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Comparative Life Cycle Environmental Impact Assessment of Fruit and Vegetable Waste Valorization by Anaerobic Digestion as an Alternative in a Mediterranean Market

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Abstract: Landfilling and incineration are the most widely used methods for the management and treatment of fruit and vegetable waste (FVW) in Mediterranean markets, despite their potential environmental impact. A comparative life cycle assessment was conducted in this study to evaluate the environmental improvements from replacing the current landfill disposal method for FVW management and treatment in the wholesale market of Amman (Jordan) with an integrated anaerobic digestion process followed by composting. The proposed FVW treatment scenario is the best treatment option for all the assessed impact categories under the system expansion approach. Significant reductions in global warming and terrestrial ecotoxicity impacts categories would be achieved, reaching up to 322% and 352%, respectively, when compared to the current treatment scenario. Furthermore, the higher production of electrical energy (413%), as well as the production of co-products that would avoid the production of 100 kg/d of inorganic fertilizers, would contribute to such a low value of avoided impacts.

Keywords: anaerobic digestion; bioprocess; global warming; landfill; organic waste; wholesale market



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1. Introduction

The rapidly growing population, accompanied by an increase in per-capita consumption, has resulted in a substantial rise in fruit and vegetable production, consumption, and, thus, waste volume generation in the Mediterranean Basin countries. Fruit and vegetable waste (FVW) is generated not only during production and harvesting stages, but also in large quantities during the distribution chain, resulting in a total loss of up to 30% of the produce intended for consumption [1,2].

Open or wholesale markets constitute a major source of FVW generation in many Mediterranean countries. These wholesale markets are an important sector of the food trade, having a relevant economic and social impact [3]. As wholesale markets are an important source of organic waste [4], proper waste management is still an urgent issue [5]. Improper handling of this growing waste stream can lead to negative environmental, economic, and social impacts.

Fruits and vegetables are highly biodegradable and have a very rapid degradation rate due to their high moisture and organic matter content [6]. The non-recovery or direct

landfilling of this type of waste generates undesirable gases and leachates, which can pose several risks to public health and to the environment [7]. Landfilling is currently the most common and straightforward method of disposing of organic solid waste, including FVW, in these countries, despite its potential environmental impact [8,9]. Landfill methane, produced by the anaerobic degradation of discarded organic matter, is the third-largest anthropogenic methane emissions source to the atmosphere, accounting for approximately 800 million tons of carbon dioxide (CO₂) equivalent [10,11]. The gas produced, a mixture mainly composed of methane (CH₄) and CO₂, is typically released into the atmosphere. In order to make this management option more sustainable, an increasing number of landfills are capturing biogas due to legal requirements and interest as a fuel for electricity production [9].

FVW is generated in considerable quantities within these centralized markets, thus providing a valuable opportunity for the implementation of more efficient and sustainable management technologies [6]. Anaerobic digestion (AD) is one of the safest alternatives to FVW management from an environmental perspective [1]. AD allows the on-site efficient production, capture, and use of biogas from the microbial degradation of organic matter. This sustainable process significantly reduces greenhouse gas emissions and unpleasant odor emissions, simultaneously enabling the recovery of valuable nutrients and other materials for soil amendments [12,13]. AD is a suitable technical alternative to landfill disposal for improving the treatment and management of FVW in these centralized markets. However, despite AD having been widely evaluated from an operational point of view, the environmental impacts of its implementation for FVW treatment options in Mediterranean wholesale markets as an alternative to landfilling has not yet been comprehensively studied. For that, a life cycle assessment (LCA) is necessary to quantify these specific impacts. LCA is a methodological framework used to estimate and evaluate the environmental impacts associated with the life cycle of a product, process, or service [14]. LCA has been previously applied for the evaluation of different waste treatment technologies in municipal solid waste management [15–19], but, to our best knowledge, there is no reported LCA in a fruit and vegetable wholesale market context. LCA could therefore be used to assess and compare the environmental impacts of the two different FVW treatment options.

The aim of this study is to estimate and compare the life cycle environmental impacts of two waste management and treatment scenarios for FVW in the Amman fruit and vegetable wholesale market (Jordan), i.e., (a) landfill disposal, the current scenario; and (b) AD coupling with a subsequent composting process, the proposed scenario.

2. Methodology

The comparative LCA was conducted in accordance with the ISO 14040 and ISO 14044 standards [20,21]. The goal definition and scope of this study, followed by the life cycle inventory data and overview of the impact assessment methodology employed, are described below.

2.1. Goal Definition and Scope

The main goal of this study is to estimate and compare the life cycle environmental impacts of two waste management and treatment scenarios for FVW in the Amman fruit and vegetable wholesale market (Jordan), i.e., landfill disposal, the current scenario (Scenario A); and AD coupling with a subsequent composting process, the proposed scenario (Scenario B).

The collection and transport of packaging waste generated in the market for treatment is a common life cycle stage for both scenarios in the comparative LCA, so it was excluded from the analysis. The construction and decommissioning of the treatment plants were also excluded in both scenarios under the assumption that their environmental impact per functional unit is negligible compared to that of other life cycle stages due to their long lifespan. For the LCA, the functional unit was defined as the treatment of 5000 kg of FVW per day.

2.1.1. Description of the Scenarios

The Amman fruit and vegetable wholesale market receives approximately 3350 tons of fruits, vegetables, and aromatic and edible herbs daily. Fruits, vegetables, and herbs that are not sold on the market or are not in good condition for sale, along with the waste generated from packaging, usually amount to approximately 15–22 tons per day, of which 5 tons per day are FVWs [22]. The characterization of generated market FVW is based on experimental results obtained in previous research works [3,6]: total solids (g/kg) = 150.0; volatile solids (g/kg) = 135.0; mineral solids (g/kg) = 15.0; moisture (%) = 85.0; carbon content (%) = 46.5; and nitrogen content (%) = 1.9.

