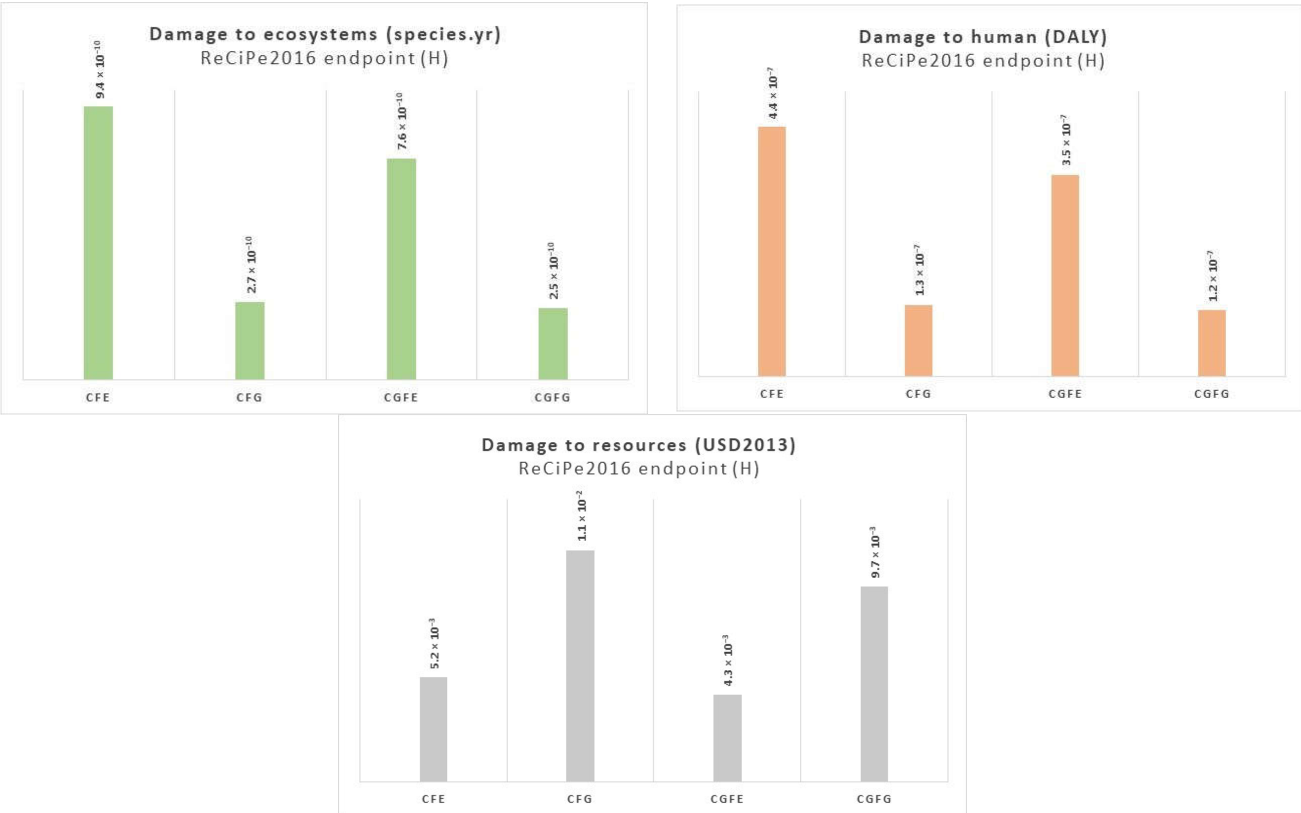

Figure 3. Damage of 1 L of hydrolysate production to ecosystems, humans, and resources. Note: CFE—chicken feathers, electricity; CFG—chicken feathers, gas and electricity; CGFE—cleaned goose feathers, electricity; CGFG—cleaned goose feathers, gas and electricity.

Since the ecoinvent database v3.8 provides updated data for renewable sources, a comparison of the impact of the use of environmentally friendly sources of electricity was performed. The data available in the same version of the ecoinvent database for the conventional production mix in the Czech Republic was used as a basis for the comparison. The calculation was done for both levels of impact, namely, the midpoint and endpoint.

