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# Unlocking New Value from Urban Biowaste: LCA of the VALUEWASTE Biobased Products

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**Abstract:** The VALUEWASTE project can offer a sustainable solution to transform biowaste into added-value bioproducts, such as proteins from microorganisms and insects and biofertilizers. The present study focused on the environmental impacts linked to obtaining these bioproducts, which was performed by the standardized Life Cycle Assessment (LCA) approach, using the Environmental Footprint methodology to evaluate the midpoint impact categories considered. At the same time, the bioproducts coming from biowaste were compared to regular ones: other protein sources and mineral fertilizers. The study results show that these new protein sources are firm candidates to reach the market from an environmental point of view. Furthermore, their environmental impacts could be improved by reducing the energy use (the main contributor) within some impact categories, such as ecotoxicity and global warming. In case of the biofertilizers, their environmental performance was overall worse compared to mineral fertilizers, except for the following impact categories: mineral and metal use and water scarcity. Nevertheless, these biofertilizers come from biowaste, extending the circularity concept, and from local places, reducing the dependency on other actors. Hence, the study showed that the obtained bioproducts are real alternatives to implement in a circular economy. However, continuous improvement of the solution should be performed.

**Keywords:** biowaste valorisation; bioproducts; circular economy; microbial proteins; insect proteins; biofertilizers

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## 1. Introduction

The population is increasing day by day, estimated to reach about 10 billion people by 2050 [1]. This continuous increase in the worldwide population creates the need to produce more food and feed, estimated to need to increase between 60% and 70% [2,3]. This challenge leads to the need of improving the yield of crops by using fertilizers (non-renewable resources) and increasing livestock populations [3], which need to be done in a sustainable way. In addition, municipal solid waste (MSW) generation is expected to rise with increasing population and food and feed consumption.

Municipal solid waste is composed of diverse kinds of waste, including the organic fraction (OFMSW, biowaste from now onwards), whose percentage is widely ranged and can reach about 70% of the total [4]. The global amount of MSW generated is about 2.01 billion tones/year and it is estimated to increase by 69% in the next three decades [5]. Not all regions throughout the world have undergone equal levels of population density, urbanization, and economic development, leading to differences in MSW generation and its treatment methods. North America, as a highly developed region, had the highest MSW generation in 2016 (2.21 kg per person per day). This region is followed by Europe and Central Asia (ECA), Latin America and Caribbean (LAC), and Middle East and North Africa (MENA), with 1.18, 0.99, and 0.88 kg per person per day, respectively. South Asia and East Asia and Pacific (EAP) generated a quarter of North America, the lowest rate (0.46 kg per person per day) belonging to Sub-Saharan Africa [6]. Concerning the MSW treatment methods in the regions mentioned above, landfilling is the most common one in South Asia, Sub-Saharan Africa, and ECA, despite its harmful impact on the environment. In 2016, about 37% of global MSW was landfilled, primarily in North America, LAC, and EAP. On the other hand, recovery technologies were applied for 30% of the MSW generated globally, especially in ECA (49%), North America (46%), EAP (36%), and South Asia (21%) [6].

In the last decades, the approach towards biowaste management has been linear, just like the economy, based on extracting raw materials, fossil fuels as an energy source, and landfill as waste management [7]. It must be kept in mind that resources are limited. However, humans consume in a few months all the biological resources that the Earth regenerates during a complete year. This day is known as the Earth overshoot day, which is reached earlier year by year. In the current year (2022), it was reached on 28 July [8]. Hence, it is necessary to preserve those resources and respect the natural cycles. Therefore, the main question is how to address these challenges. In this context, the circular economy (CE) concept was born. The CE model promotes the use of diverse types of waste, by-products, etc., to obtain new products, thereby minimizing the utilisation of raw materials and the quantity of waste generated [9].

Under the CE approach, biowaste is seen as a very valuable resource to produce a range of commodities. Among the long list of products that can be produced from biowaste, biofertilizers and other nutritional sources, such as the emerging protein from insects, yeast, and microalgae, have attracted attention in the last decade [3,9,10]. Biowaste valorisation under a CE perspective is crucial for societies to keep their current lifestyles, ensure their near future needs, reduce the environmental and social issues linked to the linear economy, and decrease the use of biological resources.

Some European projects within the H2020 programme are trying to cope with the rising population and consequent increased demand for food and feed. These projects are fully aligned with biowaste/circular economy European regulations to foster the transition to a circular economy, contributing to a cleaner and more competitive Europe. This is for example the case of WaysTUP! [11], which aims to demonstrate the establishment of new value chains for OFMSW utilisation, producing higher-value compounds in line with CE. The Scalibur project [12] demonstrates innovative value chains to transform food waste and sewage sludge into high value-added products, creating new circular economy business opportunities. In VALUEWASTE (coordinated by CETENMA) [13], urban biowaste is valorised into proteins for food and feed as well as biofertilizers. This project develops the first complete solution to fully valorise biowaste into high-value biobased products, closing the loop of this waste stream, and which can be replicated across Europe. In order to achieve this goal, three value chains, starting from anaerobic digestion, have been validated (Figure 1), obtaining four main products: (i) methane, which is used by microorganisms and transformed into microbial proteins; (ii) digestate, which is used by black soldier flies, producing insect proteins; and (iii) a nutrient rich effluent, which is transformed into biofertilizers. Figure 1 displays a dotted arrow, linking the possibility of using microbial proteins for human consumption as considered in VALUEWASTE. However, the assessment of the process for this purpose was not included in the present manuscript because it is currently under development.

When developing new products or processes, in addition to being technically feasible, they must be subject to evaluation from environmental, economic, and social points of view. As discussed by Khoshnevisan et al. [14], depending on the feedstock quality and availability, the different biowaste valorisation pathways, and the downstream strategies, the net environmental benefits of the new products may vary. To evaluate the environmental impact of new products, it is required to use adequate tools. One of the most used, standardised and sophisticated tools to perform this analysis is the Life Cycle Assessment (LCA). The LCA compiles and evaluates the inputs, outputs, and the potential environmental impacts of a product/process/service system throughout its life cycle. The LCA is a mature, multi-criteria, standardized [15,16] ISO 14040 and ISO 14044) methodology for environmental management, being very useful for the identification of priorities and the materialization of efficient policies [17].

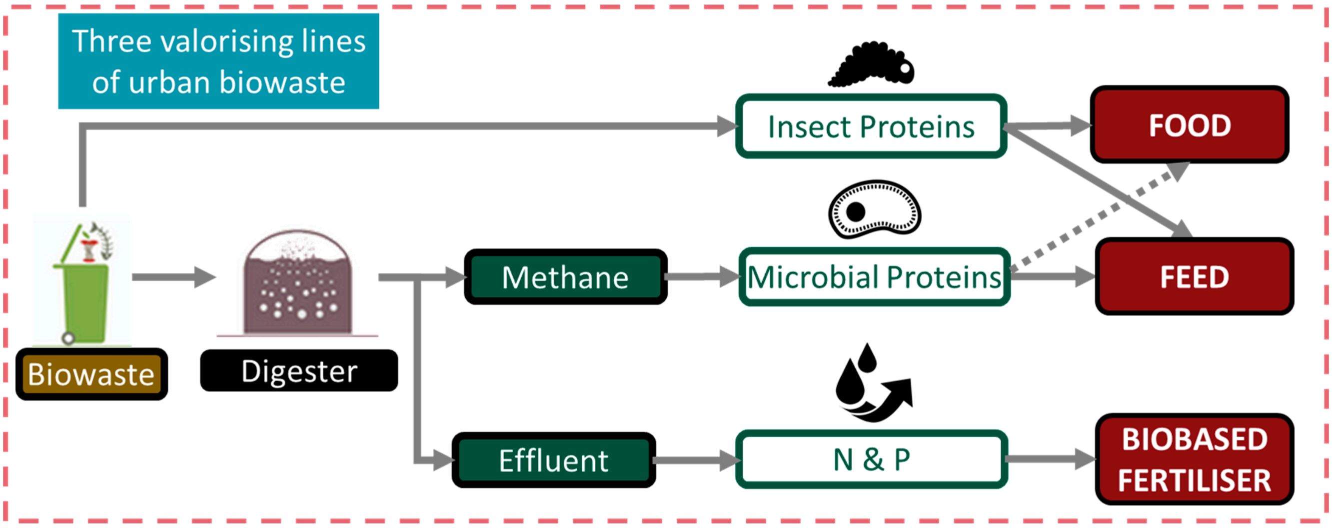

**Figure 1.** Basic scheme of the processes tested under the VALUEWASTE solution.

Therefore, the main goal of the present study is to present and assess the environmental impacts of VALUEWASTE products by the LCA methodology, including different allocations factors to appropriately evaluate the specific impact on each bioproduct. The evaluated products are single-cell proteins (SCP), black soldier fly proteins (BSFP), and biofertilizers ($(NH_4)_2SO_4$ and struvite). From the results presented in this study, one of the VALUEWASTE aims—to provide evidence-based support for EU policies/targets regarding a biobased and circular economy—can be reached.

Other studies have evaluated these products using LCA approaches: Bava et al. [18], Mertenat et al. [19], and Maiolo et al. [20] considered the strategy of using BSF. In the first case, to evaluate the growth performance of *Hermetia illucens* reared on a control hen diet; in the second case, work was carried out following a lineal rather than circular economic model; and in the third case, there was a focus on meeting the challenge of securing aquafeed. Other researchers, such as Khoshnevisan et al. [14], employed OFMSW to obtain high-value bioproducts and bioenergy, basing their data on just two batches of OFMSW. LaTurner et al. [21] used purple non-sulphur bacteria to extract resources from food waste to produce a protein supplement for animal feed. On the other hand, the LCAs performed by Styles et al. [22] and Thomsen et al. [23] merely studied the production of fertilisers and biogas from organic waste. Finally, Tian et al. [24] identified anaerobic digestion as an efficient food waste disposal technology. Therefore, none of them addressed the OFMSW valorisation developing different waste management chains at the pilot scale to close the loop. This is one of the challenges successfully tackled in the present work.