Scenario A: Landfill Disposal (LD)

The current scenario for FVW management generated in the Amman fruit and vegetable wholesale market is shown in Figure 1. The waste generated is manually collected and deposited in containers located throughout the market. Once per day, a collection truck equipped with an internal compaction mechanism loads and transports the waste to the nearest transfer station, which is located about 11 km away. At the Al Shaer transfer station, the waste is compacted.

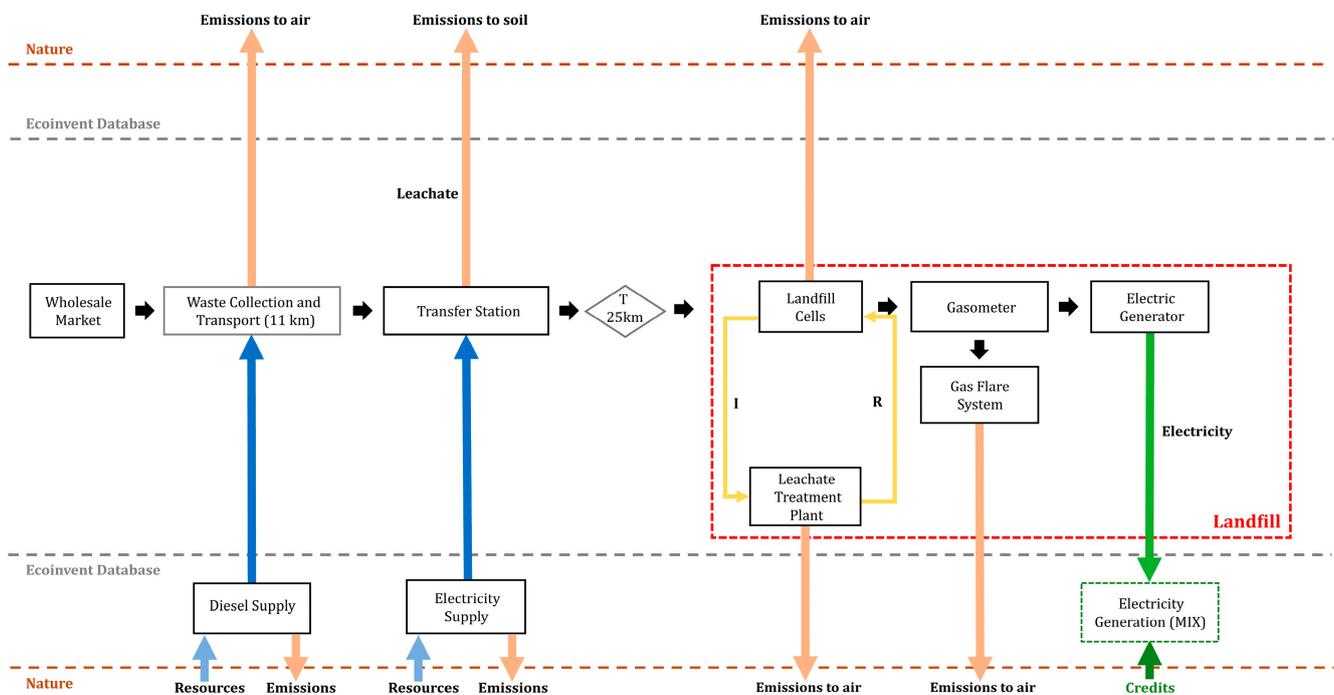


Figure 1. Landfill disposal (Scenario A) (T, transport; I, leachate input; and R, leachate recirculation).

Compacted waste is transported by trucks to the Al Ghabawi landfill, approximately 25 km away, and deposited in cells. According to Hadjidimoulas [23], the filling of the cells is carried out using agricultural or construction vehicles equipped with shovels. Landfill gas, which is approximately 50% CH₄–50% CO₂, is extracted from vertical wells with a 75% efficiency [23]. The gas extracted is stored in a gasometer and subsequently transformed into electrical energy through generation, assuming an efficiency of 30% [24]. Part of the generated electricity is used for landfill operation, while the excess electricity is sold to the Jordanian Electric Power Company (JEPCO), which is responsible for supplying Jordan with electric energy [23]. The leachate generated inside the landfill is extracted with vertical wells and pumped from the bottom of the landfill to the surface, where it is stored in leachate treatment plant ponds. A recirculation system is used as a leachate treatment method to increase the moisture content of the disposed waste, which leads to an increase in the landfill gas production rate in the cells [23].

Scenario B: AD Coupling with a Subsequent Composting Process (ADC)

The proposed scenario for FVW management generated in the Amman fruit and vegetable wholesale market is shown in Figure 2. This alternative scenario involves the separation of the waste generated, composed of packaging and discarded fruit and vegetables, through selective collection. Plastic packaging will be sent to the transfer station and disposed of at the Al Ghabawi landfill. Selectively collected FVW will be transported by conventional hand trucks to a storage tank located at the AD plant to be built on land attached to the market site.