The transition to a greener source of electricity helped to reduce the pressure on resources, of course mainly fossil fuel, by one order of magnitude in general. It also ensured reductions in impacts concerning freshwater and marine ecotoxicity and eutrophication, carcinogenic and non-carcinogenic human toxicity, ozone formation, and terrestrial acidification. A similar positive response was observed for both the midpoint and endpoint impact categories. The summarized results of the change in three endpoint damage categories—ecosystems, humans, and resources—are provided in Table 6 and Figure 4. Data from the midpoint impact calculation is not provided.

Table 6. Influence of renewable energy usage on the total damage caused by 1 L of hydrolysate production—ReCiPe2016 endpoint (H).

Damage to	Unit	CF_{ER}	CGF_{ER}
Ecosystems	species.yr	1.35887×10^{-10}	1.16266×10^{-10}
Human	DALY	6.80275×10^{-8}	5.82646×10^{-8}
Resources	USD2013	3.57527×10^{-3}	3.06203×10^{-3}

Note: DALY—disability-adjusted life years; USD2013—US dollar reference year 2013; species.yr—damage to water and terrestrial species annually [37]; CF—chicken feathers; CGF—cleaned goose feathers; $_{ER}$—renewable electricity used completely for heating and steering.

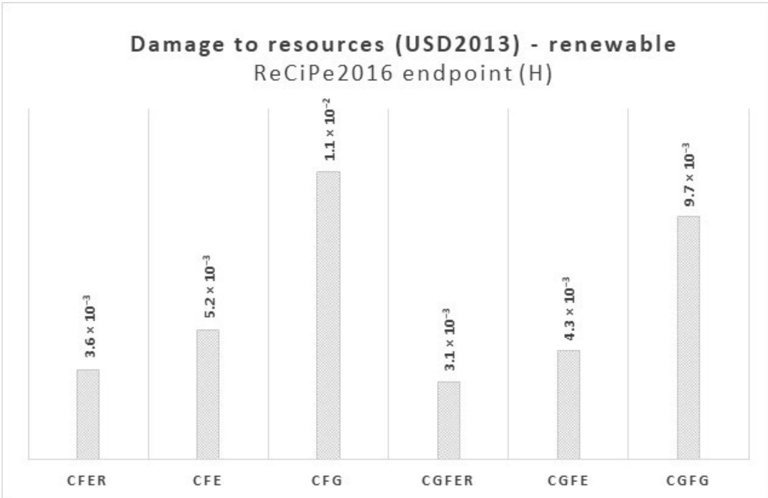

Figure 4. Comparison of damage of 1 L of hydrolysate production to resources using renewable energy, an energy mix, and natural gas. Note: CFER—chicken feathers, renewable electricity only; CFE—chicken feathers, electricity mix; CFG—chicken feathers, gas and electricity mix; CGFER—cleaned goose feathers, renewable electricity only; CGFE—cleaned goose feathers, electricity mix; CGFG—cleaned goose feathers, gas and electricity mix.

In addition, a sensitivity analysis was performed to confirm the dependence of the quantity of the hydrolysate production impact on the type of energy source used. For the sensitivity assessment, attention was paid to the production of 100 g of amino acids and peptides, which was set as a new functional unit (FU). For this purpose, the operational inputs and outputs of processing CF and CGF given in Table 2 were recalculated to this FU based on the maximal and minimal sums of amino acids and peptides. During the calculation, only the consumption of electricity for reactor heating and steering was considered. The gas variant was not calculated. The system boundaries and physical allocation of the production system remained the same.