## 2. Materials and Methods

### *2.1. Life Cycle Assessment (LCA)*

The LCA intends to be an integrated tool for the multi-criteria assessment of products and services through its whole value chain, covering a wide variety of pressures and impacts related to human health, environment, and resources [25]. In brief, the LCA is composed of four steps: (i) goal and scope, where the aim of the study is defined together with the system boundaries and the functional unit (FU), which is the computing reference unit; (ii) inventory analysis, where data (inputs and outputs) are gathered and referred to the FU; (iii) environmental impact assessment, where inputs and outputs identified in the inventory are related to their impact on the environment, which is quantified; and (iv) results interpretation.

### 2.1.1. Goal and Scope Definition

Goal: The aim of the present study was to quantify the environmental differences between the products (proteins for feed and food, and fertilizers) obtained through the new processes proposed by VALUEWASTE and those manufactured in a regular way (baseline).

Scope: Figure 2 shows the production process of VALUEWASTE to obtain both bioproteins (SCP and BSF proteins) and biofertilizers (struvite and ammonium sulphate) in the course of the biowaste (feedstock) valorisation. Additionally, the different by-products (compost and water treated) are shown as well. The VALUEWASTE process consists of several steps both upstream and downstream to optimise the valorisation of the biowaste in the aforementioned bioproducts, integrating the entire process in a city context. The type of LCA considered is "cradle-to-gate", where the raw material (biowaste) was treated, all the inputs and outputs throughout the valorisation were considered, and the product use was not included in the studied system. Therefore, the environmental burdens related to the use and end-of-life disposal phases of these products were not included. Following, the VALUEWASTE process is briefly described.

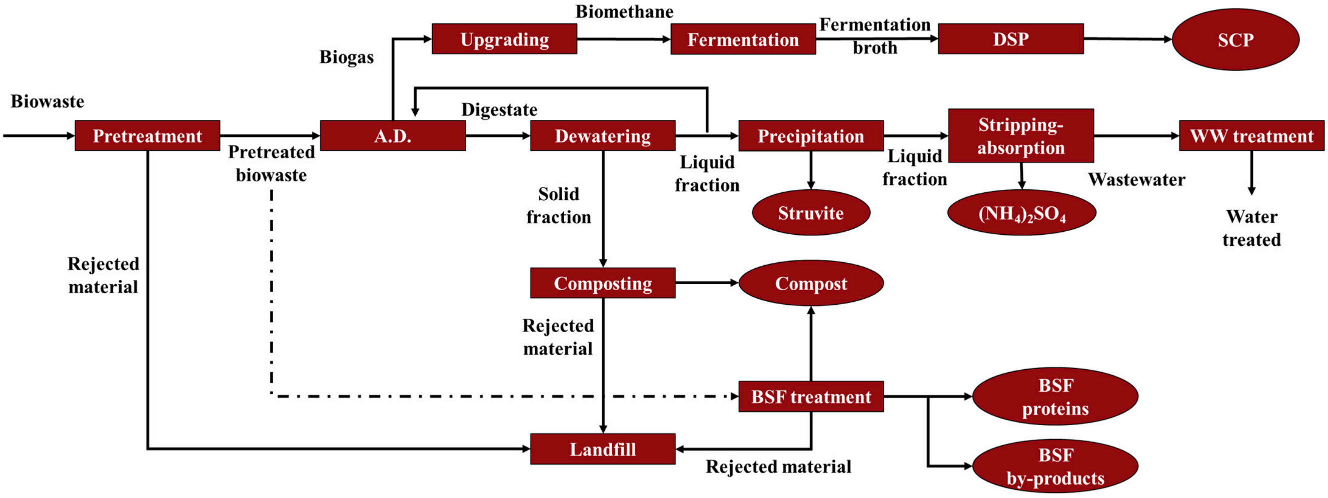

**Figure 2.** Flowchart of the VALUEWASTE production processes. A.D.: anaerobic digestion; BSF: black soldier fly; DSP: downstream process; SCP: single-cell protein; $(NH_4)_2SO_4$: ammonium sulphate.

First of all, the biowaste is pre-treated (PBW), as some inappropriate material content can be expected, which must be removed as much as possible. The obtained fines are the material used as biowaste in the subsequent stages. The rejected fraction is removed by landfilling. Afterwards, an anaerobic wet digestion of the biowaste is performed, producing biogas and digestate. Water is added in order to reduce the solid matter concentration, which is too high for this kind of process. As observed in Figure 2, there is a water recirculation coming from the dewatering step of the digestate to minimize the freshwater consumption. Each of these two products is, in turn, the raw material of a particular value chain: biogas to produce SCP and digestate to obtain biofertilizers.

Single-cell protein (SCP): Biogas is upgraded (carbon dioxide ($CO_2$) and impurities removal) and biomethane ($bCH_4$) is obtained. Subsequently, the $bCH_4$ is used in the fermentation process, which is consumed by methanotrophic bacteria producing new biomass. This new biomass passes through a centrifuge and a concentrate (20–25% of solid matter) is obtained. Thereafter, the supernatant is recirculated and returned back to the U-Loop fermentor and used again as a substrate; thus, reducing the water consumption. The cells are broken by a high-pressure homogenization process (HMG) and treated by an ultra-high-temperature process (UHT). Lastly, the concentrate is spray dried, attaining the final product: a granular solid, with 4 to 8% moisture, and a protein content between 70 and 73% (dry basis). This process is performed to obtain microbial proteins for use in feed.

Biofertilizers: The digestate contained a high amount of organic matter, in addition to nitrogen and phosphorus, mainly ammonium and phosphate, respectively. The solid and liquid digestate fractions were separated by a screw press, forming two streams. The solid fraction (sludge) is a good raw material to produce compost: another VALUEWASTE by-product. The liquid fraction contains a high concentration of phosphates and ammonium. Firstly, magnesium chloride ($MgCl_2$) is added to precipitate struvite ($NH_4MgPO_4{\cdot}6H_2O$), which is performed increasing the pH (pH $\approx$ 9) by air stripping and adding NaOH. The precipitated struvite is then removed from the precipitation reactor, washed, and dried. Secondly, and after the precipitation stage, there remained ammonium without reacting. This ammonium is transformed into ammonia ($NH_3$) and extracted by means of an air-stripping treatment. The air charged with the stripped $NH_3$ is then bubbled in an absorption column with $H_2SO_4$, producing the ammonium sulphate ($(NH_4)_2SO_4$) by an acid–base reaction. This last precipitate is removed and dried. As observed (Figure 2), wastewater is generated during the biofertilizers production, which need to be treated before releasing it into the environment.

Black soldier fly protein (BSFP): The PBW was also used to obtain proteins from *Hermetia illucens* (BSF) larvae (Figure 2). To manufacture this product, PBW was used as feed by BSF larvae for 15 days (fattening period). During this period of time, larvae transform the PWB into proteins and fats, excreting a stabilized substrate. After the fattening period, the substrate and larvae were separated. The first one was also used as compost; whereas, the larvae were washed, sanitized with steam, and crushed, obtaining a wet paste that is the raw material of the downstream process. Afterwards, the wet paste was subjected to severe conditions (high temperature and pressure) to hydrolyse the proteins. The hydrolysate passed through a three-phase centrifuge, where the water (which is recirculated to the process), fats, and a solid paste are produced. Fats can be used as an insect oil (by-product), whereas the solid paste is the main product, whose protein content ranges between 65 and 72% after drying. At this point, it is interesting to mention that not all the larvae are used to produce BSF proteins, as 5% of the larvae were left to reach their adult stage, in order to ensure the next generation.

Functional unit: The FU is the quantification of an input or output flow that serves as a reference for all the inputs and outputs, which is necessary for assuring the representativity of the system and the comparability among systems. Considering the goal of the study, the FU selected was one kilogram of product at the gates of the production facility, being 1 kg of protein coming from microorganism and insect, 1 kg of $(NH_4)_2SO_4$, and 1 kg of nitrogen content in struvite.

### 2.1.2. Life Cycle Inventory

Life Cycle Inventory (LCI) involves both the data collection and calculations performed to quantify the inputs (energy and raw materials) and outputs (emissions to air, soil and water) of the studied system, taking as reference the functional unit. The inventory data to perform the present study are summarized in Tables 1–3.

