



The Composting of Water Hyacinth: A Life Cycle Assessment Perspective

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Abstract

Water hyacinth is an invasive species that causes eutrophication in lentic waters. While mechanical removal is effective, it generates hazardous waste with biological contamination risk. Composting is a safe waste treatment option, inhibiting seeds and yielding agriculturally suitable compost. Life cycle assessment evaluated the environmental impacts of six composting piles using eight different by-products (potato peel, cattle manure, wood chip, rice straw, potato leftovers, olive pomace and biochar), all formulations containing water hyacinth. The worst environmental performances were the M2 pile (water hyacinth + olive pomace + cattle manure + potato leftovers) which achieved the highest AP (47.33 kg SO₂ eq.) and EP (10.56 kg PO₄³⁻ eq.), while M3 (water hyacinth + olive pomace + rice straw + potato leftovers) had the highest GWP (816.51 kg CO₂ eq.) and OLD (2.99E-11 kg R11 eq.). The biological composting process contributed the most to the overall increase in the impact categories for all piles due to air emissions (CH₄ and N₂O). M3 and M5 (water hyacinth + wood chip) had the worst performance in fossil fuel consumption due to distances travelled from by-products and energy use in the maintenance of composting piles. Concerning packaging, Big Bags with polypropylene had a greater impact than polyethylene bags (50 kg capacity). Evaluating the potential avoidance of mineral fertilisers, M3 compost showed potential for reducing TSP fertiliser production by 46%. Overall, M4, which incorporated a mixture of water hyacinth, olive pomace, wood chips and biochar, was the most favourable option from an environmental point of view.

Statement of Novelty

This study comprehensively evaluates the environmental impacts of composting water hyacinth, an invasive species that causes eutrophication in lentic waters. Although composting has been recognized as a safe waste treatment technique, this research explores the environmental implications of different compost formulations containing water hyacinth and various by-products. Furthermore, to the author's knowledge, no life cycle assessments of water hyacinth composting are yet presented in the literature. The novelty lies in the detailed evaluation of six compost piles using eight different byproducts, clarifying their contributions to environmental indicators such as the potential for acidification, eutrophication potential, global warming potential and ozone layer destruction. Additionally, the study explores the impact of packaging materials and evaluates the potential reduction of mineral fertilizers through compost. Notably, this research identifies the most

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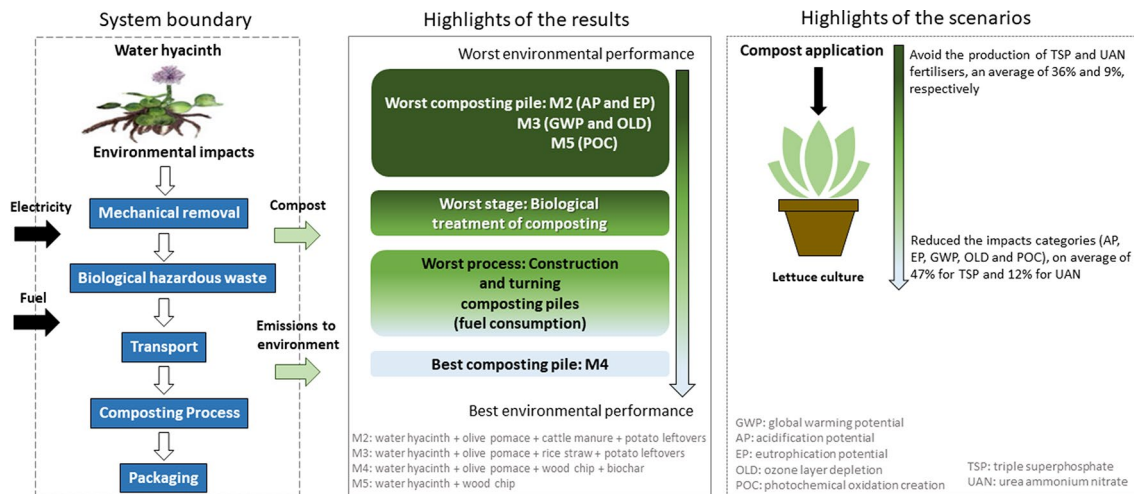
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environmentally friendly composting option, offering insights into sustainable waste management strategies to address challenges posed by invasive species like water hyacinth.

Graphical Abstract



Keywords Compost · Waste · By-product · Impact categories · Invasive species · Biological process

Abbreviations

LCA	Life Cycle Assessment
GWP	Global warming potential
AP	Acidification potential
EP	Eutrophication potential
POP	Photochemical oxidation potential
OLD	Ozone layer depletion
LCI	Life cycle inventory
IPCC	Intergovernmental Panel on Climate Change
LDPE/PE-LLD	Linear low-density polyethylene granulate
PP	Polypropylene
UAN 30% N	Urea ammonium nitrate
TSP 46% P ₂ O ₅	Triple superphosphate
KCl/MOP, 60% K ₂ O	Potassium chloride

Introduction

Invasive species are organisms introduced to a new environment that cause negative impacts, often displacing native species and altering ecosystems. This can lead to biodiversity loss, changes in ecological interactions, and economic damage [1]. Usually, these disturbances are attributed to globalization, due to the anthropic actions that distribute and spread the invaders incompetently [2].

Among the biggest drivers of negative impacts on nature, the expansion of invasive species represents the

fifth largest global cause for the decline in ecosystem biodiversity (terrestrial, freshwater, and marine) [3]. These invasive species pose a significant threat to the European Union's (EU) biodiversity, economy and health sector [4]. The damage amounted to up to 12 billion euros in annual costs on human health, damaged infrastructure and agricultural losses [4]. Overall, among the most damaging invasive species found in Europe, 36% are plants, 32% are invertebrates, 27% are vertebrates and 4% are fungi, and the environments most affected by these species are 64% of the terrestrial environment, 26% of fresh water and 10% of marine habitats [5].

Water hyacinth (*Pontederia crassipes* Mart.) is an aquatic plant that is considered one of the 10 worst invasive aquatic plants spread around the world and generating environmental, economic, and social impacts [6]. Originally from South America, the water hyacinth was introduced to Africa, Asia, the South Pacific, North America and Europe due to its ornamental appearance and became a potent invader [7].

Water hyacinth is in 11th place among the worst exotic species found in Europe, according to its total impact factor, covering environmental and socio-economic impacts, and is one of the top six European invaders with the greatest potential for global impacts [5, 8]. Water hyacinth was included in the list of invasive species from Europe [9]. In Portugal, water hyacinth is the most mentioned plant in the "Top 10" of invasive species between Portugal and Spain [10].

Moreover, this aquatic plant has a high reproductive capacity, because it can reproduce both sexually and

asexually, develops rapidly at high temperatures and lacks predators, all of these circumstances increase the problem of proliferation [11, 12]. Water hyacinth can form dense carpets of plants intertwined with a complex root structure that invade freshwater bodies limiting their use. This infestation prevents fishing and boat navigation, blocks the entry of sunlight and oxygen into the water, alters water clarity, and decreases biodiversity, phytoplankton production, dissolved oxygen and nutrients in the waterbodies [12, 13].

Many studies have investigated the control and removal of water hyacinth, using strategies including chemical, biological and/or mechanical principles with short-term goals (1 year), to reduce biomass and plant vigour, and long-term goals (1–5 years) to evaluate the percentage of coverage [11]. Many experiments use biotechnologies to inhibit seed germination and valorize plant biomass, such as composting and anaerobic digestion [6]. In large-scale composting, seed mortality tests showed that water hyacinth seeds did not survive at temperatures above 57°C, that are reached during and after the process [14]. Large-scale water hyacinth composting is, therefore, a promising and recommended technology, as the seeds of this weed will not proliferate [6, 14].