The conversion to 100 g production of amino acids and peptides showed that 2.71–4.41 L of CF hydrolysate compared with 1.90–2.16 L of hydrolysate made from CGF waste were needed, depending on the minimal and maximal amino acids and peptides contents in both compared hydrolysates. At the same time, the dependence of the total environmental impact of the hydrolysate production on energy consumption was confirmed, as the processing of CGF waste was less energy-demanding and also served as a better substrate for the production of amino acids and peptides. Moreover, the CF hydrolysate with the maximum content of amino acids and peptides did not reach the level of environmental impacts caused by the production of the CGF hydrolysate with the minimum content of amino acids and peptides. For both levels, i.e., the midpoint and endpoint, the worst relative impacts on the environment were associated with the CF hydrolysate with the minimum content of amino acids and peptides (the relative indicator result = 100% in all assessed impact categories), followed by the CF hydrolysate with the maximum content of amino acids and peptides (62%), the CGF hydrolysate with the minimum content of amino acids and peptides (41–47%), and the CGF hydrolysate with the maximum content of amino acids and peptides (36–40%). Figure 5 shows the calculated relative indicator results of the total impact related to the FU of 100 g amino acids and peptides production. Full data from the midpoint and endpoint impact calculations are not given.

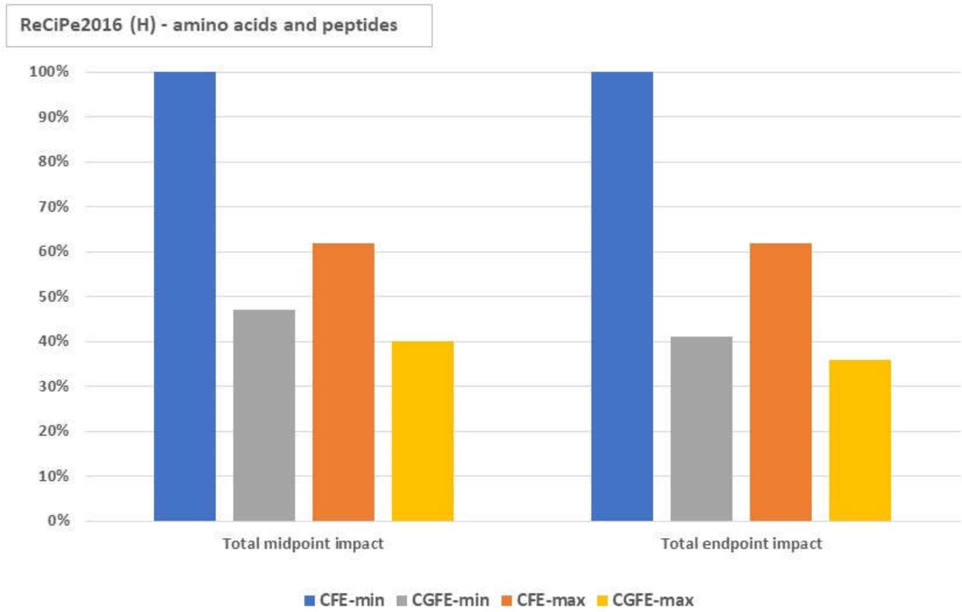

Figure 5. Relative indicator results of 100 g amino acids and peptides production—total of midpoint and endpoint indicators. Note: CFE-min—chicken feathers, electricity, minimum content; CFE-max—chicken feathers, electricity, maximum content; CGFE-min—cleaned goose feathers, electricity, minimum content; CGFE-max—cleaned goose feathers, electricity, maximum content of amino acids and peptides.

4. Economic Analysis

The analysis of the economic efficiency of the proposed technology of processing feathers as the waste from chicken meat production or cleaning of goose feathers is focused on the assessment of the efficiency of the technology of processing this type of waste without the influence of the other activities of the enterprise. The following assumptions were chosen for the analysis:

- In terms of energy consumption (electricity and natural gas), the company was a medium-sized enterprise consuming electricity from the high-voltage network (consumption above 500 MWh and up to 2500 MWh per year) and the medium-pressure natural gas network (consumption between approx. 2800 and 28,000 GWh of gas per year).
- For the economic analysis, the Czech Republic's price level for 2021 was used, with the average profitability of industrial companies in the Czech Republic taken from 2019 data (excluding the impact of anti-COVID measures).
- The economic efficiency of the feather hydrolysis technology was assessed using the levelized cost indicator [38]. This approach assessed the technology as such in terms of direct investment and operating costs and excluded the impact of taxes and financing.
- One batch of feathers (in both options considered) was processed within 24 h. This included both the direct time for heating and cooling of the mixture and the time associated with draining and cleaning the reactor and refilling it.
- A total of 200 batches were assumed to be processed in one year, i.e., 200 effective shifts (only working days were assumed to be used, subtracted from the days for the plant maintenance).