**Table 1.** Life Cycle Inventory for the single-cell protein to obtain 1 kg of protein from microorganisms (SCP).

| Stage | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|
| Biowaste pretreatment and anaerobic digestion | Biowaste | 71.4 kg | Leftover biogas (to upgrade) | | | 7.1 kg |
| | $FeCl_3$ | 0.1 kg | Solid fraction of digestate | | | 47.5 kg |
| | Polyelectrolyte | 0.04 kg | Liquid fraction of digestate | | | 39.2 kg |
| | Tap water | 28.8 kg | Rejected materials to landfill | | | 6.4 kg |
| | Diesel | 0.09 kg | Emissions to air | | | |
| | Electricity | 12.0 MJ | $CH_4$ | 0.083 kg | CO | 1.07 g |
| | | | $CO_2$ | 0.296 kg | $NO_x$ | 1.96 g |
| | | | $N_2O$ | 0.014 g | $SO_2$ | $6.00 \times 10^{-3}$ g |

**Table 1.** *Cont.*

| Stage | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|
| | | | $NH_3$ | $8.00 \times 10^{-4}$ g | NMVOCs | 0.156 g |
| | | | PM10 | 0.079 g | PM2.5 | 0.079 g |
| Biogas upgrading | Leftover biogas (to upgrade) | 7.1 kg | Biomethane | | | 2.51 kg |
| | Activated carbon | 9.6 g | Thermal energy | | | 0.058 MJ |
| | Electricity | 6.2 MJ | Electrical energy | | | 0.035 MJ |
| | | | Emissions to air | | | |
| | | | $CH_4$ | $2.00 \times 10^{-4}$ g | CO | $2.00 \times 10^{-3}$ g |
| | | | $CO_2$ | 0.023 g | $NO_x$ | 0.048 g |
| | | | $N_2O$ | $3.00 \times 10^{-4}$ g | $SO_2$ | 0.189 g |
| | | | As | $9.55 \times 10^{-4}$ mg | NMVOCs | $2.30 \times 10^{-4}$ g |
| | | | PM10 | $5.76 \times 10^{-3}$ g | PM2.5 | $2.75 \times 10^{-3}$ g |
| | | | Cd | $5.73 \times 10^{-5}$ mg | Cr | $9.55 \times 10^{-4}$ mg |
| | | | Cu | $1.91 \times 10^{-3}$ mg | Hg | $9.55 \times 10^{-4}$ mg |
| | | | Ni | $1.91 \times 10^{-3}$ mg | Pb | $4.78 \times 10^{-3}$ mg |
| | | | Zn | $5.73 \times 10^{-3}$ mg | DIOX | $2.30 \times 10^{-5}$ mg |
| | | | PAHs | $1.56 \times 10^{-5}$ mg | PCBs | $7.59 \times 10^{-10}$ mg |
| SCP production | Chemicals * | 62.38 kg | Uniprotein (8% $H_2O$) | | | 1.55 kg |
| | | | Protein from microorganism | | | 1.00 kg |
| | | | Wastewater to WWTP | | | 8.6 kg |
| | | | $CH_4$ | 0.057 g | CO | 2.23 g |
| | | | $CO_2$ | 1.019 kg | $NO_x$ | 5.08 g |
| | | | $N_2O$ | $6.00 \times 10^{-3}$ g | NMVOCs | 0.15 g |
| | | | PM10 | 0.051 g | PM2.5 | 0.051 g |
| | Electrical energy | 19.5 MJ | | | | |

* The term "Chemicals" includes biomethane, oxygen, water, natural gas, sodium hydroxide and the sources of nitrogen, phosphorus and sulfur. The information related to each input is not provided to maintain the confidentiality of the company's information (UNIBIO S/A). For further information, please contact UNIBIO (unibio@unibiogroup.com).

**Table 2.** Life Cycle Inventory to obtain 1 kg of protein from the black soldier fly (BSFP).

| Stage | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|
| Biowaste pretreatment | Biowaste | 72.3 kg | Rejected materials to landfill | | | 6.5 kg |
| | Diesel | 0.09 kg | Biowaste (pretreated) | | | 65.8 kg |
| | Electricity | 2.4 MJ | Emissions to air | | | |
| | | | $CH_4$ | $3.00 \times 10^{-3}$ g | CO | 0.664 g |
| | | | $CO_2$ | 0.297 kg | $NO_x$ | 1.417 g |
| | | | $N_2O$ | 0.013 g | $SO_2$ | $2.00 \times 10^{-3}$ g |
| | | | $NH_3$ | $1.00 \times 10^{-3}$ g | NMVOCs | 0.129 g |
| | | | PM10 | 0.073 g | PM2.5 | 0.073 g |
| BSF protein production | Biowaste (pretreated) | 65.8 kg | New fresh larvae | | | 10.1 kg |
| | Tap water | 7.0 kg | Insect meal | | | 1.45 kg |
| | Process water | 8.3 kg | Protein from insect meal | | | 1.00 kg |

**Table 2.** *Cont.*

| Stage | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|
| | Feed (insect diet) | 3.3 kg | Fatty fraction | 1.27 kg | | |
| | Natural gas | 0.14 kg | Compost (larval fattening) | 3.2 kg | | |
| | Electricity | 53.3 MJ | Compost (incubation and colony) | 1.3 kg | | |
| | | | Rejected materials to landfill | 0.6 kg | | |
| | | | Wastewater | 7.0 kg | | |
| | | | Emissions to air | | | |
| | | | $CH_4$ | 0.033 g | CO | 0.255 g |
| | | | $CO_2$ | 0.363 kg | $NO_x$ | 0.582 g |
| | | | $N_2O$ | 0.560 g | NMVOCs | 0.017 g |
| | | | PM10 | $6.00 \times 10^{-3}$ g | PM2.5 | $6.00 \times 10^{-3}$ g |
| | | | Emissions to air | | | |
| Compost application | Compost (larval fattening) | 3.2 kg | $CH_4$ | $5.00 \times 10^{-5}$ g | CO | $9.78 \times 10^{-3}$ g |
| | Substituted N fertiliser (CAN27) | −0.20 kg | $CO_2$ | 4.08 kg | $NO_x$ | 0.022 g |
| | Substituted P fertiliser ($TS46P_2O_5$) | −0.20 kg | $N_2O$ | 1.42 g | $SO_2$ | $3.00 \times 10^{-5}$ g |
| | Diesel | $1.3 \times 10^{-3}$ kg | $NH_3$ | 13.24 g | NMVOCs | $1.93 \times 10^{-3}$ g |
| | | | PM10 | $8.90 \times 10^{-4}$ g | PM2.5 | $8.90 \times 10^{-4}$ g |

**Table 3.** Life Cycle Inventory to obtain 1 kg of biofertilizer.

| Stage | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|
| **$(NH_4)_2SO_4$** | | | | | | |
| Biowaste pretreatment and anaerobic digestion | Biowaste | 245 kg | Leftover biogas (to upgrade) | 24.3 kg | | |
| | $FeCl_3$ | 0.33 kg | Solid fraction of digestate | 163 kg | | |
| | Polyelectrolyte | 0.15 kg | Liquid fraction of digestate | 134.5 kg | | |
| | Tap water | 99 kg | Rejected materials to landfill | 22.1 kg | | |
| | Diesel | 0.32 kg | Emissions to air | | | |
| | Electricity | 41.0 MJ | $CH_4$ | 0.285 g | CO | 3.66 g |
| | | | $CO_2$ | 1.01 kg | $NO_x$ | 6.68 g |
| | | | $N_2O$ | 0.048 g | NMVOCs | 0.531 g |
| | | | PM10 | 0.269 g | PM2.5 | 0.269 g |
| | | | $SO_2$ | 0.020 g | $NH_3$ | 0.026 g |
| Composting of solid fraction digestate | Solid fraction of digestate | 163 kg | Compost | 45.7 kg | | |
| | Diesel | 0.26 kg | Rejected materials to landfill | 2.1 kg | | |
| | Electricity | 5.87 MJ | Emissions to air | | | |
| | | | $CH_4$ | 326 g | CO | 1.84 g |
| | | | $CO_2$ | 0.83 kg | $NO_x$ | 3.93 g |
| | | | $N_2O$ | 32.6 g | $SO_2$ | $5.00 \times 10^{-3}$ g |
| | | | $NH_3$ | 39.1 g | NMVOCs | 0.36 g |
| | | | PM10 | 0.20 g | PM2.5 | 0.20 g |
| | | | Emissions to air | | | |
| Compost application | Compost | 45.7 kg | $CH_4$ | $6.86 \times 10^{-4}$ g | CO | 0.14 g |
| | Substituted N fertiliser (CAN27) | −3.29 kg | $CO_2$ | 0.057 kg | $NO_x$ | 0.306 g |