Water hyacinth also has a high macronutrient content (phosphorus, nitrogen and potassium), increasing the added value to your compost due to nutrient cycling [6]. Water hyacinth is a plant that easily absorbs heavy metals, although the composting process can reduce the heavy metals of the organic wastes [6]. In the work of Mazumder et al. [15], the compost of Water hyacinth, showed no phytotoxicity when doing a germination test in tomatoes (*Lycopersicon esculentum*) and cabbage (*Brassica oleracea*). Therefore, the water hyacinth compost has high economic value, salinity relief and bioremediation [6].

However, the biochemical composition of water hyacinth increases the difficulty of the composting process due to its high moisture content, presence of heavy metals, lignocellulosic properties of little degradation, and high nitrogen content which leads to ammonia volatility [6, 16–18]. Inoculation and biological accelerators should be tested to increase the biodegradation of this fibrous biomass during composting [6]. Care must be taken with the application of compost formed from aquatic macrophytes, as there may be a high presence of heavy metals, damaging soil and water resources [19].

As with any industrial process, the composting of bio-wastes has environmental impacts that can be accounted for and evaluated through the Life Cycle Assessment (LCA) approach. LCA is a methodology used to quantify the environmental aspects and impacts of a product, process or service, from the extraction of raw materials to the disposal or

recovery of waste, under the cradle-to-gate, cradle-to-grave, gate-to-gate or cradle-to-cradle concept [20, 21].

The most frequently used impact categories attributed to the composting process are global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), photochemical oxidation potential (POP) and ozone layer depletion (OLD) [22, 23]. These impact categories are mainly related to the emissions from the composting process and are influenced by the type of waste that will be processed [24].

The BioComp_2.0 project engaged two research institutions and a private company, to provide solutions for the control of the water hyacinth through the combination of removal, transportation, and composting processes. The wet biomass of water hyacinth is then incorporated as the main feedstock in composting piles, alongside additional wastes that can help to enrich the compost.

This study aims to compare the environmental impacts of six different composting piles formulations with different proportions of raw material through the LCA approach. The outcome is to determine which of these composting piles was the least harmful to the environment, as each one was subjected to an individual analysis within the LCA framework. The main feedstock incorporated in all piles was the water hyacinth. In addition, this study aims to evaluate the most efficient formulation that can deliver the most suitable compost for agronomic purposes, avoiding inorganic fertilisers.

Materials and Methods

Since this study approached the management of an invasive species, safety regulations were applied following the diploma DL n.º 565/99, December, to ensure that there is no dissemination of biological material during the process [25].

The water hyacinth was collected in the central region of Portugal, specifically at Figueira da Foz and Montemor-o-Velho municipalities, both of which are under the influence of a wide water hyacinth proliferation. The collection regions were chosen based on the use of the surrounding land, generally downstream sites of intense agricultural activity, as these sites are more subject to eutrophication. The composting process was performed at the Agrarian School of the Polytechnic Institute of Coimbra (IPC), located in the central region of Portugal, with over 28,000 km², an average annual temperature of 14.9 °C and annual precipitation of 1056.2 mm [26].

After removing the water hyacinth from the water body, the biomass was transported to the composting site. At the composting site, the wet biomass of water hyacinth was mixed with eight by-products in different proportions,

forming six distinct composting piles. The piles are designated according to the by-products used in the formulations:

Formulation M1: water hyacinth + olive pomace + potato peel

Formulation M2: water hyacinth + olive pomace + cattle manure + potato leftovers

Formulation M3: water hyacinth + olive pomace + rice straw + potato leftovers

Formulation M4: water hyacinth + olive pomace + wood chip + biochar

Formulation M5: water hyacinth + wood chip

Formulation M6: water hyacinth + potato leftovers + olive pomace + rice straw

Chemical Characterization

Total solids (TS), moisture content, ash content, volatile solids (VS), and chemical composition (C, H, N, O), were analyzed. The TS content and moisture content were determined by drying samples at 105 °C to constant weight for about 24 h. The VS content was determined as the mass loss after heating the samples at 550 °C until constant weight in a muffle furnace. The remaining fraction after the oxidation at 550 °C is the ash content. The collected samples were further blended, mixed, and grinded to a powder (<0.5 mm). Then, the finely grained samples (1–2 g), the elemental composition (C, H, N, O) in the solid and oily phases was determined using a CHNS analyzer Flash 2000 (Thermo Fisher Scientific, Massachusetts, USA), equipped with a thermal conductivity detector (TCD). To analyze oxygen content, a nickel-coated carbon, essential as a reaction medium, was lacking in the laboratory. Consequently, the oxygen content of the samples was estimated solely through a calculation using Eq. 1. This serves as an approximate prediction for the oxygen content of the compost under consideration [27].

$$X_O = TS - X_C - X_H - X_N - X_{ash} \quad (1)$$

Where X_C , X_H , X_N , and X_{ash} are the contents (%) of carbon, hydrogen, nitrogen and ash, respectively, and TS is the total solids (%).

The physicochemical composition of each by-product used in the formulations and of the finished compost from the six composting piles is presented in Tables S1 and S2, respectively.

Life Cycle Assessment

The LCA approach was applied in this study to evaluate the environmental impacts of the composting process of Water hyacinth according to International Standards Organization guidelines, ISO 14,040 (2008) and ISO 14,044 (2009) [21, 28]. It consists of four stages: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment and (4) interpretation of the results.

Goal and Scope Definition

The goal of this LCA is to compare and evaluate the least impactful feedstock option using water hyacinth as the main element in the composting piles mixes. The scope considers the entire waste management from the removal of the water hyacinth species from the water body until the simulation of the application of the compost on the lettuce crop to avoid the production of synthetic fertiliser, using a “cradle-to-grave” concept of the LCA approach. The stages considered in the system boundary included all processes from water hyacinth collection from the water body, with its transport to the composting location, the complementary transport of the by-products used in the formulations, and the emissions from the biological composting process. Additional stages and scenarios included packaging and the application of the compost to avoid the production of synthetic fertilisers (Fig. 1).

The functional unit (FU) provides a reference value from which input and output data need to be measured [28]. In this study, one ton of compost was established as the FU [29–32]. The input flows were the materials, energy, and resources. The output flows corresponded to the finished compost, and emissions to air, soil, and water.

For this study two additional scenarios were considered:

Scenario 1: A 50 kg capacity packaging with low-density polyethylene material was assumed in this scenario. Includes producing and transporting polyethylene material until the composting process site. The inventory data used for the packaging stage evaluation is described in Table S13.

Scenario 2: This scenario includes the production and transport of synthetic fertiliser and the application of the compost from the six composting piles on the chosen crop. Compost from composting piles can be used as a soil conditioner and replace/complement the use of synthetic fertilisers, thus reducing the production of these chemicals [33]. The effectiveness of compost can be compared to a conventional fertiliser considering the rate of nutrient release [34]. The reference crop chosen for compost application was lettuce (table S14). The NPK values from the six composts