The basic formula for the levelized cost per batch (LC_{batch}) is

$$LC_{batch} = \frac{CRF_{i,T} \cdot CAPEX}{No_{batch}} + OPEX_{batch} \quad (1)$$

where:

$CRF_{i,T}$—capital recovery factor for the required return on investment i and equipment lifetime T;
$CAPEX$—investment cost;
$OPEX_{batch}$—direct operating costs per batch;
No_{batch}—number of batches per year.

Data on the material and energy inputs were taken from the input data for the LCA analysis mentioned above. The option of processing waste feathers from chicken meat production was chosen as the baseline option. The goose feather waste treatment option differed slightly in both the amount of solid waste (residue) after hydrolysis and the shorter reactor heating time (5 h as opposed to 6 h for chicken feathers). In both cases, the cooling time of the reaction mixture was assumed to be the same, namely, 10 h. Regarding the second case (waste from goose feather cleaning), although the reactor heating time was shorter, the same amount of energy would need to be supplied to the process to heat the mixture of feathers, water, and malic acid being treated (the reaction temperature was the same in both cases). The shorter reaction time would only result in a reduction in the energy required to cover the process losses (reactor heat leakage). This amount of energy was insignificant compared with the total amount of energy required to heat the mixture.

Energy prices were taken from Eurostat data for 2021 and the Czech Republic. The average price of electricity for this category of companies was 90.5 EUR/MWh [39], and for natural gas, the price was 32.8 EUR/MWh [40]. The prices are without VAT and include both the commodity part and the costs associated with electricity and gas distribution. The price of water was taken as the average price of water supplied by individual water companies in the Czech Republic, namely, EUR 1.7/m^3 (water supply only, excluding wastewater treatment costs) [41]. Labor costs were assumed to be at the average rate for the business sector for 2021, namely, EUR 1514/month (gross). That, together with the 2021 working time of 2088 effective hours (paid by employers) and social and health insurance paid by employers, resulted in an average personnel cost per hour of EUR 11.66 [42]. The malic acid costs were taken from the suppliers' offers for the medium category of customers (average value from the 2021 price survey from internet offers), namely, EUR 5.2/kg. The direct operating costs included other operating costs related to the handling of the feathers and the output product and the cleaning of the reactor after one batch. These costs were estimated at EUR 14 per batch. A summary of the direct operating costs of the technology is given in the following Tables 7 and 8.

Table 7. Inputs for the economic analysis—chicken feathers.

Input	Per Batch
Chicken feathers (kg)	340.0
Electricity * (kWh)	543.0
Electricity ** (kWh)	81.5
Natural gas ** (kWh)	687.5
Water (m^3)	2.5
Malic acid (kg)	18.0
Labour (h)	10.0

Note: * Alternative where electricity was used for both the technology and the actual heating of the reaction mixture. ** Alternative where natural gas was used to heat the reaction mixture, electricity was only for technological consumption.

Table 8. Prices of the inputs and per batch—chicken feathers.

		Per Batch *	**Per Batch ****
Item	**Price**	**EUR**	**EUR**
Electricity (EUR/MWh)	90.5	49.1	7.4
Water (EUR/m^3)	1.7	4.2	4.2
Natural gas (EUR/MWh)	32.8	0.0	22.5
Personnel cost (EUR/h)	11.7	116.6	116.6
Malic acid (EUR/kg)	5.2	93.5	93.5
Other costs	-	14.0	14.0
Total Direct OPEX (EUR)	**-**	**277.4**	**258.2**

Note: * Alternative where electricity was used for both the technology and the actual heating of the reaction mixture. ** Alternative where natural gas was used to heat the reaction mixture, electricity was only for technological consumption.

The investment costs were estimated to be EUR 210,000. These costs included only the radial flow agitator itself and the necessary associated technology, and they did not include the additional costs of the necessary plant infrastructure. To calculate the annual fixed costs, an assumption of a technology lifetime of 10 years and an average return to manufacturing companies of 10–11% (excluding the effect of inflation) was used [43]. The value of the annual fixed costs then reached EUR 34,177 (for a return of 10%) and the fixed costs per batch were EUR 171.