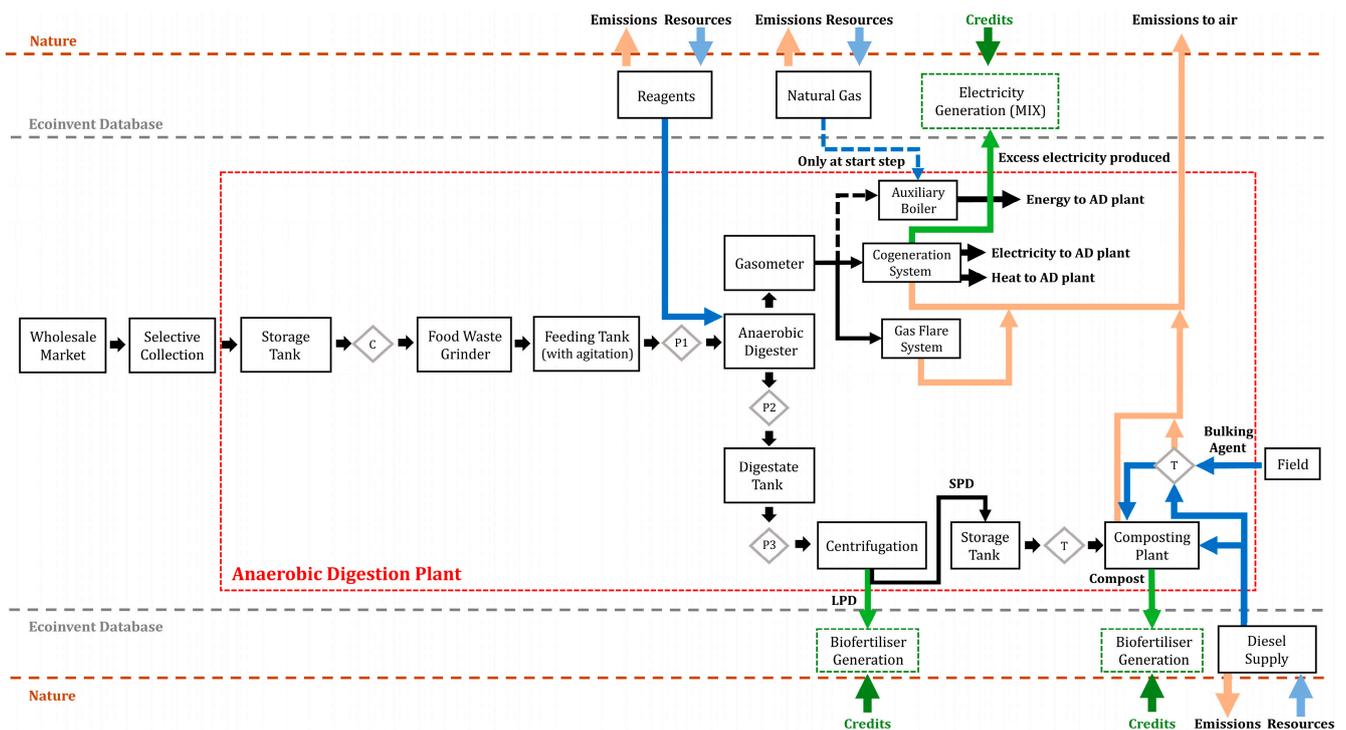


Figure 2. AD coupling with a subsequent composting process (Scenario B) (C: conveyor belt; P: pump; T: transport; LDP: liquid-phase digestate; SPD: solid-phase digestate).

The first stage of the proposed AD plant involves storing the FVW in a storage tank at ambient temperature (25 ± 5 °C). The waste is then transported by a conveyor belt (C) to the mechanical pre-treatment unit, which reduces the particle size to 3 mm. In these first stages, the plant will be operated in discontinuous mode. From the mechanical pre-treatment unit, the grinder waste is directly deposited into a feeding tank. The feeding tank is equipped with an agitation system to ensure proper mixing and has a maximum capacity of 3000 kg of chopped waste per day. From the feeding tank, the chopped and homogenized substrate will be fed to the anaerobic digester with a pump.

The anaerobic digester will be a continuous stirred tank reactor (CSTR) with a total volume of 432 m^3 (340 m^3 of working volume). The operational conditions of the anaerobic digester are based on experimental results obtained in previous research works and will be as follows: a hydraulic retention time of 25 days, an organic loading rate of $2.5 \text{ kg VS/m}^3 \cdot \text{d}$, and a working mesophilic temperature range of 35 ± 2 °C [25–28]. The digester will also be equipped with a thermal heating system to maintain mesophilic conditions and an electrical system to operate the radial agitator. The AD process will generate two main products, biogas and digestate. Biogas composition will be considered to be 60% CH_4 –40% CO_2 according to the data provided by Trujillo-Reyes et al. [6], which reported a biogas composition range of 63–50% of CH_4 and 37–50% of CO_2 . The biogas generated in the digester will be stored in a gasometer equipped with a gas flare system [29]. The biogas generated will be treated by cogeneration to generate thermal and electrical energy, with an efficiency

of 45% and 39%, respectively [30]. The thermal energy generated by cogeneration will be used to heat the anaerobic digester, while the electrical energy generated will be used to for pumping, stirring, and centrifugation. The Greater Amman Municipality has an agreement with the power companies to treat the electricity generated from biogas [23], whereby surplus electricity will be sold to the power grid.

The digestate generated at the end of the AD process will be temporarily stored in a tank and then pumped into a tubular centrifuge. The centrifuge will separate the digestate into two phases, obtaining a liquid-phase digestate (LPD) and a solid-phase digestate (SPD). The LPD will be used as a biofertilizer in gardening (irrigation) and the SPD will be treated by composting to finally obtain an organic fertilizer (compost). Then, composting of the SPD obtained after the application of AD to FVW would require the addition of a bulking agent to adjust the composition and physical structure to allow aerobic degradation to occur. In the present assessment, the use of a bulking agent from pruning fruit and garden trees (mixed pruning) generally available in the Mediterranean area was proposed. The bulking agent will be supplied by the municipality of Amman's operators over a distance of approximately 25 km.

2.1.2. System Expansion Approach

System expansion was applied to compare waste management and treatment scenarios for FVW from the wholesale market, for which some products differed. Each scenario was credited for avoiding the production products that the different valuable outcomes could substitute. The credits were equal to the environmental impacts of the production of the replaced products by current production processes. The inventory data for these avoided production systems were sourced from the last available version of the Ecoinvent 3 database [31,32]. To calculate the amount of inorganic fertilizer that would be avoided with the generated LPD and compost, ammonium nitrate was considered the most widely used inorganic fertilizer [33–35]. Table 1 summarizes the credits associated with the avoided products for each waste management and treatment scenario.