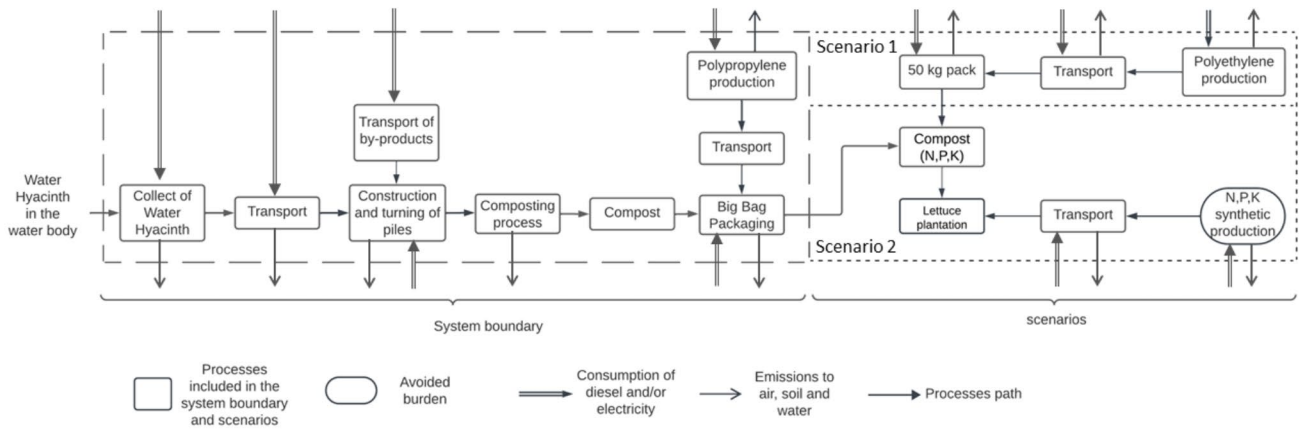


Fig. 1 System boundary of the composting process of the water hyacinth for the six composting piles

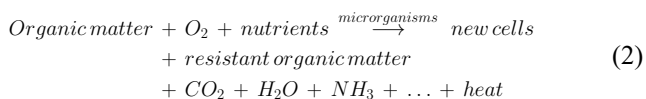
are shown in Table S15. The availability of NPK present in compost and in fertiliser dose at 10 t compost/ha are presented in Table S16.

Life Cycle Inventory

The primary data used in the development of the life cycle inventory (LCI) were collected on-site, directly on the location of the composting process. The secondary data were sourced from literature, as well as from the GaBi Professional software and Ecoinvent database.

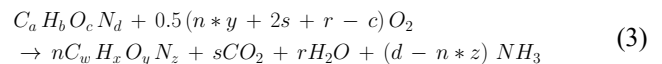
The primary data of the input flows regarding the collection of the water hyacinth from the water body, its transport, and the transport of the by-products until the location of the composting process, are presented in tables S3, S4, S5, S6, S7 and S8 for composting piles M1, M2, M3, M4, M5 and M6, respectively. Most environmental issues from the processes of transport and machinery of the raw materials are related to diesel consumption [35, 36]. For the inventory of the transport of by-products (except water hyacinth) the value of the original mass was assumed to be the same as that used in the composting pile.

In composting processes, the aerobic and biological transformation of solid waste generates a stable humus-like material known as compost, carbon dioxide (CO₂), water and ammonia (NH₃) [37]. This transformation is presented in Eq. 2.



If the biosynthesis of new cells, and the production of sulfate and phosphate are not considered, the initial elemental composition of formulations from composting piles and the

final product elemental composition (Tables S1 and S2) can be calculated for the stoichiometric coefficient in Eq. 3.



Where $r = 0.5[b - n * x - 3(d - n * z)]$, $s = a - n * w$, n = moles of organic matter in the output/mole of organic matter in the input.

These coefficients enabled the estimation of the molecular amount of CO₂ and NH₃ produced by the aerobic biodegradation of the feedstock.

The emission of CO₂ in the composting process is considered to have a biogenic origin and is not accounted for by the Intergovernmental Panel on Climate Change (IPCC) in the inventory of LCA [38]. However, if the composting pile are poorly managed, methane (CH₄) and nitrous oxide (N₂O) emissions should be counted in inventory by Eqs. 4 and 5, respectively [38].

$$CH_4\ Emissions = \sum_i (M_i * EF_i) * 10^{-3}
 \tag{4}$$

$$N_2O\ Emissions = \sum_{i2} (M_{i2} * EF_{i2}) * 10^{-3}
 \tag{5}$$

Where:

CH₄ Emissions = total CH₄ emissions in inventory year, Gg CH₄.

M_i = mass of organic waste treated by biological treatment type, Gg.

EF = emission factor for treatment _i, g CH₄/kg waste treated. In this case was used on a wet weight basis 4 g CH₄/kg waste treated.

_i = composting or anaerobic digestion.

N_2O Emissions = total N_2O emissions in inventory year, Gg N_2O .

M_{i2} = mass of organic waste treated by biological treatment type i_2 , Gg.

EF = emission factor for treatment i_2 , g N_2O /kg waste treated. In this case was used on a wet weight basis of 0.24 g N_2O /kg waste treated.

i_2 = composting or anaerobic digestion.

Additional Technical Information and Assumption The primary data and processes used for the water hyacinth collection stage are presented in Table S9. The primary data and processes used for the transport of by-products to the composting piles site stage are presented in Table S10. For the transport of the by-products, except for water hyacinth and cattle manure, the same type of transport was chosen to allow a comparative analysis. The primary data and the processes used for the construction and turning composting piles stage are presented in the table S11 and S12. The composting of this study was carried out at an experimental scale, and there was an extrapolation of the hours worked by the machines of the construction and turning of composting piles, and therefore there was a large fossil fuel consumption. The packaging used for one ton of compost was a Big Bag made from polypropylene fibres (PP) with a capacity of 1000 kg. As an alternative scenario, a 50 kg capacity package made from linear low-density polyethylene granulate (LDPE/PE-LLD) material was considered (table S13) [39].

Information from fertilisation manuals [40, 41] was used as secondary data for the scenario of fertiliser production (tables S18, S19, S20, S21, S22 and S23). The chemical fertilisers selected to supply the nutrient needs of the lettuce crop were urea ammonium nitrate (UAN, 30% N), triple superphosphate (TSP, 46% P_2O_5) and potassium chloride (KCl/MOP, 60% K_2O) because they are the most used by European countries [42].

Life Cycle Impact Assessment

In the third stage of the LCA, the CML environmental impact assessment method was used, because it is more used for LCAs for composting [23] and the GaBi professional software was chosen to develop the model of the LCA for the composting process and analyze the inventory. The impact categories considered were the most cited in the literature and more relevant to the composting process: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion (OLD) and photochemical oxidation creation (POC) [23]. As CO_2 emitted from the composting

process is considered biogenic, that is within the carbon cycle and not fossil-derived, it is not considered a greenhouse gas and is not included in the LCA accounting [30, 31, 43].

Interpretation of Results

In this phase, the compiled data from the life cycle inventory and the results from the impact assessment were analysed and discussed according to the scope of work. The discussion includes the comparison among different bulking agents while using water hyacinth as the main material in the formulation of the composting piles. Also was evaluated which of the six formulations was less polluting covering all its stages from composting them.

Results

The results are organized based on specific stages and processes within the system boundary. These stages include extracting water hyacinth, transporting the water hyacinth and its by-products to the composting site, constructing and turning the composting piles, managing the biological composting process, and packaging the final product. Additionally, the compost from the six composting piles is compared.

Overall Life Cycle Assessment Analysis

From a generic perspective, considering all stages within the system boundary, the M2 pile obtained the highest contribution for the impact categories AP and EP, the M3 pile had the highest values for the GWP and OLD, and the M5 pile got the highest contributions for POC (Table 1).

Considering the estimated impacts for the full product system, the composting stage contributed the most for GWP, EP and AP in the case of five of the composting piles, except for pile M4 (Fig. 2). During the composting process, there may be leaks of greenhouse gases (CH_4 and N_2O), that directly contribute to the GWP category, and NH_3 emissions affect the AP and EP categories [44].

The stage of construction and turning piles contributed about 51% for the category POC in the six composting piles, with greater influence in the M5 and M6 piles (54.7% and 54.8%, respectively). This can be attributed to nitrogen oxides emissions from fossil fuel combustion by the machinery used in the construction and in turning the piles [36]. The Packaging with Big Bags was the stage that most impacted the OLD category, with an average of 55% in the six composting piles, prominently in the M4 pile with 64%.