**Table 3.** *Cont.*

| Stage | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|
| | Substituted P fertiliser ($TS46P_2O_5$) | −0.88 kg | $N_2O$ | 23.90 g | $SO_2$ | $3.67 \times 10^{-4}$ g |
| | Diesel | 0.018 kg | $NH_3$ | 223.0 g | NMVOCs | 0.027 g |
| | | | PM10 | 0.013 g | PM2.5 | 0.013 g |
| | | | Emissions to freshwater | | | |
| | | | $PO_4$ | 42.5 g | | |
| | | | Emissions to agricultural soil | | | |
| | | | $PO_4$ | 3.65 g | | |
| Ammonium sulphate production | Struvite process effluent | 129 kg | Fertilizer (95% $H_2O$) | | | 1.11 kg |
| | $H_2SO_4$ (96%) | 1.0 kg | Ammonium sulphate (pure) | | | 1.00 kg |
| | Natural gas | 2.27 kg | Wastewater to WWTP | | | 128.9 kg |
| | Electrical energy | 4.68 MJ | Emissions to air | | | |
| | | | $CH_4$ | 0.11 g | CO | 4.24 g |
| | | | $CO_2$ | 6.04 kg | $NO_x$ | 9.68 g |
| | | | $N_2O$ | 0.0106 g | PM2.5 | 0.11 g |
| | | | PM10 | 0.11 g | NMVOCs | 0.28g |
| **Struvite** | | | | | | |
| Biowaste pretreatment and anaerobic digestion | Biowaste | 17,654 kg | Leftover biogas (to upgrade) | | | 1741.0 kg |
| | $FeCl_3$ | 23.6 kg | Solid fraction of digestate | | | 11,672 kg |
| | Polyelectrolyte | 10.60 kg | Liquid fraction of digestate | | | 9631 kg |
| | Tap water | 7086 kg | Rejected materials to landfill | | | 1579 kg |
| | Diesel | 22.8 kg | Emissions to air | | | |
| | Electricity | 167 MJ | $CH_4$ | 20.4 kg | CO | 262 kg |
| | | | $CO_2$ | 72.2 kg | $NO_x$ | 479 g |
| | | | $N_2O$ | 3.44 g | NMVOCs | 38.0 g |
| | | | PM10 | 19.3 g | PM2.5 | 19.3 g |
| | | | $SO_2$ | 1.46 g | $NH_3$ | 0.19 g |
| Composting of solid fraction of digestate | Solid fraction of digestate | 11,672 kg | Compost | | | 3274 kg |
| | Diesel | 18.7 kg | Rejected materials to landfill | | | 149 kg |
| | Electricity | 421 MJ | Emissions to air | | | |
| | | | $CH_4$ | 23.37 kg | CO | 132.2 g |
| | | | $CO_2$ | 59.10 kg | $NO_x$ | 281.90 g |
| | | | $N_2O$ | 2.34 kg | $SO_2$ | 0.37 g |
| | | | $NH_3$ | 2.80 kg | NMVOCs | 25.6 g |
| | | | PM10 | 14.6 g | PM2.5 | 14.6 g |
| Compost application | Compost | 3274 kg | Emissions to air | | | |
| | Substituted N fertiliser (CAN27) | −236.10 kg | $CH_4$ | 0.049 g | CO | 9.93 g |
| | Substituted P fertiliser ($TS46P_2O_5$) | −62.90 kg | $CO_2$ | 4.14 kg | $NO_x$ | 21.9 g |
| | Diesel | 1.31 kg | $N_2O$ | 1.72 kg | $SO_2$ | 0.026 g |
| | | | $NH_3$ | 14.6 kg | NMVOCs | 1.960 g |
| | | | PM10 | 0.904 g | PM2.5 | 0.904 g |
| | | | Emissions to freshwater | | | |
| | | | $PO_4$ | 3.04 kg | | |
| | | | Emissions to agricultural soil | | | |
| | | | $PO_4$ | 0.262 kg | | |
| $MgCl_2$ production | Slaked lime | 4.22 kg | $MgCl_2$ (100%) | 7.16 kg | | |
| | HCl (32%) | 17.2 kg | | | | |
| | Thermal energy | 48.7 MJ | | | | |
| | Electrical energy | 4.1 MJ | | | | |

**Table 3.** *Cont.*

| Stage | Inputs | | Outputs | | | |
|---|---|---|---|---|---|---|
| Struvite production | Liquid fraction of digestate | 9631 kg | Fertilizer (95% $H_2O$) | 19.37 kg | | |
| | $MgCl_2$ (100%) | 7.2 kg | N in fertilizer | 1.00 kg | | |
| | NaOH (100%) | 0.48 kg | Struvite process' effluent | 9263 kg | | |
| | Tap water | 57.8 kg | Emissions to air | | | |
| | Natural gas | 39.3 kg | $CH_4$ | 1.88 g | CO | 73.4 g |
| | Electrical energy | 132.10 MJ | $CO_2$ | 104.49 kg | $NO_x$ | 167.5 g |
| | | | $N_2O$ | 0.188 g | NMVOCs | 4.89 g |
| | | | PM10 | 1.68 g | PM2.5 | 1.68 g |

It is worth it to clarify some points regarding LCI. Firstly, several items were integrated into another, but which could not be considered additive. For instance, the flow "protein from insect meal" was included in the flow "insect meal", and the latter was included in the flow "fresh larvae", as well as "fatty fraction". Two other examples are (i) the flow of "ammonium sulphate (pure)", which was included in the flow of "fertilizer (5% $H_2O$)"; and (ii) "protein from microorganisms" was integrated in the "Uniprotein" stream. Secondly, due to the FU selected, the weights of the biowaste treated are different for every product; that is, the FU is 1 kg of the corresponding VALUEWASTE product.

The inventory data used in the VALUEWASTE systems were calculated from primary and secondary data; the latter were used when the primary data were unavailable or were not representative of an industrial-scale system. Primary data were obtained from the experimental phase of the VALUEWASTE project; i.e., from the operation of the pilot plants. Whereas, secondary data came from bibliographic sources and from those processes included in GaBi software. The bibliographic sources consulted were [18,26–46]. Each inventory flow was estimated using either primary or secondary or both sorts of data. Tables 1–3 show the inventories constructed for the case of the VALUEWASTE solution.

Tables 1–3 included the flows of the foreground processes, which are those processes of the VALUEWASTE system for which all inputs and outputs were calculated or measured for the present study. In addition, there are several background processes included in the scope whose inputs and outputs were not included in the inventory tables because they were purchased and made up of an enormous number of inputs and outputs. Examples of background processes are the landfill treatment and the production of electrical energy, whose inputs and outputs were not indicated in the inventories but were taken into account in the scope of the LCA, and thus were evaluated as well.

### 2.1.3. Life Cycle Impact Assessment

The LCA was carried out using professional GaBi v10.5 software (Sphera Solutions GmbH, Chicago, IL, USA). The midpoint potential environmental impacts (impact categories) were calculated by the Environmental Footprint [47] v3.0 methodology, included in the GaBi software. The Environmental Footprint methodology analyses a total of 16 impact categories. However, only six impact categories were considered for the present study: (i) climate change; (ii) freshwater ecotoxicity; (iii) freshwater eutrophication; (iv) human toxicity—cancer; (v) human toxicity—non-cancer; and (vi) water scarcity. These impact categories were selected according to other studies [22,48–50] addressing similar products or processes to the VALUEWASTE ones and according to the authors' consideration as the most relevant for VALUEWASTE products. Additionally, the impact category "Resource use, mineral & metals" was included in the case of biofertilizers as mineral fertilizer production is avoided, which is relevant for the study. This impact category was also considered for the BSFP production as one of the by-products was compost, which directly impact on avoiding the production of mineral fertilizers. The environmental impacts related to the manufacturing of the regular products (baseline) were also estimated.

Allocations: As observed in Figure 2, there are two production processes valorising biowaste within the VALUEWASTE solution. On one hand, the production of BSFP and its by-products, and, on the other hand, the manufacture of SCP and biofertilizers. Therefore, it was required to estimate the allocations linked to every product. The environmental impacts for the pretreatment, such as the landfilling of the rejected material from the pretreatment and anaerobic digestion, were distributed among SCP, struvite, and $(NH_4)_2SO_4$. The allocation factors were calculated based on the lower calorific value (LCV) of the biogas and digestate. In this way, the biogas had an allocation factor of 0.55, whereas that of the digestate was 0.45. The allocation factor of the digestate, in turn, must be divided between struvite and $(NH_4)_2SO_4$. Their allocation factors were calculated considering the amount of each product (solid) obtained from the digestate, being 20% and 80% for struvite and $(NH_4)_2SO_4$, respectively. Therefore, the allocation factors were 0.09 (struvite) and 0.36 ($(NH_4)_2SO_4$) for the following processes: pretreatment, anaerobic digestion, and landfilling (rejected material from the pretreatment process). On the other hand, the allocations linked to the processes involved in the digestate management to obtain struvite and $(NH_4)_2SO_4$ were divided between both biofertilizers, the allocation factors being 0.2 and 0.8 for struvite and $(NH_4)_2SO_4$, respectively. The involved processes are composting of the solid fraction of the digestate, compost application in the field, landfilling of the rejected material from the composting stage, and the treatment of the wastewater generated during the management of the digestate liquid fraction. In the case of BSF proteins, there were two by-products (fats and compost). The allocation factors were estimated using economic values based on those reported by Smetana et al. [51], in this study being 0.79 (BSFP), 0.17 (fats), and 0.04 (compost).

## 3. Results and Discussion

This section is divided into three subsections to present and discuss the results obtained. It is worth it to highlight that one innovative aspect of the VALUEWASTE project lies in dealing with MSW valorisation from a circular point of view. Current solutions to this issue are based on lineal models, which might score better in some impact categories when individually evaluated.

### *3.1. Production of Proteins from Single Cells*

The production of 1 kg of SCP from biowaste was modelled and the results are shown in Figure 3. The process to manufacture the SCP (solid product for feed) from biomethane was the most important one in five out of six considered impact categories: ecotoxicity (42.5%), global warming (39.2%), human toxicity—cancer (59.5%), human toxicity—non-cancer (48.3%), and water scarcity (70.1%). Whereas, the impact of landfilling (rejected material from pretreatment) was the main contributor to freshwater eutrophication.

As mentioned in the previous paragraph, since the SCP production process was the main contributor in the five impact categories, it is required to deeply analyse this process. In this way, it was observed that electricity consumption was the key factor responsible for the SCP production process in five out of six impact categories (ecotoxicity, eutrophication, global warming, and human toxicity—cancer and non-cancer). The electricity contribution ranged from 43.7% to 72.7% (Table 4). Hence, it would be very interesting to invest in renewable sources in order to obtain green energy, reducing the environmental burdens, as reported by Järviö et al. [52]. In the mentioned study, for instance, microbial protein production from autotrophic hydrogen-oxidizing bacteria (HOB) had about an 88% lower impact on global warming when using hydropower as an energy source instead of the electricity mix in Finland.