Table 1. Credits associated with avoided products for each waste management and treatment scenario.

| Landfill Disposal (LD) | | |
|--|--------------------------------------|-------------------|
| Outcomes | Credits for avoided products | Equivalence ratio |
| Electricity | Jordan electric mix | 1:1 (kWh) |
| AD coupling with a subsequent composting process (ADC) | | |
| Outcomes | Credits for avoided products | Equivalence ratio |
| Electricity | Jordan electric mix | 1:1 (kWh) |
| Total nitrogen from liquid biofertilizer | Total nitrogen from ammonium nitrate | 1:1 (kg) |
| Total nitrogen from compost | Total nitrogen from ammonium nitrate | 1:1 (kg) |

2.2. Life Cycle Inventory Data

The inventory analysis was based on data provided by the European CEOMED project, scientific bibliography, and the 'Ecoinvent 3—Allocation at point of substitution—unit' database. These data were used to calculate the mass and energy balances of the scenarios to be studied. All the data obtained in the inventory are referenced for a working day. The life cycle inventory (LCI) data for both scenarios for FVW management are summarized in Table 2.

Table 2. Inventory data referring to 5000 kg of FVW per day.

| Current | Category | Value per Functional Unit | Landfill Disposal | AD Coupling with a Subsequent Composting Process |
|--|--------------------------------|---------------------------|-------------------|--|
| Input | FVW | kg/d | 5000 | 5000 |
| | Diesel | | | |
| | Consumed by truck | L diesel/d | 45.83 | n.a |
| | Consumed by turning | TJ diesel/d | n.a | 4.37×10^{-5} |
| | Transport | tkm/d | 112.5 | 27.5 |
| | Electricity consumed | kWh/d | 2.074 | n.a |
| Output | Emission to soil | | | |
| | Carbon | kg C/d | 23.25 | n.a |
| | Nitrogen | kg N/d | 0.95 | n.a |
| | Emissions to air | | | |
| | CO ₂ (fossil) | kg CO ₂ /d | 123 | 3.24 |
| | N ₂ O | kg N ₂ O/d | 0.00647 | 0.000171 |
| | CH ₄ | kg CH ₄ /d | 0.00647 | 0.000171 |
| | CH ₄ disposal cells | kg CH ₄ /d | 18.3 | n.a |
| | NH ₃ | kg NH ₃ /d | n.a | 1.87 |
| | Liquid biofertilizer | kg/d | n.a | 3058 |
| | Compost | kg/d | n.a | 1542 |
| Electric energy generated ^a | kWh/d | 217 | 1113 | |

n.a; not applied. ^a Electric energy generated as surplus to be sold to the power grid.

2.2.1. Landfill Disposal (LC) Inventory Data

Waste collection and transport to transfer station stage: The distance between the wholesale market and the Al Shaer transfer station was 11 km. The diesel consumption by the hydraulically compacted truck was obtained from a personal communication, i.e., a consumption of 110 L of diesel when transporting 12 tons. CO₂, N₂O, and CH₄ emissions produced during the waste collection and transport process were calculated using the method proposed by the IPCC Model [36].

Transfer station stage: Leachate production and characteristics highly depend on the compression degree, solid waste composition, moisture content, and the depth and intensity of rainfall [37]. In this study, it was assumed that 10% of the total mass of FVW is lost during compaction, generating leachate that is discharged directly into the soil. The electrical energy consumed by the hydraulic compactor was 2.074 kWh/d, based on calculations by Mendia [38] for a hydraulic compactor for municipal solid waste treatment.

Transport to landfill stage: The distance between the Al Shaer transfer station and the Al Ghabawi landfill was 25 km. The diesel consumption and emissions data were obtained from the Ecoinvent database.

Landfill stage: The IPCC method, developed for solid waste disposal, was used to calculate the amount of methane emitted at the landfill [36,39]. The emission factors and parameters were chosen according to the recommended default value. However, to calculate the value of methane recovered in the year (RT), a 75% efficiency in biogas collection was assumed [23]. In addition, 95% of the biogas generated was used for generation, while the remaining 5% was burned entirely in the safety flare [40]. The electric energy generation efficiency in a generation biogas engine was considered 30% for electricity [24].

2.2.2. AD Coupling (ADC)—A Subsequent Composting Process—Inventory Data

For the mass and energy balance calculations in the proposed ADC scenario, the sizing of the AD plant for the total waste generated daily in the market was carried out. For this purpose, the information provided by the CEOMED project for designing a small-scale pilot plant and bibliographic data were used.

Mechanical pre-treatment stage: The conveyor belt was designed with an output of 0.336 CV. Based on these design data, the electrical energy consumption was calculated to be 2.8 kWh/d. To calculate the electric energy consumed by the grinder, the following assumptions were made: the food waste grinder has a capacity of 150 kg/mm·h, the grinder cuts the waste into cubes with a smooth surface, and the particle size of the ground FVW is 3 mm, i.e., the grinder has a total capacity of 450 kg/h and a power requirement of 2.2 kW [41].

Feeding tank with stirring stage: To calculate the electric energy consumed by the agitation of the storage tank, the power consumed by the agitation was considered, whose value was 300 kJ/m³reactor·d according to Serrano et al. [30].