Table 1 Overall environmental impact characterization concerning all stages of the composting process from the six piles

	AP [kg SO2 eq.]	EP [kg PO4 ³⁻ eq.]	GWP [kg CO2 eq.]	OLD [kg R11 eq.]	POC [kg C2H4 eq.]
M1	37.26	8.4	695.51	2.50E-11	0.17
M2	47.33	10.56	632.51	2.32E-11	0.14
M3	42.04	9.48	816.51	2.99E-11	0.21
M4	1.20	0.41	436.71	2.15E-11	0.12
M5	44.31	9.97	805.51	2.97E-11	0.23
M6	10.66	2.56	651.21	2.57E-11	0.17

Best performance ← → Worse

M1: water hyacinth + olive pomace + potato peel; M2: water hyacinth + olive pomace + cattle manure + potato leftovers; M3: water hyacinth + olive pomace + rice straw + potato leftovers; M4: water hyacinth + olive pomace + wood chip + biochar; M5: water hyacinth + wood chip; M6: water hyacinth + potato leftovers + olive pomace + rice straw.

AP: acidification potential; EP: eutrophication potential; GWP: global warming potential; OLD: ozone layer depletion; POC: photochemical oxidation potential.



Fig. 2 Environmental impact assessment of each composting pile, data normalized as a percentage of the total value

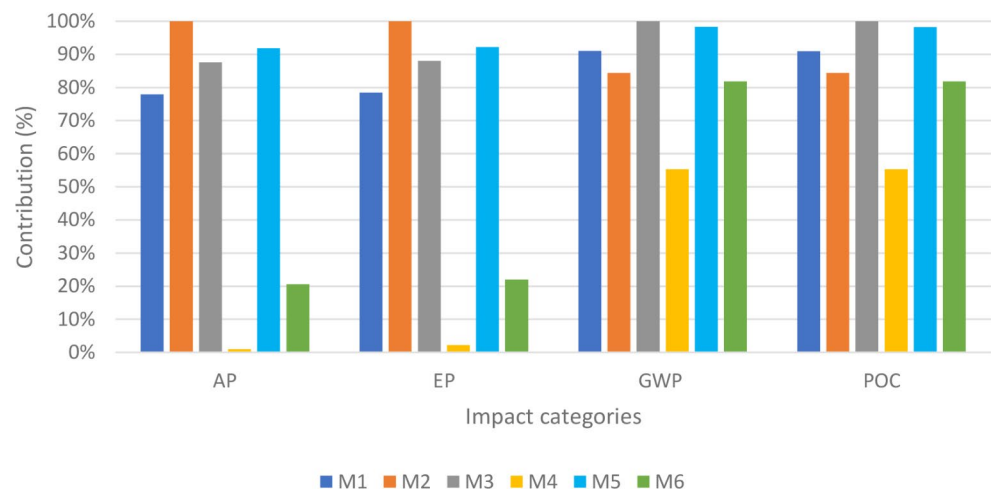
The Biological Process of Composting

The composting stage consists of a biological process of degradation of organic matter, has releases gases (i.e. CO₂, water vapour, NH₃) produced by reaction from microorganisms [45]. If the composting pile is poorly ventilated, small anaerobic pockets of CH₄ and N₂O can be generated in the pile, which can directly contribute to the category GWP [29]. As CH₄ and N₂O directly contribute to an emission factor of 25 and 298 times, respectively, more than CO₂, the values attributed to them are highly relevant [31]. Looking at the pile formulations, the pile that most contributed to GWP was the M3 (Fig. 3) with 14,31 kg CH₄/ tonne of

compost and 0,86 kg N₂O/ tonne of compost (589 kg CO₂ eq.) (Tables S5 and S27).

The NH₃ emission is mostly emitted when the temperature in the composting pile is above 40–50 °C, causing the nitrification of ammonium to NH₃, instead of the NO₂ [46], and as a consequence contributes to an increase in the AP and EP categories [47]. In this study, the M2 pile contributed with the highest value for AP and EP categories with 46.6 kg SO₂ eq. and 10.42 kg phosphate eq., respectively (table S26), as the amount of ammonia emitted is around 29.1 kg/ tonne of compost (table S2). This amount of NH₃ estimated in this study is significantly high compared to data found in the literature, 0.025–1.3 kg of NH₃/tonne of

Fig. 3 Environmental impact assessment of the contribution of biological process emissions from the six composting piles for each impact category. Data normalized as a percentage of the total value



feedstock [29, 32]. Nonetheless, the M4 pile, with the lowest contributions to the AP and EP categories, 0.29 kg NH₃/tonne of compost was inside that margin.

For the POC category, the interaction of air pollutants, such as nitrogen oxides (NO_x) and volatile organic compounds (VOCs), with oxygen in the air are the biggest contributors. As in composting, there are emissions of CH₄, NO_x and VOCs, even if in small quantities, they affect the POC category [48].

In the composting process, there is no gaseous emission interfering with the OLD category (chlorine, bromine, chlorofluorocarbons and halogenated substances) [49] and, therefore, the composting process has no direct impact on this category (Table S27).

Fossil Fuel Consumption

In general, any process requires some type of energy for its operation and it is difficult to avoid the use of fossil fuels nowadays. The burning of fossil fuels is one of the aspects that most contribute to the categories of environmental impacts in a composting system [23].

In this study, the M3 was the pile that most impacted all analysed categories, followed by the M5 with around 99% (Fig. 4, Table S28).

In the six composting piles, the stages that most contributed to the impact results were the construction and turning of the piles (Fig. 5). It was the stage that most used fossil fuel and operating hours of agricultural machinery, corresponding to around 35 kg of diesel/tonne of compost and 13 h per pile, respectively. Because it was an experimental essay, the construction and turning stages consumed a large amount of fossil energy, associated with the operating time. In this analysis, it is necessary to consider that on an industrial scale, the processes will be optimized to increase energy and economic efficiency, with a smaller impact on the results for the impact categories considered.

The transportation of by-products was the second stage that had the most significant impact on the increase in impact categories. This stage had notable hotspots because it required the largest distances to transport water hyacinths from the water body and feedstock from their source to the composting site using trucks, increasing the use of fossil fuel.

The transport of feedstocks for the M3 pile had a major contribution in the five impact categories analysed, due to the higher distance and greater consumption of fossil fuel (300 km and 17 kg of diesel/tonne of compost). The pile that used potatoes leftover by-products as secondary material for the piles was the one that most influenced processes, contributing to the increase in the impact categories related to the transportation of by-products, due to its high fuel consumption and distance. Comparing the eight by-products, potato leftovers have the greatest distance from the origin (208 km) and this affects the total distance of the piles that have potato leftovers in their formulation (M3 and M2 piles with 300 km and 251 km in the total, respectively). Regarding fuel consumption by distances travelled from the origins of the by-products, the M3 and M2 piles were the first and second largest fuel consumers, respectively. This happened mainly due to potato leftovers, which accounted for approximately 90% of the total diesel consumption in pile M3 and 72% in pile M2, representing the highest percentages observed (Fig. 6). In contrast, pile M4 had the lowest contribution among the composting piles, as it consumed less fuel and presented to be the most efficient transport.