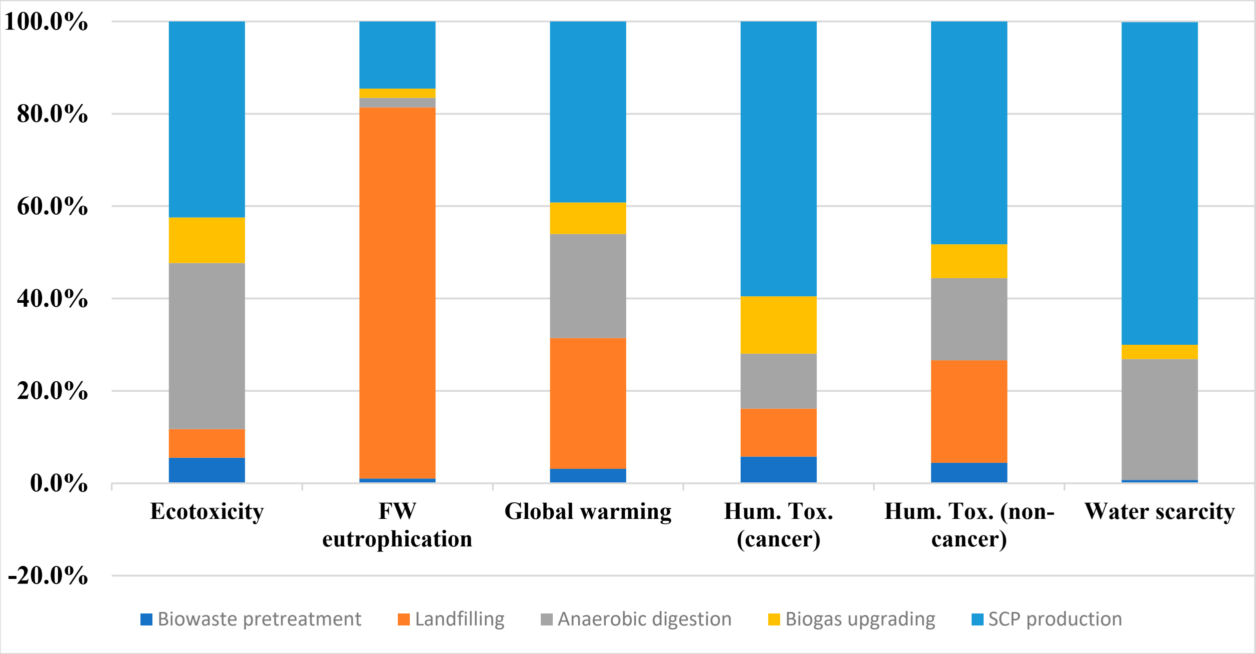

**Figure 3.** Relative contributions of each considered environmental category linked to the protein production from single cells (SCP) in the VALUEWASTE solution.

**Table 4.** Environmental burdens (%) provided within the SCP production chain in the VALUEWASTE project.

| Impact Category | Environmental Burden (%) of Every Stage | | Environmental Burden (%) within the SCP Production Stage | |
|---|---|---|---|---|
| Ecotoxicity | Anaerobic digestion | 36.0 | Ammonia ($NH_3$) [1] | 0.7 |
| | Biogas upgrading | 9.9 | Natural gas [1] | 0.8 |
| | Biowaste pretreatment | 5.5 | Oxygen [1] | 14.1 |
| | SCP production stage | 42.4 | Processes [2] | - |
| | Landfilling | 6.2 | WW [3] treatment | 5.3 |
| | | | Electricity | 72.7 |
| | | | Rest [4] | 6.4 |
| Global warming | Anaerobic digestion | 22.5 | Ammonia ($NH_3$) | 8.2 |
| | Biogas upgrading | 6.8 | Natural gas | 4.3 |
| | Biowaste pretreatment | 3.1 | Oxygen | 9.9 |
| | SCP production stage | 39.3 | Processes | 24.5 |
| | Landfilling | 28.3 | WW treatment | 0.1 |
| | | | Electricity | 51.3 |
| | | | Rest | 1.7 |
| Human toxicity (cancer) | Anaerobic digestion | 11.9 | Ammonia ($NH_3$) | 3.6 |
| | Biogas upgrading | 12.4 | Natural gas | 7.8 |
| | Biowaste pretreatment | 5.8 | Oxygen | 12.8 |
| | SCP production stage | 59.5 | Processes | - |
| | Landfilling | 10.4 | WW treatment | 5.9 |
| | | | Electricity | 66.1 |
| | | | Rest | 3.8 |
| Human toxicity (non-cancer) | Anaerobic digestion | 17.8 | Ammonia ($NH_3$) | - |
| | Biogas upgrading | 7.3 | Natural gas | 15.5 |
| | Biowaste pretreatment | 4.4 | Oxygen | 9.0 |
| | SCP production stage | 48.3 | Processes | 6.5 |
| | Landfilling | 22.2 | WW treatment | 13.1 |
| | | | Electricity | 46.3 |
| | | | Rest | 9.6 |

**Table 4.** *Cont.*

| Impact Category | Environmental Burden (%) of Every Stage | | Environmental Burden (%) within the SCP Production Stage | |
|---|---|---|---|---|
| Water scarcity | Anaerobic digestion | 26.2 | Ammonia ($NH_3$) | - |
| | Biogas upgrading | 3.1 | Natural gas | - |
| | Biowaste pretreatment | 0.7 | Oxygen | 2.3 |
| | SCP production stage | 69.8 | Processes | - |
| | Landfilling | 0.2 | WW treatment | 11.6 |
| | | | Electricity | 10.9 |
| | | | Tap water | 74.1 |
| | | | Rest | 1.1 |

[1] Production process of the chemicals. [2] Processes included are biomethane fermentation, homogenization UHT treatment, and spray-drying. [3] WW: wastewater. [4] The term "Rest" includes other processes, such as tap water, process water, and other chemicals (e.g., sulphuric acid). Tap water was excluded in "Rest" in the water scarcity category.

Depending on the impact category, the results obtained for the production of 1 kg of SCP were more or less similar to other regular proteins manufacturing:

- For instance, the ecotoxicity was about 2.5-fold higher for the SCP production compared to the proteins coming from gluten feed and fish meal.
- Compared to gluten feed, the SCP production was about 3-fold lower in the human toxicity (non-cancer).
- Moreover, it was practically equal compared to soybean meal within the human toxicity (cancer) category.
- On the other hand, the production of SCP provided a between 3- and 6-times lower impact on water scarcity compared to gluten feed and soybean meal proteins; whereas, it was 4-times higher compared to sunflower meal.
- The impact of producing 1 kg of SCP on freshwater eutrophication was between 11- and 23-times lower compared to the proteins from the gluten feed, soybean meal, and sunflower meal.
- Finally, within the global warming impact category, it is necessary to point out that the largest environmental impact was provided by SCP manufacturing compared to the other protein sources (up to 11-fold higher).

As observed, the environmental burdens depend on the protein source used; thus, one protein source is not completely better or worse than the others. The use of SCP as a protein source has attracted the attention of researchers in the last decade due to the identification of new and cheaper production processes, together with the potential environmental benefits of SCP over other regular protein sources [21,53,54]. For instance, according to Matassa et al. [55], soybean meal is highly inefficient, since about 60% of the nitrogen applied to crops via fertilizers, biological fixation, or animal manure is lost due to volatilization/runoff processes; whereas, the majority of nutrients are assimilated by microorganisms [21] and these issues can be avoided. It is also worth mentioning that huge surfaces of agricultural lands are devoted to producing animal feed such as soybeans [56], which is not required to produce SCP, freeing the land up for other purposes. Therefore, the use and production of SCP would decrease the dependency on these sources; at the same time, the biowaste is valorised.

Studies to evaluate the environmental impacts of SCP manufacturing have been performed, for methanotrophic bacteria [14] and other microorganisms, such as HOB [52] and purple non-sulphur bacteria [21]. However, to the best of the authors' knowledge, no study has applied to the production of proteins from methanotrophic bacteria the valorising biowaste, and this at a pilot scale, which provides relevance to the present study and the VALUEWASTE project.

### 3.2. Production of Proteins from Black Solider Fly

Figure 4 shows the relative contributions of each selected impact category. As observed, the production of BSFP was clearly the most significant stage of the process for four out of seven impact categories: ecotoxicity (75.5%); human toxicity—cancer (74.9%); human toxicity—non-cancer (51.7%); and water scarcity (84.3%). Moreover, the BSFP production was also significant within the global warming impact category (48.2% of the total), besides landfilling (45.7%).