Anaerobic digester stage: To calculate the electric energy consumption for pumping, a value of 1800 kJ/m³ fed to the digester reported by Serrano et al. [30] was considered. A 10% thermal energy loss in the digester walls was assumed to calculate the total thermal energy consumption [30]. To calculate the electric energy consumed by the agitation, the power consumed by the agitation was considered, whose value was 300 kJ/m³reactor·d according to Serrano et al. [30]. The biogas generated in the anaerobic digester was calculated considering that for each kilogram of volatile solids degraded, 1120 L of biogas/d is generated, assuming a biodegradability of 70% [22]. In addition, 95% of the biogas generated was used for co-generation, while the remaining 5% was burned entirely in the safety flare [40]. According to Zirkler et al. [42], during AD, the nitrogenous organic compounds in the substrate (proteins, amino acids) are mineralized to N-NH₄ or used for the growth of microorganisms in the digester. However, most nitrogen remains in the digested material, i.e., digestate. It was assumed that the carbon content during the AD process was reduced, leading to a carbon content of 28% in the digestate. In addition, it was assumed that there was no loss of water and nitrogen during the AD process, i.e., the digestate will have the same nitrogen and water quantity as the fed mass.

Co-generation process stage: The data for thermal and electric energy generated in the co-generation process were calculated considering 45% and 39% efficiency, respectively [30]. The 1350 kWh/d of thermal energy was consumed to be used to maintain the mesophilic conditions of the digester during the AD process. The electric energy consumption in the AD plant reached 5% of the total electricity generated by the co-generation biogas.

Centrifugation of digestate stage: To calculate the electric energy consumption for pumping and centrifugation, values of 1800 kJ/m³ fed to the digester and 3.5 kWh/m³ digestate, respectively, were considered [30]. Hahn and Hoffstede [43] reported that, after solid–liquid separation of the digestate, the SP usually has alkaline pH values, a variable salt content, a lower proportion of N-NH₄ (30% of total N) than the raw digestate, and appreciable P and K contents. Phase separation distributes the nutrients in both fractions, with 70–95% of the initial N-NH₄ content remaining in the LPD, while organic matter and P remain in the SPD, depending on the separation system used. In this study, it has been assumed that 70% of the nitrogen content and water of raw digestate remains in the LPD. In comparison, 70% of the total organic and inorganic matter of raw digestate remains in the SPD.

Composting stage: Using the application CompostUMH v. 2.5.6. developed by the Applied Research Group in Agrochemistry and Environment (GIAAMA) of the Miguel Hernández University (Spain), it was considered that the total weight loss of the pile would be 40% and that the final mature compost would have a 25% moisture content and an average nitrogen composition of 1.51% (1.51 kg N per 100 kg compost). Furthermore, during the composting process, 0.6 kg N per ton of the composted mixture would be emitted, i.e., 1.872 kg NH₃/d. During compost maturation, it was assumed that all nitrogen

emissions during the composting process corresponded to ammonia emissions [44]. It was assumed that the bulking agent would be supplied by the operators of the Amman Municipality, considering approximately 25 km of distance. The compost piles would be turned with agricultural machinery equipped with shovels whose diesel consumption was assumed to be 0.47 L per ton of waste [40]. To calculate the CO₂, N₂O, and CH₄ emissions produced during bulking agent transport and turning, the compost windrows process was calculated using the combustion emissions calculation method proposed by the IPCC Model [36].

2.3. Selected Impact Categories and Impact Assessment Methodology

SimaPro[®] v.8.3. software from Pré Consultants B.V. (Amersfoort, The Netherlands) was used to model the LCA. The latest available version of ReCiPe 2016 v1.1. Midpoint (H) (RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability; September 2019 version) impact assessment method was used to calculate the environmental impacts [45]. The ReCiPe 2016 Midpoint (H) method includes 18 impact categories and all were assessed: global warming (GW); stratospheric ozone depletion (SOD); ionizing radiation (IR); ozone formation, human health (OFHH); fine particulate matter formation (FPMF); ozone formation, terrestrial ecosystems (OFTes); terrestrial acidification (TA); freshwater eutrophication (FE); marine eutrophication (ME); terrestrial ecotoxicity (TE); freshwater ecotoxicity (FEco); marine ecotoxicity (Meco); human carcinogenic toxicity (HCT); non-carcinogenic human toxicity (NCHT); land use (LU); mineral resource scarcity (MRS); fossil resource scarcity (FRS); water consumption (WC).

3. Results and Discussion

Figure 3 shows the environmental impacts associated with each category when the system expansion approach is applied. The results indicate that the proposed ADC scenario is the best option for all 18 impact categories considered. This is explained due to the higher amount of biogas generated by the FVW biodegradation with respect to the gas generated in the landfilling, which leads to a higher electric energy production, specifically 413%. Moreover, the two organic biofertilizer streams generated in the ADC scenario (Figure 2) would avoid the production of 100 kg/d of inorganic fertilizers such as ammonium nitrate (Table 2). The proposed ADC scenario is the best option with negative net values for these five categories: −1436.08 kg CO₂ eq. (global warming), −1456.94 kg 1,4-DCB (terrestrial ecotoxicity), −367.33 kg 1,4-DCB (non-carcinogenic human toxicity), −129.72 m²a crop eq. (land use), and −353.59 kg oil eq. (fossil resource scarcity) (Figure 3). Electrical energy is the main source of credits for the fossil resource scarcity category (69%) in the proposed scenario, while liquid biofertilizer and compost production are the main sources for the global warming (57%), terrestrial ecotoxicity (76%), non-carcinogenic human toxicity (97%), and land use (99%) categories (Figure 4 and see Supplementary Material Table S2).