Scenarios

Big bag Packaging Stage and Scenario of the 50 kg Packaging

In the Big bag packaging and scenario of the 50 kg packaging, the impacts associated with the diesel and electricity

Fig. 4 Environmental impact assessment of the contribution of total consumption of fossil fuels used during the system stages of each composting pile. Data normalized as a percentage of the total value

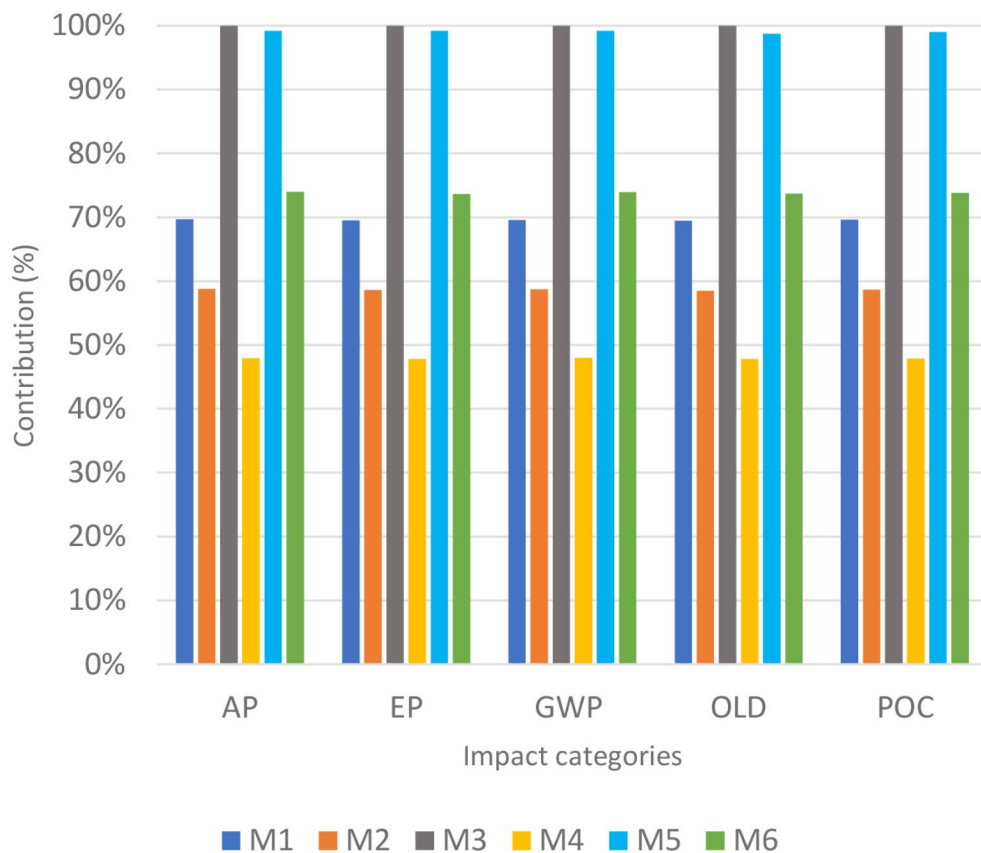
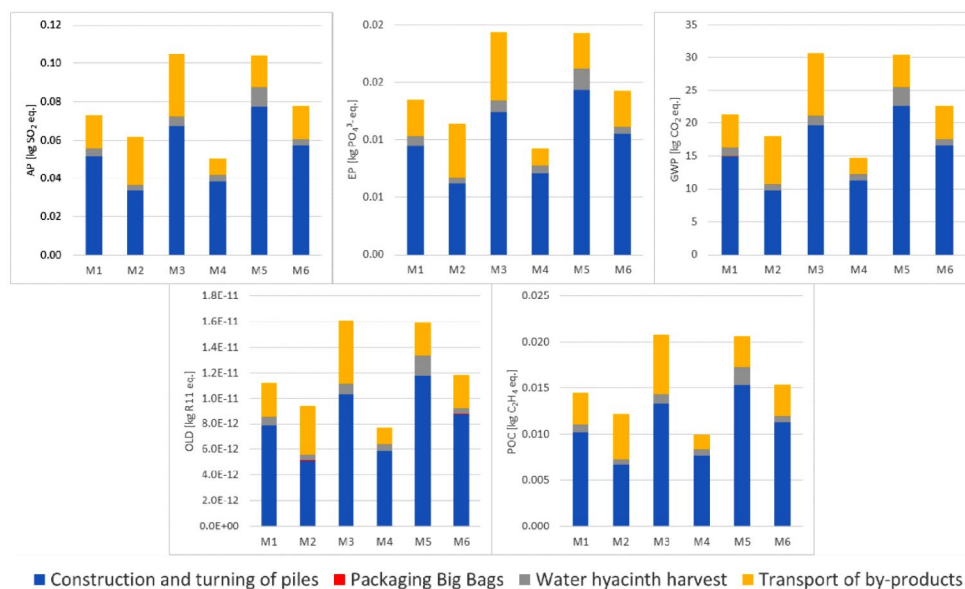


Fig. 5 Environmental impact assessment of fossil fuel consumption of each stage of the six composting piles. Data normalized as a percentage of the total value



consumption processes were compared for both options. Emissions related to the use of the truck for transport, polypropylene (PP) fibres process for the big bag material and polyethylene linear low-density granulate (LLDPE/PE-LLD) for the 50 kg packaging material. The processes that caused the most impact were the polypropylene (PP) fibres process for the Big bag packaging stage and polyethylene

linear low-density granulate (LLDPE/PE-LLD) for the 50 kg packaging scenario (Fig. 7, table S29 and S30).

Globally, packaging using the big bag increased the estimated AP, EP and GWP impact categories by around 25%, 12% for POC and 65% for OLD when compared with the 50 kg packaging. (Fig. 8). The process of producing polypropylene fibres is considerably more impactful than the

Fig. 6 On the left: percentage of the distance of each byproduct and the total distance (km) of each pile. On the right: percentage of diesel consumption of each byproduct and the total consumption (kg of diesel) of each pile