The total cost per batch for the processing of 340 kg of waste chicken feathers then reached about EUR 429–448 (depending on the reactor heating variant), which subsequently reached about EUR 0.158–0.165 per 1 L of hydrolysate. This is the direct cost of hydrolysate production, which included neither the cost of product logistics (storage, packaging, dispatch to final consumers) nor the cost of the procurement of feedstock. Regarding the nature of the feedstock processed (waste feathers from chicken meat processing or waste from cleaning goose feathers), it could be assumed that processing these feedstocks saves on waste disposal costs. Therefore, it can be assumed that the costs associated with the procurement of the feedstock are borne by the waste producer, and therefore, the valuation of the feedstock is zero. Concerning the option of processing waste from cleaning goose feathers, there was a small saving in energy costs (shorter reaction time); however, at the same time, the solid waste was slightly lower. Related to this, it led to a reduction in the cost per liter of hydrolysate of about 4–5%.

The energy costs (electricity, natural gas) were a relatively significant item in the total production cost of 1 L of hydrolysate. For example, in the case of processing waste chicken feathers and using only electricity as an energy input for the process, the energy cost share (in average 2021 prices) was about 11%. Toward the end of 2021, and especially during 2022, all energy prices have been rising dramatically, with spot prices for natural gas (commodity part only) reaching approx. 130–150 EUR/MWh in the second half of October 2022. This means approx. 5 times higher prices (after supply costs) than the average supplier prices to medium-sized enterprises in 2021. Therefore, this aspect was proportionally reflected in the cost of hydrolysate production. For example, with the option of using natural gas to heat the reaction mixture and a natural gas price of EUR 130/MWh, the total cost of producing 1 L of hydrolysate increased only slightly to approx. EUR 0.183/L from the original EUR 0.165/L.

5. Case Study—Fertilization of Cayenne Pepper with Hydrolysate from Chicken Feathers

The aim of the experiment was to evaluate the fertilizing effect of nitrogen from the hydrolysate on the production characteristics of crops in a greenhouse with controlled growing conditions.

Crop: The variety ‘Golden Cayenne’ of cayenne pepper (*Capsicum annuum*) was chosen as a model plant suitable for growing during the ‘summer window’, ensuring standard greenhouse production. Photographs of the experiment are provided in Figure 6.

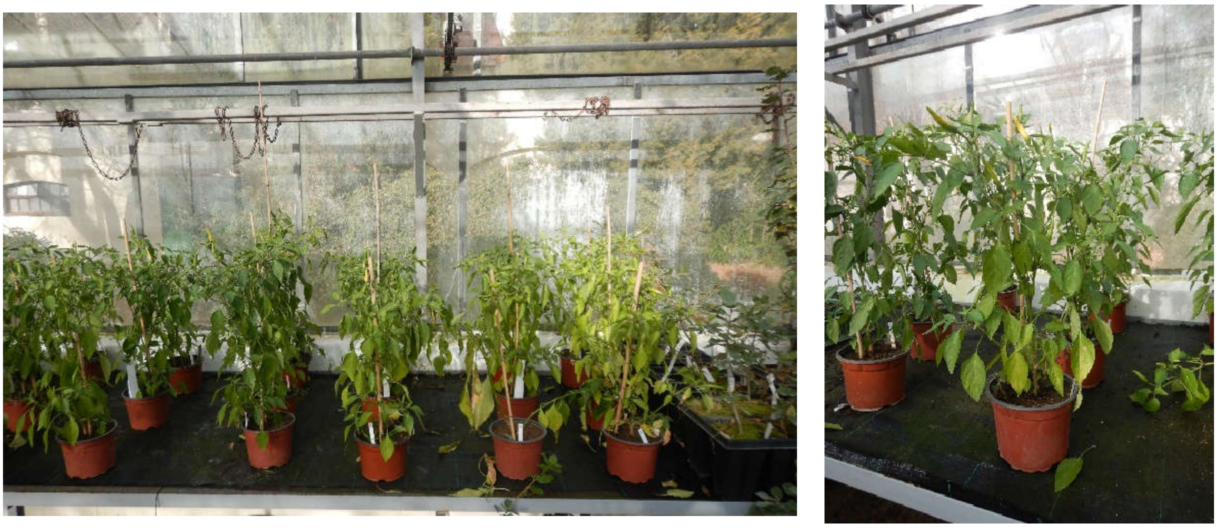

Figure 6. Greenhouse experiment with cayenne pepper 'Golden Cayenne' fertilized with hydrolysate (view of the experiment and plant with ripening peppers).