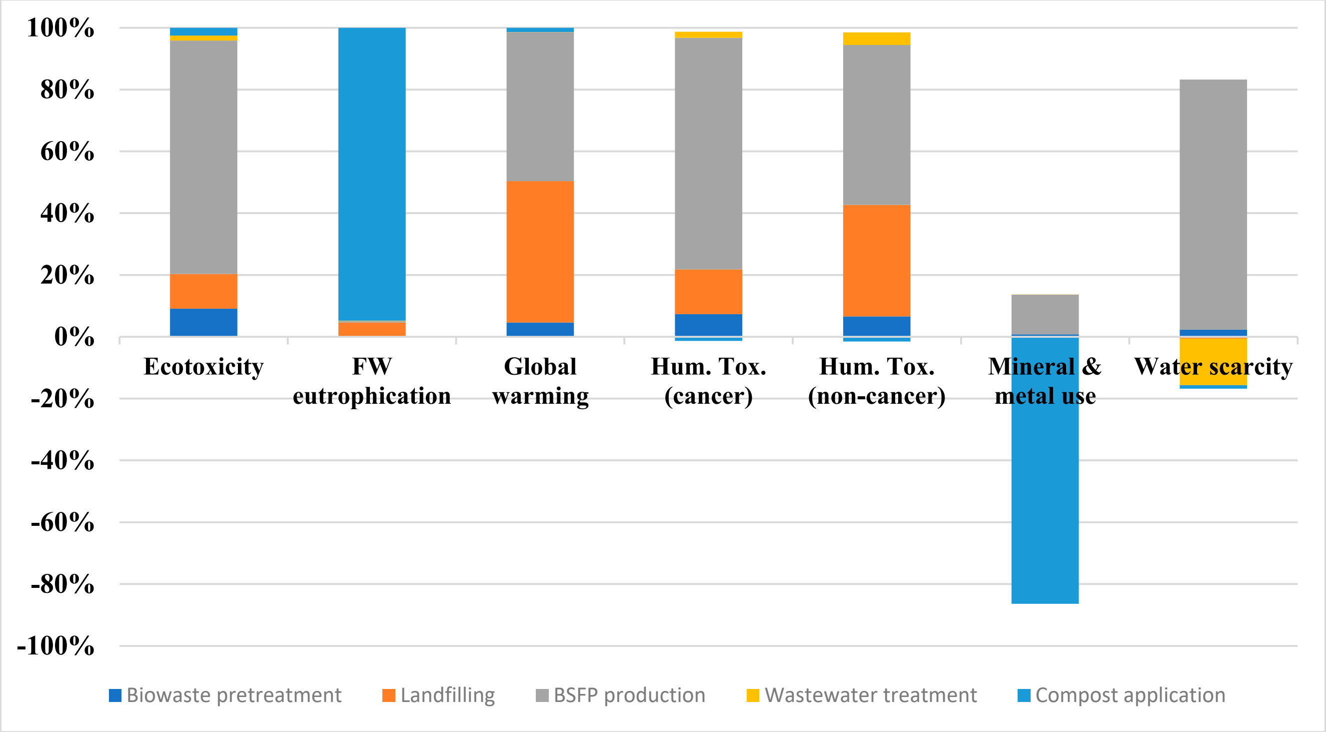

**Figure 4.** Relative contributions of each considered environmental category linked to the protein production from black soldier fly (BSFP) in the VALUEWASTE solution.

These results were mainly caused by electricity use. The use of electricity was responsible for providing more than 90% of the environmental burdens regarding freshwater ecotoxicity, human toxicity (cancer and non-cancer), and global warming; whereas, it provided nearly 60% of the burden regarding water scarcity (Table 5). Energy use was also reported by other authors [18,19,51,57–60] as one of the largest contributors within the studied impact categories, confirming that this factor is the main factor to act upon in order to decrease the environmental burdens related to BSFP production. Therefore, as previously mentioned for the SCP case, the use of green energy sources would reduce the environmental impact caused by the BSFP manufacturing throughout the present solution, improving the results obtained.

**Table 5.** Environmental burdens (%) provided during the BSFP production line within the VALUEWASTE project.

| Impact Category | Environmental Burden (%) of Every Stage | | Environmental Burden (%) within the BSFP Production Stage | |
|---|---|---|---|---|
| Ecotoxicity | Pretreatment | 9.2 | Electricity | 99.4 |
| | Landfilling | 11.2 | Tap water | 0.1 |
| | BSFP [1] production stage | 75.5 | Process water | 0.4 |
| | WW [2] treatment | 1.6 | Natural gas | 0.1 |
| | Compost application | 2.5 | Insect meal production | - |

**Table 5.** *Cont.*

| Impact Category | Environmental Burden (%) of Every Stage | | Environmental Burden (%) within the BSFP Production Stage | |
|---|---|---|---|---|
| Global warming | Pretreatment | 4.6 | Electricity | 90.7 |
| | Landfilling | 45.7 | Tap water | - |
| | BSFP [1] production stage | 48.2 | Process water | 0.2 |
| | WW [2] treatment | 0.1 | Natural gas | 1.0 |
| | Compost application | 1.4 | Insect meal production | 8.1 |
| Human toxicity (cancer) | Pretreatment | 7.3 | Electricity | 98.2 |
| | Landfilling | 14.5 | Tap water | 0.1 |
| | BSFP [1] production stage | 74.9 | Process water | 0.2 |
| | WW [2] treatment | 2.0 | Natural gas | 1.5 |
| | Compost application | 1.3 | Insect meal production | - |
| Human toxicity (non-cancer) | Pretreatment | 6.6 | Electricity | 94.6 |
| | Landfilling | 36.1 | Tap water | 0.1 |
| | BSFP [1] production stage | 51.7 | Process water | 0.6 |
| | WW [2] treatment | 4.1 | Natural gas | 4.1 |
| | Compost application | 1.5 | Insect meal production | 0.6 |
| Water scarcity | Pretreatment | - | Electricity | 58.8 |
| | Landfilling | - | Tap water | 18.8 |
| | BSFP [1] production stage | 84.3 | Process water | 22.4 |
| | WW [2] treatment | 15.7 | Natural gas | - |
| | Compost application | - | Insect meal production | - |

[1] BSFP: black soldier fly protein. [2] WW: wastewater.

The production of BSFP generates compost as a by-product, which is the main contributor to the eutrophication and mineral and metals use categories (about 95% and 86%, respectively) during its application. However, it is required to mention that the environmental effect in mineral and metal use was positive (Figure 4) as compost can substitute those minerals to manufacture the regular fertilizers, thus reducing its consumption and lessen the environmental impact.

It is worth examining those categories where BSFP provided significance results considering other protein sources.

- The impact on the freshwater ecotoxicity category was a bit higher for BSFP compared to gluten feed, fish meal, and gluten meal (lower than 2-fold). The difference was higher (about 7-fold) compared to soybean meal. However, it was much lower than the proteins coming from milk and whey concentrate (about 16- and 5-time higher than BSFP).
- Similarly to freshwater ecotoxicity, BSFP production provided a higher environmental impact for eutrophication and global warming compared to gluten feed and gluten meal (about 3-times for eutrophication and 3.5-times for global warming), but much lower compared to milk concentrate (9-fold, eutrophication; and 18-fold, global warming) and whey concentrate (3.4-times, eutrophication; and 5.3-times, global warming).
- In the case of human toxicity (cancer), the results of producing BSFP were close to those proteins obtained from fish meal, gluten feed, gluten meal, and sunflower meal (about 1.6-fold lower) and equal to soybean meal. Whereas, it was clearly a better option compared to whey and milk concentrate, highlighting the difference with the last one; 16-fold.
- These results were similar to those obtained for human toxicity (non-cancer); that is, BSFP provided a higher impact than fish meal (7-fold) and sunflower meal (3.7-fold),

and equal to those proteins coming from soybean meal. On the contrary, BSFP provided a lower environmental impact than the rest of the protein sources: gluten feed (3.4-fold), gluten meal (3-fold), whey (4.7-fold), and milk concentrate (12.8-fold).

- In the case of water scarcity, the production of proteins from fish provided better results (61-fold) than the BSFP. On the other hand, the protein from BSF required between 8.3 and 122.5-times lower $m^3_{eq}$ than the other protein sources.
- The case of the minerals and metals use is especially remarkable since the BSFP was the only protein source that provided a positive environmental effect for this category due to the use of the generated compost as a fertilizer.

As observed, the obtained results fostered the use of *Hermetia illucens* larvae not only to reduce the amount of biowaste, as reported by other authors [51,57,60,61], but also to generate an alternative and sustainable protein source for feed and food. It must be underlined that the BSFP provided better environmental effects than milk concentrate and whey proteins in all the impact categories. These supplements are widely consumed worldwide, and thus BSFP is a real alternative to these protein sources. Nevertheless, it is required to mention that the use of these kinds of proteins (both from microorganisms and insects), using biowaste as feedstock, are not allowed for human consumption yet. This situation might change in the near future, since new waste legislation is being developed by the European Union for 2024 that will be based on scientific results, such as those provided in the present work.

## *3.3. Production of Biofertilizers*

As mentioned before, during the course of the VALUEWASTE project, two different biofertilizers were produced: ammonium sulphate ($(NH_4)_2SO_4$) and struvite. The environmental impacts linked to these biofertilizers are displayed in the present subsection.

### 3.3.1. Ammonium Sulphate ($(NH_4)_2SO_4$) Obtained in the VALUEWASTE Project

As observed in Figure 5, the value chain to produce $(NH_4)_2SO_4$ from biowaste provided a positive effect on the environment in two categories: mineral and metal use and water scarcity. In the case of mineral and metal use, the VALUEWASTE process avoided the consumption of mineral compounds, which are required to produce traditional fertilizers. During anaerobic digestion, a solid fraction of the digestate is generated and used as compost. Its field application was the main contributor (96.6%) to this impact category. Hence, the biowaste managed by the VALUEWASTE system reflected environmental benefits caused by a good use in agriculture, demonstrating that regular fertilizers can be substituted, thus leading to a lower use of raw materials.

The water scarcity category is linked to the use of water during the process studied or related to its reclamation. The net environmental impact was also negative during the course of the $(NH_4)_2SO_4$ production during biowaste valorisation (Figure 5), mainly caused by the wastewater (effluent generated after biofertilizers production processes) treatment performed, to be able to release it into the water bodies. This means that the process provided water savings, its contribution being higher than 64% within the water scarcity impact category.

Interesting is the fact that field application was the main contributor (about 97%) for the freshwater eutrophication category (Figure 5). This was mainly caused by phosphate released into the freshwater. This is line with other studies, where fertilizer application on agricultural land was the main contributor to the freshwater eutrophication impact category [22,62,63].

The environmental effects of producing $(NH_4)_2SO_4$ provided negative values for the mineral and metal use and water scarcity categories; that is, the effect was positive. Taking into account that the mineral fertilizer considered as a baseline provided positive values (negative environmental effects) in both categories, it is concluded that $(NH_4)_2SO_4$ manufacturing is the best option. However, it is required to mention that the $(NH_4)_2SO_4$ production from biowaste provided higher environmental burdens compared to mineral fertilizers within the remaining impact categories. For instance, the impact on the global warming category was about 100-times higher, which was mainly caused (42.3%) by composting. According to Sayara and Sánchez [64], the main contributor to global warming is the energy required for the composting operation together with the biochemical reactions that release $CO_2$, $CH_4$, and $N_2O$ (dinitrogen monoxide). However, this was not observed in the present study, since the electricity consumption only provided 3% of the total environmental burden (data not shown). The largest contribution (96%) was caused by the direct emissions of gases (i.e., $CH_4$ and $N_2O$) generated in the composting process. These results align with those obtained by other studies, such as those performed by Mertenat et al. [18] and Colon et al. [65]. For instance, as reported by Mertenat et al. [18], direct emissions represented 98% of the total burden in the global warming category for composting.