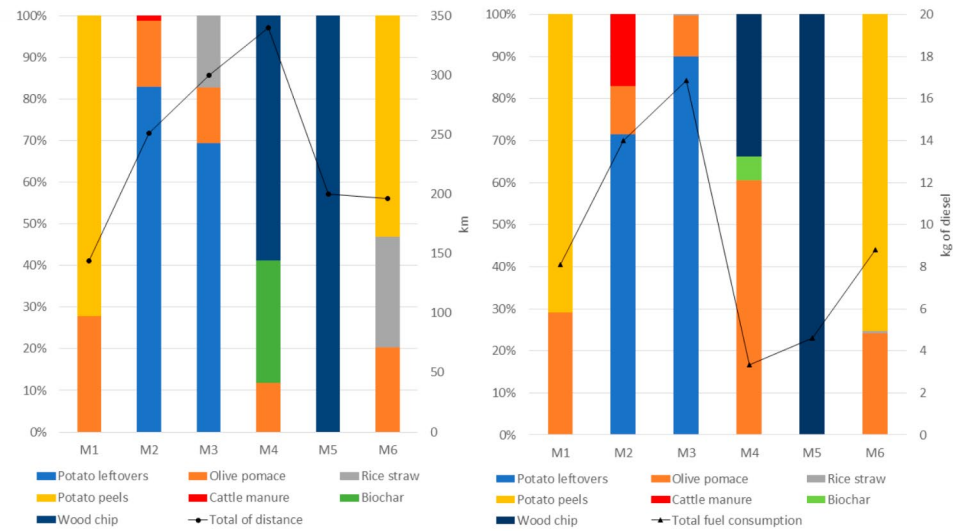
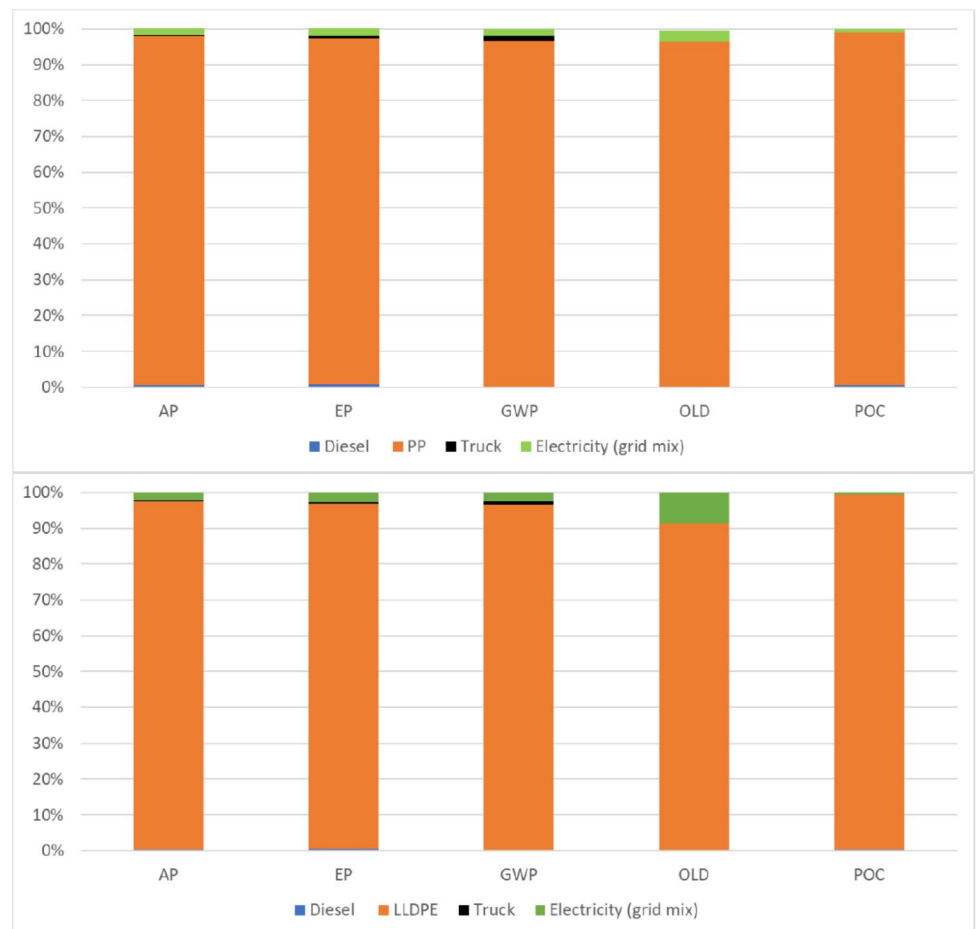


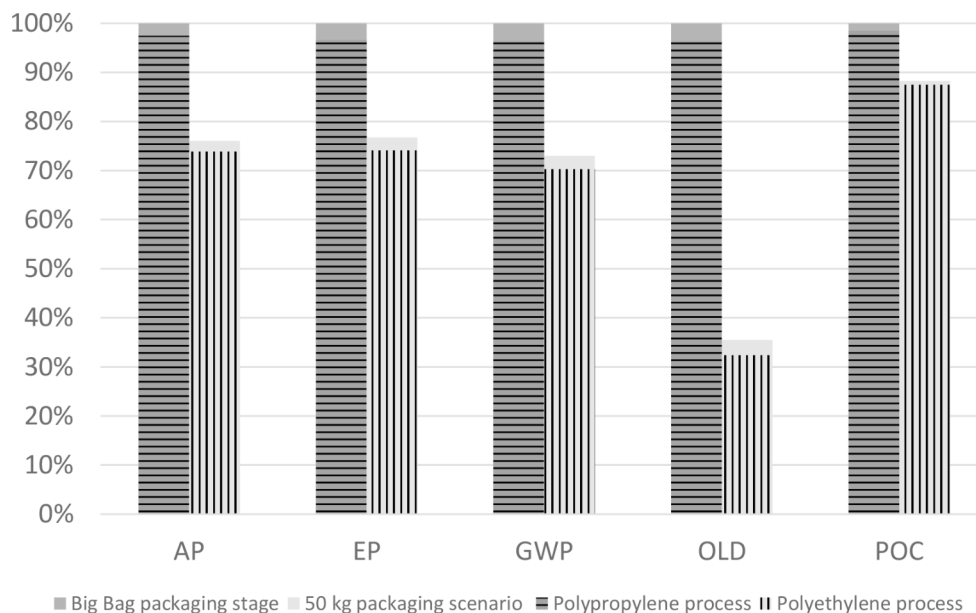
Fig. 7 On top: Percentage contribution of the packaging stage with PP (polypropylene) big bags and its processes. Below: Percentage contribution of the scenario with the LLDPE (linear low-density polyethylene) 50 kg packaging and its processes. Data normalized as a percentage of the total value



process of producing linear low-density polyethylene granulate [50]. However, the potential for the reuse of 1000 kg big bags with polypropylene material is superior to that of polyethylene packaging (which is generally discarded), thus reducing their environmental impacts, when multiple

uses are considered. Polypropylene bags that are thick and durable must be used an estimated 10–20 times to have the same impacts as polyethylene, thinner but still reusable 5–10 times [39]. The reduction in the expected impact magnitude related to plastic bags is not necessarily linked

Fig. 8 Comparison between the Big Bag packaging stage and the 50 kg packaging scenario, with its most environmentally impactful processes, polypropylene and polyethylene, respectively



to the durability of the bag, but rather to the extent to which the durable bag is reused. In the study by Civancik-Uslu et al. [51] which evaluated some bags made of polypropylene, polyethylene and other materials, the results showed that PP bags (20 uses) had an impact of 7, 3, 5 and 3 times higher in the categories AP, GWP, EP and POC, respectively, than LDPE (10 uses). The big bag with PP may have a high impact according to conventional results from LCA, however, when considering it is a highly resistant material with a higher price, it increases the chances of being reused more times than LDPE and, therefore, becoming the best environmental choice [52].

Application of Compost

By delving into the impact categories of chemical fertiliser production and transportation, it can be discerned that the UAN, TSP, and KCl/MOP processes significantly influence the five key impact categories. This is primarily due to the substantial energy requirements for their raw material extraction and manufacturing processes (Fig. 9, Table S31).

In particular, TSP considerably affects the AP, EP and POC categories due to its emissions being linked to the use of sulfuric acid to produce phosphoric acid, phosphates released to water, fluorides and particulate matter to the air and heavy metal emissions to the soil [53]. UAN obtained the highest percentage in the GWPs categories because CO₂ is produced as a by-product during the production of NH₃ and, consequently is used for the synthesis of urea [54].

KCL/MOP is the lowest impact process compared to the production of the chemical fertilisers TSP and UAN, as its production results are mainly from the mining and