Transport stages are the largest contributors in 7 of the 18 impact categories for both scenarios, with the most significant impact on the terrestrial ecotoxicity category (Figure 3). The current LD scenario has a much higher impact on the terrestrial ecotoxicity category than the proposed ADC scenario, i.e., 658 and 151 kg 1,4-DCB, respectively, representing a 77% reduction with the proposed alternative (see Supplementary Material Tables S1 and S2). As shown in Figure 4, in the current LD scenario, 10% and 90% of the impact come from FVW collection and its transport to the treatment facility, respectively. These impacts are considered nonexistent in the proposed ADC scenario. This is because the AD plant would be located on the land next to the market, eliminating the need for transporting FVW to a transfer station and then to the landfill. In the proposed ADC scenario, 100% of the terrestrial ecotoxicity impact category corresponds to the bulking agent transport and turning of the compost during the composting process (Figure 4). Therefore, the terrestrial ecotoxicity category would have a significant reductions impact, reaching up to 352% of reduction, when compared to the current LD treatment scenario (Figure 3).

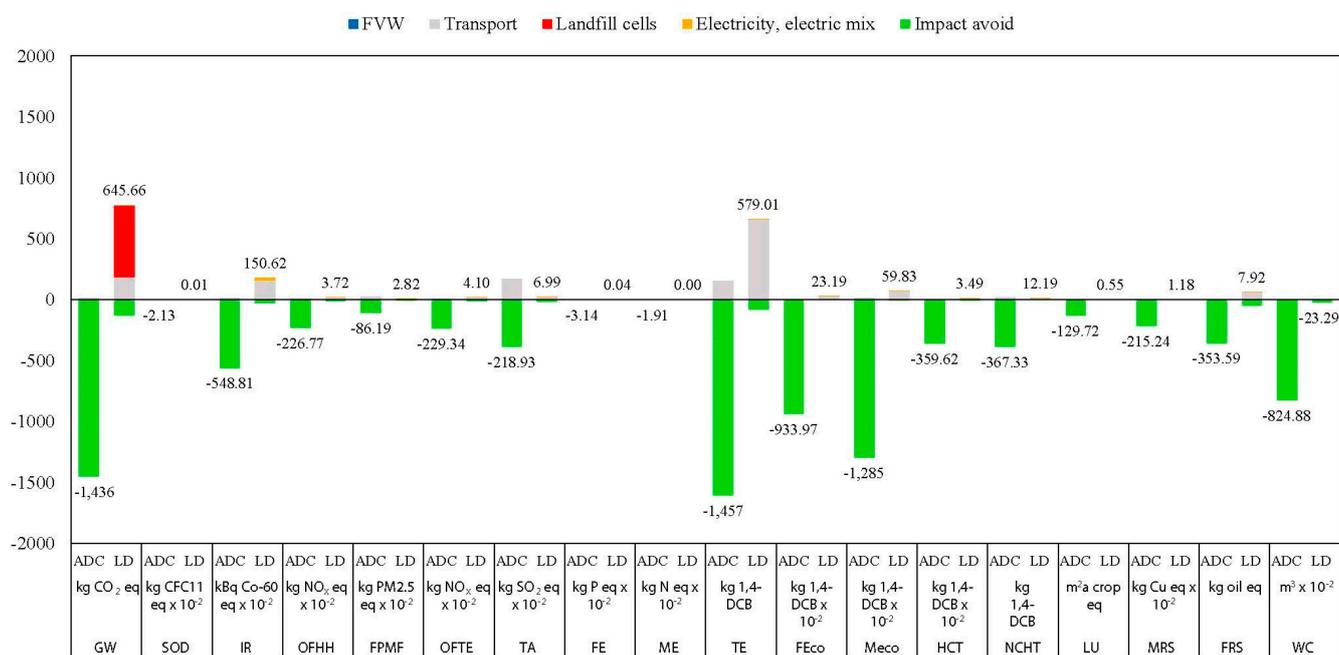


Figure 3. Comparative life cycle environmental impacts associated with each impact category for the landfill disposal (LD) and the ADC coupling with a subsequent composting process (ADC) (the values shown on top of each bar represent the total impact after the system credits have been applied). Some impacts have been scaled to fit. To obtain the original values, multiply by the factor shown on the x-axis for the relevant impacts. GW: global warming (kg CO₂ eq.); SOD: stratospheric ozone depletion (kg CFC11 eq. × 10⁻²); IR: ionizing radiation (kBq Co-60 eq. × 10⁻²); OFHH: ozone formation, human health (kg NO_x eq. × 10⁻²); FPMF: fine particulate matter formation (kg PM2.5 eq. × 10⁻²); OFTE: ozone formation, terrestrial ecosystems (kg NO_x eq. × 10⁻²); TA: terrestrial acidification (kg SO₂ eq. × 10⁻²); FE: freshwater eutrophication (kg P eq. × 10⁻²); ME: marine eutrophication (kg N eq. × 10⁻²); TE: terrestrial ecotoxicity (kg 1,4-DCB); FEco: freshwater ecotoxicity (kg 1,4-DCB × 10⁻²); Meco: marine ecotoxicity (kg 1,4-DCB × 10⁻²); HCT: human carcinogenic toxicity (kg 1,4-DCB × 10⁻²); NCHT: non-carcinogenic human toxicity (kg 1,4-DCB); LU: land use (m²a crop eq.); MRS: mineral resource scarcity (kg Cu eq. × 10⁻²); FRS: fossil resource scarcity (kg oil eq.); WC: water consumption (m³ × 10⁻²)).