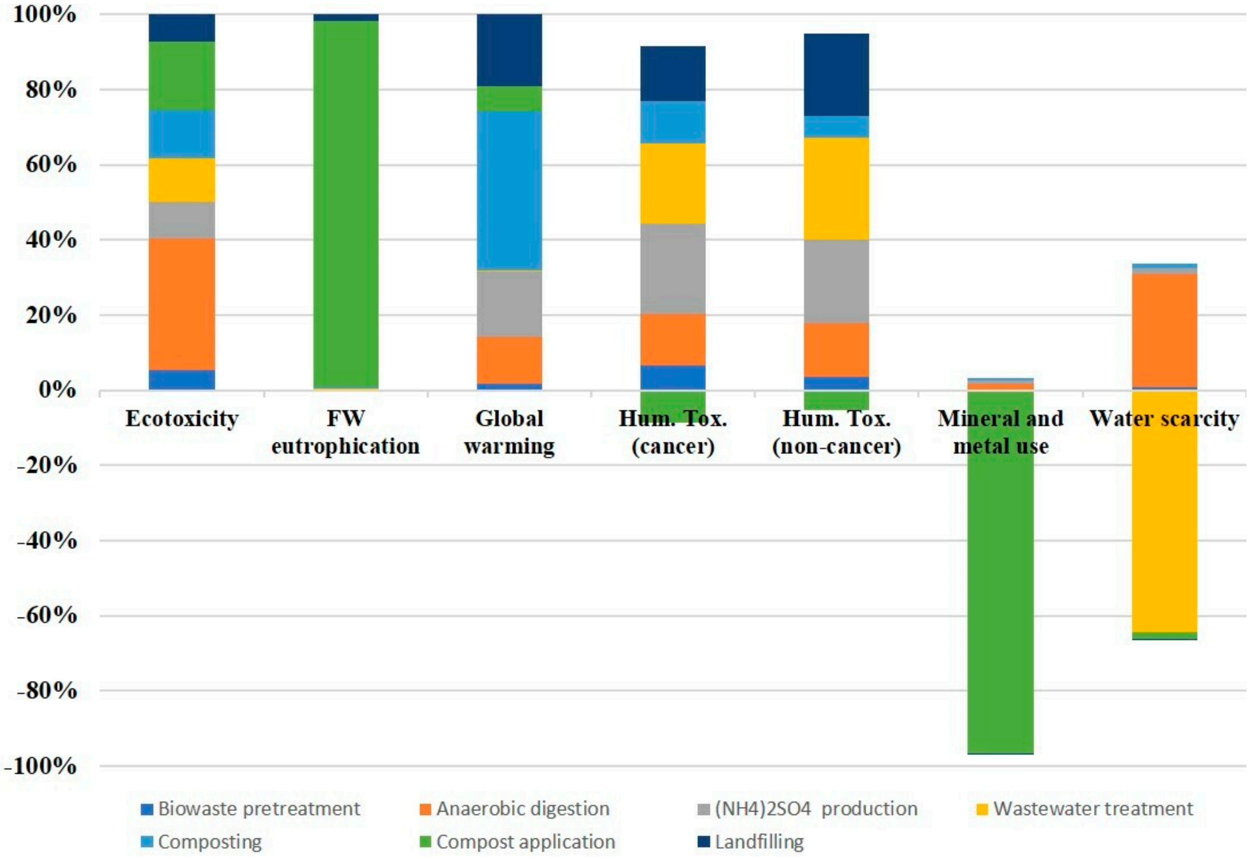

**Figure 5.** Relative contributions for each considered environmental category linked to ammonium sulphate ($(NH_4)_2SO_4$) obtained from the VALUEWASTE solution.

### 3.3.2. Struvite Obtained in the VALUEWASTE Project

The case of the struvite produced by the VALUEWASTE system was analogous to the previous biofertilizer ($(NH_4)_2SO_4$); that is, the struvite provided positive effects from an environmental point of view for the mineral and metal use and water scarcity impact categories (Figure 6). In this case, compost application contributed to a reduction in the mineral and metal use (96% of the total impact), whereas wastewater treatment was the main factor reducing the environmental impact (about 63% of the total contribution). Finally, compost application was the most important contributor (97.5%) within the freshwater eutrophication impact category (Figure 6).

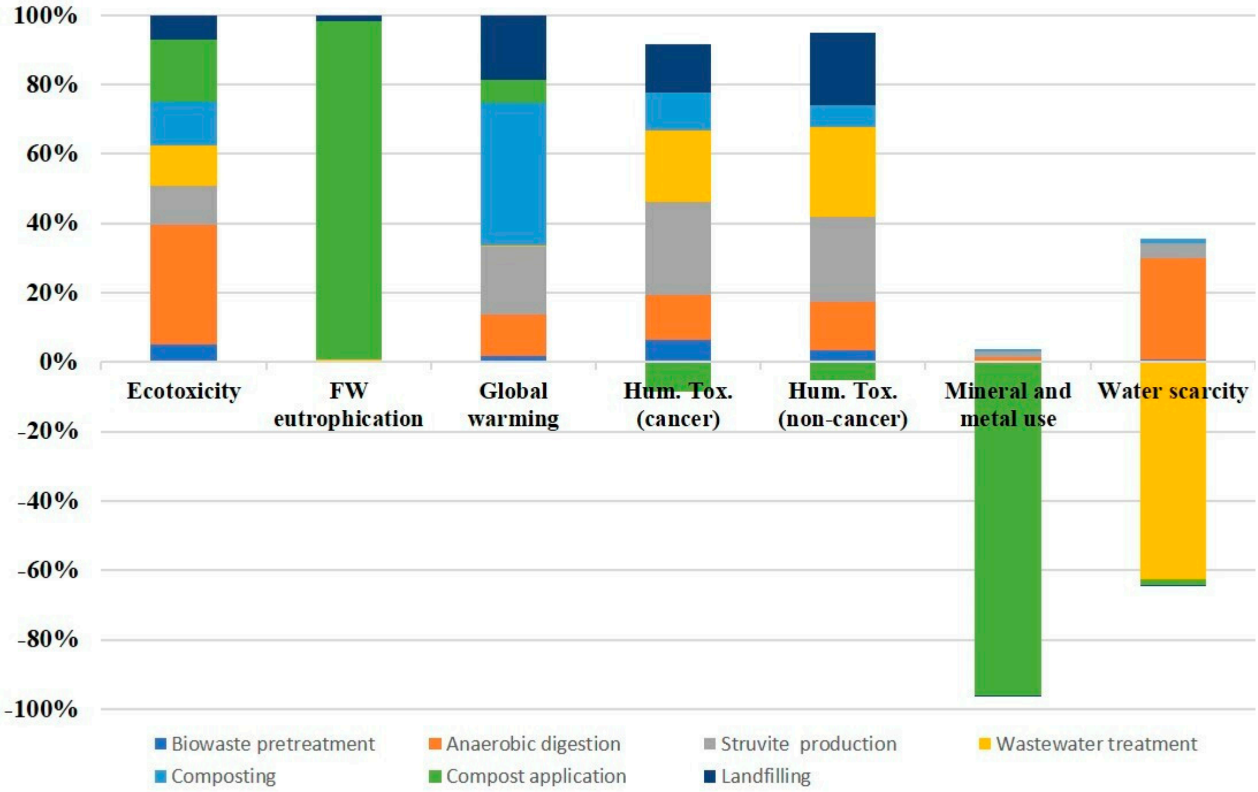

**Figure 6.** Relative contributions for each considered environmental category linked to the struvite obtained from the VALUEWASTE solution.

Similar to the $(NH_4)_2SO_4$ case, the production of struvite provided a lower environmental burden compared to the mineral fertilizer considered as the baseline for the mineral and metal use and water scarcity categories, whereas it provided higher ones for the rest of the categories. The mineral fertilizer considered for the baseline was a mix of ammonium dihydrogen phosphate and diammonium phosphate, with a similar proportion of nitrogen:phosphorus compared to struvite. Using the same example than previously, the struvite production through the VALUEWASTE system provided a higher environmental burden (124-fold) compared to the production and mixing of these traditional fertilizers, the composting stage being the largest contributor (41.2% of the total impacts) to the global warming category.

An interesting result for both $(NH_4)_2SO_4$ and struvite was the impact of landfilling for human toxicity and global warming. In both cases, landfilling provided about 20% of the total environmental burden, which is linked to the quantity of foreign materials in the biowaste. Hence, the lower the percentage of these materials in the biowaste, the lower the environmental impacts. It is also important to mention the positive effect that the compost application provided in both cases within the human toxicity (cancer and non-cancer) impact category (Figures 5 and 6).

On the other hand, the production step of both biofertilizers provided nearly 20% of the total environmental burden regarding global warming and between 22% and 27% in human toxicity (cancer and non-cancer). Within the production process, the largest contributor was the drying stage in global warming and "natural gas production" in human toxicity, both cancer and non-cancer. Electricity production also had an important contribution (Table 6). The drying process requires the use of heat, which is generated by consuming electricity and natural gas. The use of other renewable sources would reduce the environmental impact not only of the drying stage but also in the production of electricity and natural gas. For instance, the use of solar hybrid photovoltaic–thermal collectors would generate part of the electricity and thermal heat requirements, decreasing the environmental burdens linked to the drying step, as suggested by the VALUEWASTE project (Deliverable D6.3 in the blueprints from the VALUEWASTE project, a confidential document).