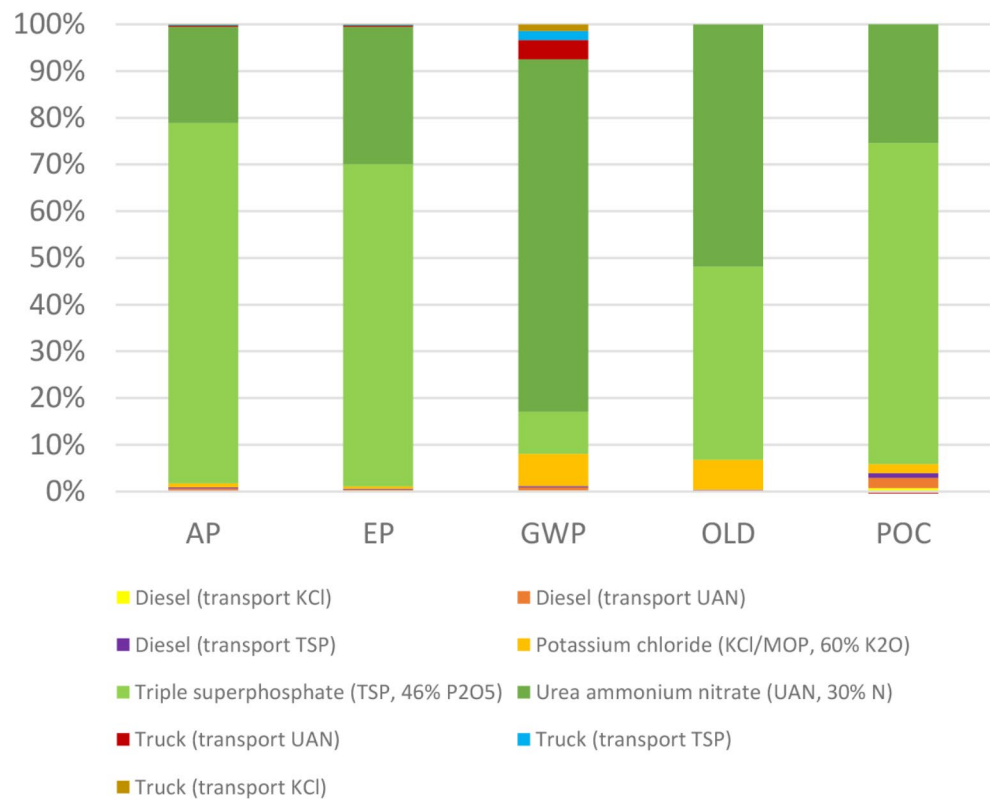
processing of potassium salt from seawater. Its emissions are associated with the GHGs CO₂ and CH₄ from fossil energy (natural gas), contributing directly to the GWP category and by particulate matter and HCl emissions, which affect the OLD category [55].

In Fig. 10 (table S32), it is possible to state that the composts produced in piles M5 and M6, were around 4% and 5%, respectively, more impactful than the other composts. These differences may be explained by the fact that the compost from pile M5 was the one with the least availability of N (0.55 kg of N/tonne of compost) and, consequently, needed to use the largest amount of UAN (36.5 kg of UAN/tonne of compost) and, therefore, also contributed more to the GWP category (33.9 kg CO₂ eq.). Compost M5 is derived from mixing only water hyacinth and wood chips. Wood chips serve as a carbon source but lack nitrogen, which can lead to lower nitrogen content in the matured compost [14]. Therefore, this may have required greater dependence on the addition of UAN chemical fertiliser.

The M6 compost had the smallest availability of P₂O₅ (2.25 kg of P₂O₅/tonne of compost) and consequently needed to use the largest amount of TSP (12.5 kg of TSP/tonne of compost), affecting categories: AP (0.136 kg SO₂ eq.) and EP (0.042 kg PO₄⁻³ eq.).

Compost M3 demonstrated a smaller impact across the AP, EP, and POC categories, primarily due to the impressive reduction of TSP production by approximately 46%. In contrast, M1 had the most notable effect on the GWP category, managing to reduce UAN production by approximately 11.23%. Although M6 managed to achieve an 11.43% reduction in UAN production, it fell short when it came to minimizing TSP production, providing a potential reduction

Fig. 9 Environmental impact assessment of the contribution of chemical fertiliser production processes (UAN, KCL/MOP and TSP) to the impact categories. Data normalized as a percentage of the total value



of 28%. As a result, it did not achieve the most significant reduction in the GWP category (Fig. 11).

Discussion

The approach to discussing results in LCA depends on the scope defined in the study and the perspective of the stakeholders. In this context, the discussion must consider the fact that the composting process focuses on an invasive plant that poses a threat to biodiversity, dealing with its residues after removal from the affected environment. Water hyacinth composting has proven to be an effective method as a complementary process in the control of this invasive plant, and it was evaluated with the addition of six different mixtures of waste.

According to the results, the worst estimated environmental performance corresponds to the M2 and M3 piles, as they were the piles that achieved the highest percentage of the two impact categories each, GWP and OLD and AP and EP, respectively. Under such circumstances, when presenting the overall results of an LCA of a study, it is up to the LCA analyser together with interested parties to define the impact category with the highest priority to reduce its environmental burdens [56].

One of the processes that most contributed to the overall increase in the impact categories of M2 and M3 piles

was the biological process of composting. In this case, it is worth highlighting the decision-making priority of reducing the GWP, AP and EP impact categories. Measures to reduce environmental loads related to composting are directly associated with fugitive emissions of gases CH₄, N₂O and NH₃ [57, 58].

Continuous improvement in the way of managing and controlling aeration, temperature, absolute humidity, and the addition of biological additives (minerals and biochar), are fundamental factors in reducing gases and GWP [59, 60]. Another factor that contributes to the gases that cause GWP, AP and EP is the choice of waste to form the composting pile mixture. Wastes with high nitrogen content, including manure, mixed municipal organic waste and wastewater treatment sludge, tend to increase N₂O [57]. Food waste tends to increase AP and EP impacts [24]. These statements are in line with the results found in this research, as the M2 pile had manure and food waste in its formulation and it had one of the highest values of N₂O and NH₃, whereas the M4, which had additives such as wood chips and biochar, got the lowest CH₄, N₂O and NH₃ values [61].

In terms of energy consumption (fossil fuel), the worst environmental performance corresponds to the M3 and M5 piles, due to the stages of transporting by-products and maintaining the composting piles, respectively. The energy consumption of electricity for the operations process and diesel in waste collection are the most significant

Fig. 10 Environmental impact assessment according to production (%) and total application (kg) of chemical fertilisers. Data normalized as a percentage of the total chemical fertiliser value