Design of the experiment: 36 seedlings of identical size were transplanted into containers on June 21. The number of replications was three. Substrate: Plants were grown in containers (Ø 15 cm, 2 liters) with a standard type of growing substrate (VÚKOZ B) consisting of a mixture of peat/bark/loess in the volume ratio of 5/3/2 m^3. It involved a supply of some additional nutrients (P, K) for the 107-day experiment period in 2021. Watering and fertilization: Water was applied to the substrate and leaves depending on the drying of the substrate. Fertilization was performed seven times during the experiment with hydrolysate (H: 5%) and control fertilizer (FC: with an identical concentration of 200 mL N/L—solution of ammonium nitrate 10 mL NH_4NO_3/L of water).

Evaluation of the peppers: The biometric parameters of the plants (height and diameter $D_{0.1}$), health status, and weight of ripe peppers (yield) were measured during the experiment. Qualitative parameters of peppers were also evaluated (concentration of capsaicin, nutrients, and amino acids). Statistical methods were used to analyze the interaction between plants and fertilizers. Differences between the effects of two fertilizers (hydrolysate and control) on the biometric parameters of the peppers were compared using the independent sample *t*-test. Statistical analyses were performed using the SW TIBCO Statistica Desktop program (version 14.0).

Results of the experiments showed the following:

- Evaluated biometric and production parameters of cayenne peppers were slightly higher in the control variant (+1–10%), but none of them were statistically significant (Figure 7; independent t-test, $p > 0.05$).
- The health of the peppers was good during the experiment. The usual occurrence of aphids on young peppers was the same for both application variants.
- The qualitative parameters of the peppers (content of capsaicin, nutrients, and amino acids) were the same for both application variants.