In the LD scenario, transport stages have also been identified as a minor contributing source to the global warming category impacts in comparison to the landfill cells contribution (Figure 4). In this LD scenario, transport-stage-associated emissions account for 186.9 kg CO₂ eq. of the total emissions associated with this category (see Supplementary Material Table S1). This is due to the fossil CO₂ emitted from the combustion of fuel used in the FVW collection and transport (18%), as well as FVW transport to the landfill (6%) (Figure 4). This impact is practically negligible in the proposed ADC scenario since these stages are considered nonexistent. Transports that would take place in this ADC scenario would only contribute to the emission of 14.65 kg CO₂ eq. (see Supplementary Material Table S2). As expected, the waste deposition and decomposition stage in the landfill cells is the other stage with the largest contribution to impacts in the global warming category. Uncaptured methane emissions contribute the largest CO₂ eq. emission, accounting for 76% (586.91 kg CO₂ eq.) of the emissions associated with this category (Figures 3 and 4). This is because the biogas capture system installed at the landfill has an efficiency of 75% [23], meaning that the remaining 25% is emitted directly into the atmosphere. The biogas composition emitted into the atmosphere is approximately 50% CH₄–50% CO₂ [23]. Although methane remains in the atmosphere for a shorter time and is emitted in smaller quantities than carbon dioxide, its global warming potential is much higher than that of carbon dioxide [46]. A high global warming potential value

implies an increase in the carbon footprint, and thus also an impact on global warming category. On the contrary, uncontrolled biogas releases into the atmosphere, as well as their impact, would be negligible in the proposed ADC scenario due to their use in the cogeneration system (Figure 3). Therefore, the reduction in the impact on the global warming category in the proposed ADC scenario would be 322% (Figure 3).

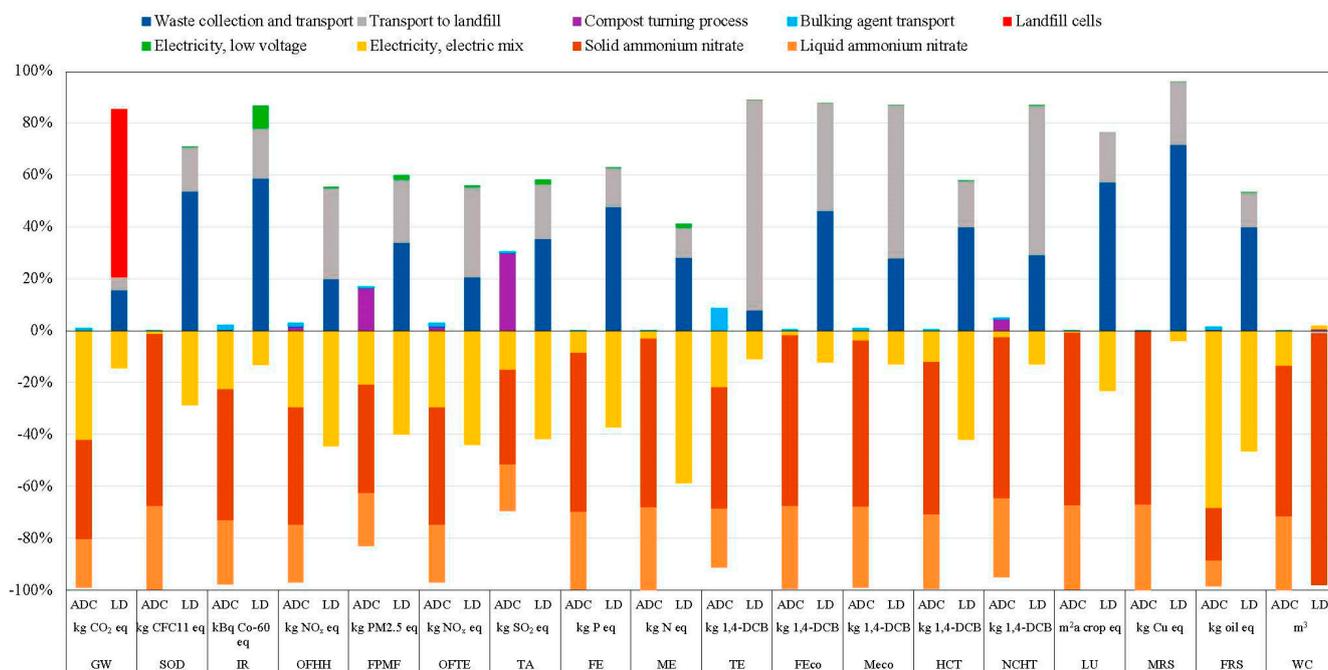


Figure 4. Percentage contribution to the impacts for the landfill disposal (LD) and the AD coupling with a subsequent composting process (ADC). (GW: global warming (kg CO₂ eq.); SOD: stratospheric ozone depletion (kg CFC11 eq.); IR: ionizing radiation (kBq Co-60 eq.); OFHH: ozone formation, human health (kg NO_x eq.); FPMF: fine particulate matter formation (kg PM2.5 eq.); OFTE: ozone formation, terrestrial ecosystems (kg NO_x eq.); TA: terrestrial acidification (kg SO₂ eq.); FE: freshwater eutrophication (kg P eq.); ME: marine eutrophication (kg N eq.); TE: terrestrial ecotoxicity (kg 1,4-DCB); FEco: freshwater ecotoxicity (kg 1,4-DCB); Meco: marine ecotoxicity (kg 1,4-DCB); HCT: human carcinogenic toxicity (kg 1,4-DCB); NCHT: non-carcinogenic human toxicity (kg 1,4-DCB); LU: land use (m²a crop eq.); MRS: mineral resource scarcity (kg Cu eq.); FRS: fossil resource scarcity (kg oil eq.); WC: water consumption (m³)).