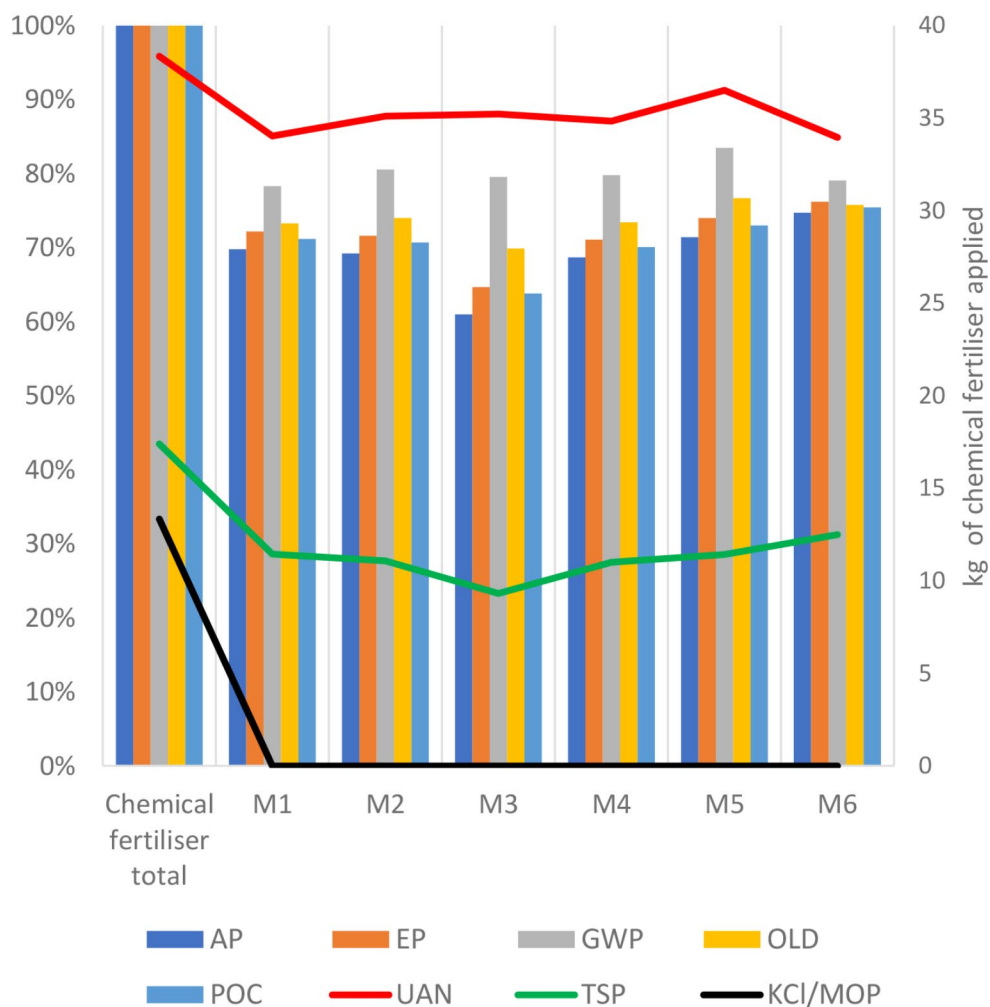
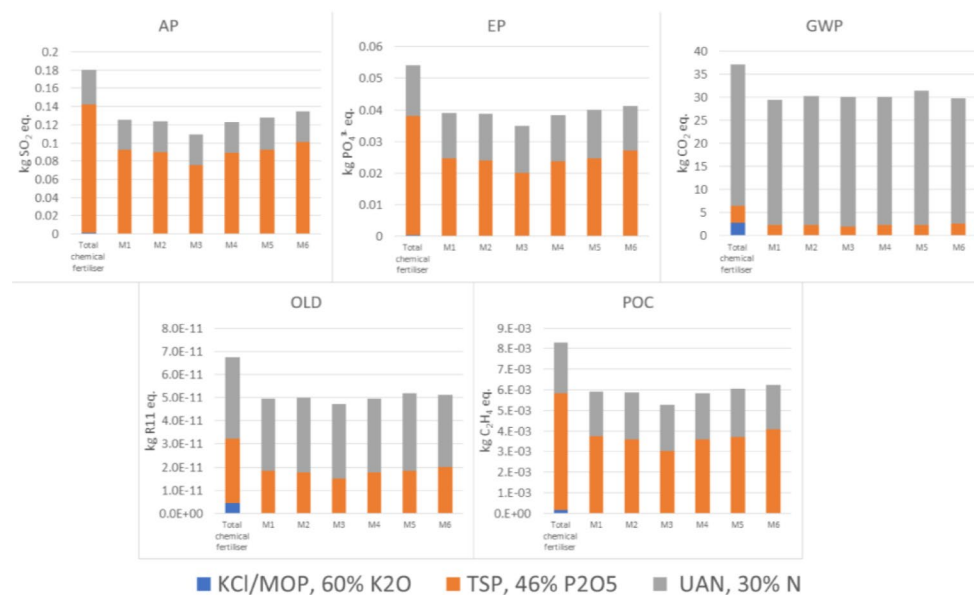


Fig. 11 Environmental impact assessment of the contribution of chemical fertiliser production (UAN, KCL/MOP and TSP) for each impact category analysed. Data normalized as a percentage of the total chemical fertiliser value



contributors to the GWP category [62, 63]. Energy consumption also affects other categories (OLD, human toxicity, abiotic depletion and fossil depletion potential) and therefore stages and processes that consume a lot of fossil energy tend to have higher impact values in these categories [23, 62].

The transportation of by-products also needs to be well-dimensioned, opting for alternatives closer to the composting site. This is a very important issue, as the lack of optimization and efficiency of processes can bring large financial, economic and, mainly, environmental costs, making the composting process less sustainable. A mixture from a given compost pile that uses more fossil fuels will emit more GHG in its life cycle and consequently have a higher GWP. Such results provide useful information for decision-making, as they allow the identification of the most impactful system under these conditions.

When considering only the packaging manufacturing, the Big Bags with polypropylene had the greatest impact, per tonne of compost, when compared to the alternative 50 kg capacity polyethylene packaging. Such an assessment did not consider the options for recycling and reusing such materials. However, more simulations and new approaches must be developed to evaluate the impacts and compensation of the PP and LLDPE/PE-LLD packaging recycling. The choice of material, volume, capacity and how the packaging is used can reduce environmental and financial impacts, especially if it is possible to reuse the same package multiple times. When applying the compost, it should efficiently meet the needs of the crop and consequently reduce the environmental impacts of the production of chemical fertilisers. In this regard, the best compost was the M3, and overall, the worst was the M6. Compost M6, formed by a mixture of water hyacinth, olive pomace, potato peel and rice straw, obtained the highest impact scores for three of the five categories analysed (AP, EP and POC), that is, the efficiency replacement of chemical fertilisers by compost M6 was lower than the other composts.

In future LCA studies, It is noteworthy to emphasize the need for the incorporation of a complex model that accounts for the application of compost in the soil, including nutrient dynamics, crop yield, and their associated emissions [64]. The compost substitution factor is crucial, as compost application does not entirely replace the use of chemical fertilisers and the compost application rate and its associated benefits will vary depending on the type of crop being cultivated [44]. From another point of view, there is also the issue of farmers' preference for applying chemical fertilisers because they increase the apparent productivity of crops in the short term, reducing the application of compost and opportunities that investigate their advantages [65].

In general terms, the M4 composting pile, which incorporates a mixture of water hyacinth, olive pomace, wood chips and biochar, can be considered the most environmentally favourable option. This is because, in practically all phases and processes involved, this pile had the lowest estimated environmental impact. In the compost application stage, its effectiveness was not the worst, presenting only around 10% more environmental impact compared to the M3 pile, which was the least impactful in environmental terms.

Conclusion

This work evaluated the environmental impacts of the water hyacinth composting process by considering six composting pile formulations, using the LCA approach.

The highest GWP contributions are related to the GHG emissions from the composting process, which can be reduced through more efficient management. Another reason that causes great environmental burdens on solid waste treatment processes is the high consumption of fossil energy by machinery required for operations. If the energy transition towards renewable and non-fossil alternatives is not implemented, the operation and maintenance stages will continue to have an important contribution in all environmental impact categories. Additionally, it is also worth optimizing routes and means of transportation for waste collected for composting.

In general, the M4 compost pile, with the mixture of water hyacinth, olive pomace, wood chip and biochar, obtained the best environmental performance, including the application of compost and the ability to credit the replaced loads related to the production of chemical fertiliser. Despite the factors that led to this identification, further modelling still needs to be carried out with the lettuce crop yield test to confirm and validate the nutrient availability of the six composts involved.

The use of Water Hyacinth for composting has proven to be a valuable mechanism to produce quality compost, as it provides a destination to an invasive species and transforms it into a valuable product, albeit producing some inevitable environmental impacts. The composting of water hyacinth in combination with different types of feedstocks provided quality composts and a good nutrient content (NPK) that can help curb the use of chemical fertilisers.

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Author Contributions Laís Fabiana Serafini: Conceptualization; Methodology; Data curation; Investigation; Software; Visualization; Formal analysis; Roles/Writing - original draft; Writing - Review & Editing. Margarida Arrobas: Methodology; Resources; Validation. Manuel Ângelo Rodrigues: Methodology; Resources; Validation; Writing - review & editing; Funding acquisition; Project administration. Manuel Feliciano: Validation; Writing - Review & Editing. Filomena Miguens: Methodology; Validation; Data Curation. Daniela Santos: Methodology; Validation; Data Curation. Veronica Oliveira: Methodology; Validation; Data Curation. Jose Luis Diaz De Tuesta: Methodology; Resources. Artur Gonçalves: Methodology; Investigation; Writing - Review & Editing; Supervision; Project administration.

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Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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