**Table 6.** Environmental impacts of biofertilizer production in the VALUEWASTE system.

| Biofertilizer | Impact Category | Environmental Burden (%) of Every Stage | | Environmental Burden (%) within the Biofertilizer Production Process | |
|---|---|---|---|---|---|
| Ammonium sulphate | Global warming | $(NH_4)_2SO_4$ production | 17.5 | Drying | 77.6 |
| | | Anaerobic digestion [1] | 12.4 | Electricity | 5.1 |
| | | Biowaste pretreatment | 1.7 | Natural gas | 13.7 |
| | | Compost application | 6.9 | Tap water and $H_2SO_4$ | 3.3 |
| | | Composting | 42.3 | Precipitation | 0.3 |
| | | Landfilling | 19.0 | | |
| | | WW treatment [2] | 0.2 | | |
| | Human toxicity (cancer) | $(NH_4)_2SO_4$ production | 24.1 | Drying | - |
| | | Anaerobic digestion | 13.7 | Electricity | 15.1 |
| | | Biowaste pretreatment | 6.6 | Natural gas | 56.8 |
| | | Compost application | 8.6 | Tap water and $H_2SO_4$ | 28.1 |
| | | Composting | 11.4 | Precipitation | - |
| | | Landfilling | 14.4 | | |
| | | WW treatment | 21.4 | | |
| | Human toxicity (non-cancer) | $(NH_4)_2SO_4$ production | 22.3 | Drying | 9.4 |
| | | Anaerobic digestion | 14.4 | Electricity | 6.5 |
| | | Biowaste pretreatment | 3.6 | Natural gas | 70.0 |
| | | Compost application | 5.2 | Tap water and $H_2SO_4$ | 13.7 |
| | | Composting | 5.9 | Precipitation | 0.3 |
| | | Landfilling | 21.7 | | |
| | | WW treatment | 27.0 | | |
| Struvite | Global warming | Anaerobic digestion | 12.1 | Drying | 68.1 |
| | | Biowaste pretreatment | 1.7 | Electricity | 9.6 |
| | | Compost application | 6.8 | Natural gas | 12.0 |
| | | Composting | 41.2 | Rest [3] | 10.4 |
| | | Landfilling | 18.5 | | |
| | | Struvite production | 19.5 | | |
| | | WW treatment | 0.2 | | |
| | Human toxicity (cancer) | Anaerobic digestion | 13.1 | Drying | - |
| | | Biowaste pretreatment | 6.3 | Electricity | 27.7 |
| | | Compost application | 2.4 | Natural gas | 49.3 |
| | | Composting | 10.9 | Rest | 23.0 |
| | | Landfilling | 13.9 | | |
| | | Struvite production | 26.8 | | |

**Table 6.** *Cont.*

| Biofertilizer | Impact Category | Environmental Burden (%) of Every Stage | | Environmental Burden (%) within the Biofertilizer Production Process | |
|---|---|---|---|---|---|
| | | Landfilling | 13.9 | | |
| | | Struvite production | 26.8 | | |
| | | WW treatment | 20.5 | | |
| | Human toxicity (non-cancer) | Anaerobic digestion | 13.8 | Drying | 8.3 |
| | | Biowaste pretreatment | 3.5 | Electricity | 12.2 |
| | | Compost application | 5.0 | Natural gas | 62.0 |
| | | Composting | 6.2 | Rest | 17.4 |
| | | Landfilling | 20.9 | | |
| | | Struvite production | 24.5 | | |
| | | WW treatment | 26.1 | | |

[1] Chemicals production processes (acrylonitrile, iron (III) chloride and tap water) and electricity in this stage are included. [2] WW: wastewater. [3] The term “Rest” in the struvite production process refers to the processes for obtaining $MgCl_2$, NaOH, and tap water.

Concerning the baseline used in this case, phosphate fertilizers were selected. In this sense, phosphorus rocks are the essential raw materials used to manufacture phosphate fertilizers; thus, it is a limited resource. According to the USGS [66], there are no imminent shortages of phosphate rock. However, other sources reported that this situation might change in the following decades, when the “phosphorus peak” (half of the reserves are consumed) is reached, estimated to be between 2025 and 2084 [67]. Moreover, there are other non-monetary or non-environmental considerations that need to be assessed, such as the European external geopolitical situation. The largest reserves of phosphate rock are in Morocco (70–75% of the total reserves), followed by China, Egypt, and Algeria [67,68]. As observed, these countries present diverse kinds of risks, such as social and/or political instability. Therefore, it is required to decrease the dependency on these types of countries, so that the EU-27 can become a self-sustainable region step by step, thereby achieving one of its main goals: implementing a real circular economy [69]. To achieve this goal, other resources must be found, with struvite from biowaste being a good alternative.

## 4. General Discussion

One of the main outputs of this study was that the production stages within the VALUEWASTE process to obtain SCP (for feed) and BSFP were the main contributor in most of the evaluated impacts. Within these stages, electricity provided the largest environmental impacts for ecotoxicity (72.7%, SCP; and 99.4%, BSFP), global warming (51.3%, SCP; and 90.7%, BSFP), and human toxicity (66.1%, SCP; and 98.2%, BSFP (cancer); and 46.3%, SCP; and 94.6%, BSFP (non-cancer)) categories. Therefore, the impact of producing both SCP and BSFP can be reduced by acting on this hotspot. At this point, it is interesting to mention that the production process to obtain SCP for food is under development by UNIBIO. Preliminary results (data not shown) of this work in progress are promising, and its environmental impacts appear to be similar and, thus, comparable to the SCP for feed and BSFP. However, this must be con-firmed by gathering more data and carrying out an additional assessment in the near future as a follow-up work to the VALUEWASTE project.

Comparing the SCP to other protein sources, the SCP provided diverse results depending on the environmental impacts evaluated and the protein source to be compared. For instance, SCP provided a higher impact on ecotoxicity (2.5-fold) and a lower impact on water scarcity (about 3-fold) than proteins from gluten feed. In the case of BSFP, results followed the same dynamics. For example, BSFP provided lower impacts on human toxicity (cancer and non-cancer) than fish meal, gluten feed, and gluten meal, but higher on global warming. However, it is interesting to mention that the BSFP presented a better environmental performance than milk and whey proteins in all the categories studied. This is important, as the consumption of these regular proteins is very wide, whose market is valued at 11.4 billion USD for 2022, and projected to grow at a CAGR of 5.6% (milk proteins); this was 10.6 billion USD in 2021, and grew at a CAGR of 7.4% (whey proteins) [70,71]. Therefore, the use of BSFP as a protein source might substitute and compete against regular ones, taking into account the best environmental performance of BSFP.

In the case of the biofertilizers, their environmental performance was overall worse compared to mineral fertilizers, except for the following impact categories: mineral and metal use and water scarcity. However, the VALUEWASTE biofertilizers present other advantages facing the mineral alternatives. On one hand, these biofertilizers come from biowaste, extending the concept of circularity by generating a valuable product from waste. On the other hand, these biofertilizers can be manufactured within the European Union borders, which diminishes the dependency of third countries that can block their production, increase the prices, etc., directly affecting the regular function of the European countries. Therefore, all the different aspects involved in new products must be analysed, paying attention to other attributes/advantages.

At this point, it is interesting to point out that the current regulation does not allow the commercialization of products coming from biowaste for feeding animals or humans. Hence, the specific objective of the present manuscript is to provide evidence to support the European policymakers to modify the mentioned legislation to implement this kind of solution and achieve a real circular economy. In this way, the ROOTS (circular policies for changing the biowaste system, formed by four Horizon 2020 projects) initiative will provide results and conclusions to the European Commission in order to overcome the mentioned challenge [72].

## 5. Conclusions

According to the results obtained, VALUEWASTE products represent real alternatives to reach the market in the near future from an environmental point of view. Specially interesting are the new protein sources (SCP and BSFP), since they present lower environmental burdens compared to the traditional ones in some of the reported impact categories. Thus, and from an environmental point of view, the proteins obtained by the VALUEWASTE solution are firm candidates to be used in feed and food applications. Energy consumption (electricity and heat) was one of the main contributors to the environmental impacts linked to VALUEWASTE products. By reducing its consumption, coming from non-renewable sources, their environmental impacts could be lower, enhancing their environmental performance by applying green energies (e.g., solar hybrid photovoltaic–thermal collectors).

VALUEWASTE is an innovative project to transform biowaste into added value products, integrating three value chains and closing the loop from a circular economy perspective. VALUEWASTE contributes to resilience and self-sufficiency, as the products are produced locally from a widely available source. Such an approach will contribute to the production of certain commodities, such as mineral fertilizers, that are typically obtained from outside Europe, and by following the sustainable biowaste valorising schemes promoted by the European Commission, will represent a real and sound alternative to incineration or landfilling. Last, but not least, and as promoted by the ROOTS initiative, the results will feed policy development at the EU level.

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## Glossary

BSF: black soldier fly (*Hermetia illucens*)
BSFP: black soldier fly proteins
CE: circular economy
FU: functional unit
FW eutrophication: freshwater eutrophication
HMG: homogenization process
HOB: hydrogen-oxidizing bacteria
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCV: lower calorific value
MSW: municipal solid waste
OFMSW: organic fraction from municipal solid waste
PBW: pre-treated biowaste
ROOTS: circular policies for changing the biowaste system
SCP: single-cell proteins
UHT: ultra-high-temperature process
WW: wastewater

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