In Table 3, other studies on LCA applied to different alternatives for the valorization of FVW are compiled. It is important to highlight that prior research has solely focused on evaluating the global warming potential category, while this study encompasses a broader range of 18 environmental impact categories. Wang et al. [47] assessed AD, incineration, and ensiling among various scenarios and identified AD as the most environmentally friendly technology. However, the global warming potential category of the AD scenario in their study (−31.0 kg CO₂ eq./t) is higher than that of the ADC proposed in this study (−287.2 kg CO₂ eq./t) (Table 3 and Figure 3). To compare the two studies, the different methodologies, the databases and software used, and the different main products obtained should be taken into account. Wang et al. [47] reported an electrical energy generation of 89.7 kWh/t, and did not consider the self-supply of electrical energy or valorization of the digestate generated. Additionally, the global warming potential of the LD scenario in this study (129.1 kg CO₂ eq./t) falls between those of the incineration process (141.7 kg CO₂ eq./t) and the ensiling process (−17.9 kg CO₂ eq./t) proposed by Wang et al. [47] (Figure 3 and Table 3). The high value of the global warming potential category of the incineration process could be due to the increased atmospheric emissions resulting from biogas leakage during capture. Conversely, the lower global warming

potential category of the ensiling process could be attributed to negligible gaseous emissions. Despite generating both electrical energy and solid biofertilizer as primary products, the AD scenario proposed by Miramontes-Martínez et al. [48] exhibits a higher global warming potential than our AD coupling with a subsequent composting process alternative, i.e., -2.8 and -287.2 kg CO₂ eq./t, respectively (Table 3 and Figure 3). This disparity in the global warming potential category can be attributed to several factors. Firstly, Miramontes-Martínez et al. [48] reported biogas losses during the pretreatment and production of biogas, and cogeneration, indicating a lower biogas capture efficiency compared to our AD coupling with a subsequent composting process system. Secondly, the biodegradability of the substrate assumed in their study might differ from ours, potentially influencing the overall global warming potential. Additionally, while the solid biofertilizer yield in their system surpasses ours, their energy requirements and N₂O emissions to the atmosphere are also higher.

Table 3. Comparison with other LCA studies about FVW valorization alternatives.

| Feedstock | Location | Functional Unit | Scenarios | Principal Product * | Methodology | Software and Database | Impact Category Evaluated and Result | Ref. |
|--|--------------------------------------|-----------------|---|---------------------------------------|---------------------------------|---|---|------|
| FVW | China | 1 ton of FVW | 3 scenarios: | | CML 2001–2016 | Not indicated | 1 category: GW (kg CO ₂ eq./t) | [47] |
| | | | AD | Electric power from biogas (89.7 kWh) | | | AD: -31.0 | |
| | | | Incineration | Electric power (82.6 kWh) | | | Incineration: 141.7 | |
| | | | Ensiling | Animal feeding (1639 kg) | | | Ensiling: -17.9 | |
| FVW in co-digestion with slaughter-house waste | Monterrey Metropolitan Area (Mexico) | 1 ton of FVW | 5AD scenarios varying digester capacity and digester number | Electricity (116.2 kWh) | Midpoint CCI–IPCC 2013 GWP 100y | SimaPro® 7.3.3 software. Ecoinvent database v 3.3 | 1 category: GW (kg CO ₂ eq./t) | [48] |
| | | | | Heat (178.0 kWh) | | | AD: -2.8 | |
| | | | | Solid biofertilizer (1857 kg) | | | | |

FVW: fruit and vegetable waste; AD: anaerobic digestion; GW: global warming category. * Amount per ton of treated FVW.

The results obtained in this comparative LCA show the impact that the implementation of the proposed scenario would have in comparison to continue with a landfill disposal management. This information could be relevant for the different factors involved in the implementation and operation of the new system, including municipality, market management officials, or researchers.

4. Conclusions

A comparative LCA was conducted to evaluate the environmental benefits of substituting the current landfill disposal method for the treatment of FVW in the wholesale market in Amman (Jordan), with an integrated anaerobic digestion process followed by composting. When system expansion approach is applied, the proposed scenario presents the lowest impact values for all the categories evaluated. This scenario offers great potential to reduce global warming (322%) and terrestrial ecotoxicity (352%) relative to the reduction in transport stages and the minimization of the emissions that can occur in an uncontrolled FVW degradation stage during landfilling. Likewise, the ADC scenario allows a higher electric energy production (413%) to be obtained, as well as avoiding the production of 100 kg/d of inorganic fertilizers. This indicates that ADC has the lowest impacts on global warming, terrestrial ecotoxicity, non-carcinogenic human toxicity, landfill use, and fossil resource scarcity categories due to system credits for electric energy and the co-products generated. Therefore, replacing the current landfill scenario of FVW management and treatment would reduce the potential environmental impacts, especially greenhouse gas emissions.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr1123397/s1>, Table S1: Environmental impacts result for all impacts categories assessed using the ReCiPe 2016 Midpoint (H) method for landfill disposal.; Table S2: Environmental impacts result for all impacts categories assessed using the ReCiPe 2016 Midpoint (H) method for AD and composting plant.

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Abbreviations

| | |
|-------------------|--|
| AD | Anaerobic digestion |
| ADC | Anaerobic digestion, a subsequent composting process |
| C | Conveyor belt |
| CO ₂ | Carbon dioxide |
| CH ₄ | Methane |
| FE | Freshwater eutrophication |
| FEco | Freshwater ecotoxicity |
| FPMF | Fine particulate matter formation |
| FRS | Fossil resource scarcity |
| FVW | Fruit and vegetable waste |
| GW | Global warming |
| HCT | Human carcinogenic toxicity |
| I | Leachate input |
| IR | Ionizing radiation |
| LCA | Life cycle assessment |
| LD | Landfill disposal |
| LDP | Liquid-phase digestate |
| LU | Land use |
| ME | Marine eutrophication |
| Meco | Marine ecotoxicity |
| MRS | Mineral resource scarcity |
| NCHT | Non-carcinogenic human toxicity |
| N-NH ₄ | Ammonium nitrate |
| N ₂ O | Nitrous oxide |
| OF | Ozone formation |
| OFHH | Ozone formation, human health |
| OFTE | Ozone formation, terrestrial ecosystem |
| P | Pump |
| R | Leachate recirculation |

| | |
|-----|-------------------------------|
| SPD | Solid-phase digestate |
| SOD | Stratospheric ozone depletion |
| T | Transport |
| TA | Terrestrial acidification |
| TE | Terrestrial ecotoxicity |
| WC | Water consumption |

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