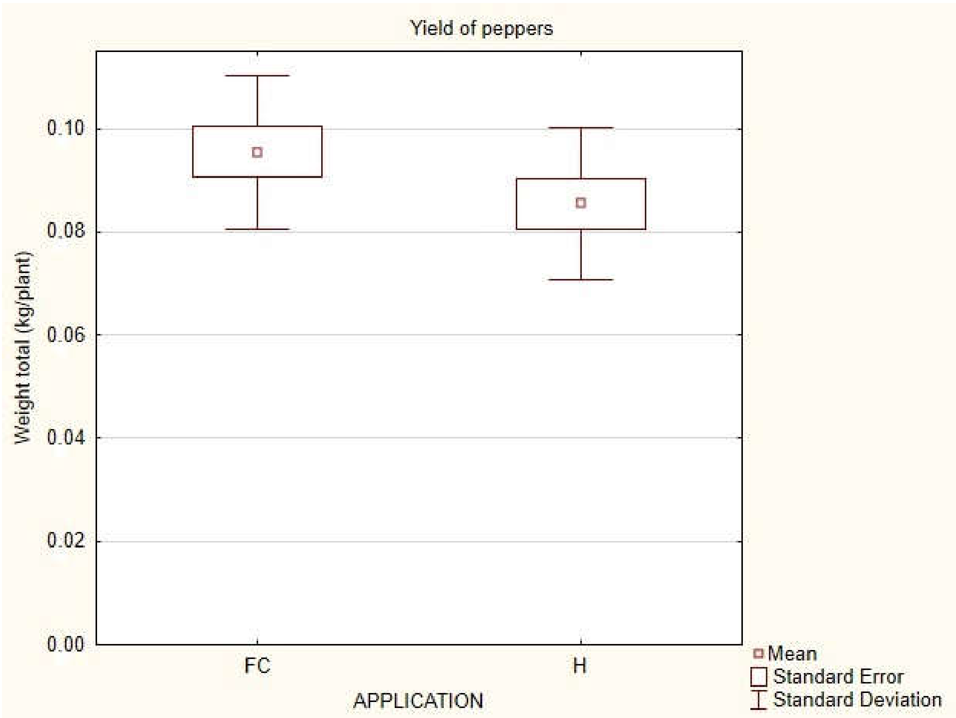

Figure 7. Cumulative yield of peppers in a greenhouse experiment fertilized with hydrolysate (H) and ammonium nitrate (FC) (*t*-test, $p = 0.1708$).

6. Conclusions

This study involved a comparative environmental life cycle assessment of the production of nutrient-rich hydrolysate from two waste materials—chicken feathers (CF) and goose feathers received after cleaning blankets (CGF). These wastes are produced by poultry slaughterhouses and industrial cleaners of duvet covering. They can be used as valuable materials for the production of nutritionally interesting liquid fertilizers, as confirmed in our case study with cayenne peppers. This idea supports the secondary use of waste, and thus, fulfills the concept of the circular economy by reintroducing them back into the economy as high-value products.

The LCA study confirmed that the environmental impacts of hydrolysate production were highly dependent on the electricity required and its sources. The better the quality of the waste feathers was and the finer they were, the less energy was needed regarding the whole process; moreover, a higher yield of amino acids and peptides was expected. This fact helped to reduce the midpoint and endpoint impacts on the individual environmental categories. The source of energy also played a significant role in the overall impact on the environment. Regarding the potential negative impacts of the process on freshwater and marine and terrestrial environments, plus the contribution to toxicity to humans and ozone formation, they can all be minimized if renewable energy is used. Furthermore, it would also minimize the pressure associated with fossil resource scarcity and the related impact on climate change.

The economic analysis calculated the total cost per batch for processing 340 kg of waste chicken feathers, namely, approx. EUR 429–448 (depending on the reactor heating variant), which subsequently meant approx. EUR 0.158–0.165 per 1 L of hydrolysate. Concerning the option of processing waste from cleaning goose feathers, there was a small saving in energy costs related to the reduction in cost per liter of hydrolysate of about 4–5%. Energy costs represented a relatively significant item in the total production cost of 1 L of hydrolysate, especially during 2022 since all energy prices have been rising dramatically. However, the total cost of producing 1 L of hydrolysate increased only slightly to approx. EUR 0.183/L from the original EUR 0.165/L.

Finally, the case study experiment confirmed the fertilizing effect of the hydrolysate on pepper plants (biometric parameters, yield) related to the level of the control (FC), i.e., doses of 10 mL NH_4NO_3/L. Therefore, it could be concluded that hydrolysate might be used for the production of liquid fertilizers as a suitable substitute for the nitrate that is commonly drawn from fossil raw materials. However, the most appropriate application of hydrolysate probably lies in its use as a bio-stimulant and the protection of plants against stresses, ensuring sustainable agriculture.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ISO	International Organization for Standardization
CEAP	Circular Economy Action Plan
CF	Chicken feathers
CFE	Chicken feathers, electricity mix
CFER	Chicken feathers, renewable electricity only
CFG	Chicken feathers, gas and electricity mix
CGF	Cleaning goose feathers
CGFE	Cleaned goose feathers, electricity mix
CGFER	Cleaned goose feathers, renewable electricity only
CFPH	Chicken feather protein hydrolysate
CGFG	Cleaned goose feathers, gas and electricity mix
CML	Center of Environmental Science, Leiden University (Centrum voor Milieukunde Leiden)
DALY	Disability-adjusted life years
DCB	Dichlorobenzene
EGD	European Green Deal
FU	Functional unit
PM	Particulate matter
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
ReCiPe	'Recipe' to calculate life cycle impact category indicators
RIVM	Dutch National Institute for Public Health and the Environment
species.yr	Damage to water and terrestrial species annually
US2013	US dollar reference year 2013
VÚKOZ B	Growing substrate for pot plants (used in the case study)
E	Electricity heating and steering
G	Gas heating and electricity steering

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