Decarbonizing university campuses through the production of biogas from food waste: an LCA analysis

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Abstract: The amount of food waste production in China's catering industry is approximately 17 to 18 Mt per year. This sector accounts for about 20% of the total food losses in China. China's National Development and Reform commission has ratified 100 pilot cities in five batches to implement food waste treatment projects. Almost the 80% of these projects is based on anaerobic digestion. So, it is very important to understand clearly which is the environmental impact of these new bioenergy, or waste to energy, chains (especially at a small scale). For this reason, a Life Cycle Assessment case study is presented in this work, based on an anaerobic digestion plant, fed with the non edible food waste produced by 29 canteens, which operate inside the campus of the Huazhong University of Science and Technology (HUST). The analyzed impacts are: Climate Change, Acidification, Eutrophication, and Photochemical Oxidation. The functional unit is represented by 1 kWh of produced electricity. This work demonstrates that small scale biogas plants can be realized inside big Chinese University campuses and can efficiently reduce the environmental impact of food waste management, especially if the pyrolysis process is coupled to dispose the digestate.

Keywords: LCA, logistics, food waste, GHG, biogas, CHP

Nomenclature

AD	Anaerobic Digestion	-
aLCA	Attributional LCA	-
CFW	Canteen Food Waste	-
CML	Impact Assessment Method developed by the CML (Institute of Environmental Sciences) of Leiden University	-
cLCA	Consequential LCA	-
EFE	Expired Food Energy Chains	
FW	Food Waste	-
GWP	Global Warming Potential	-
HORECA	Hotel Restaurants and Catering (or Café)	-
ICE	Internal Combustion Engine	-
kWhe	Kilowatt-hour of electricty produced	kWh
LCA	Life Cycle Assessment	-
LCI	Life Cycle Inventory	-
N	Students and teachers number	-
ND	Number of days	d

NMVOC	Non Methane Volatile Organic Carbon	mg
OFMW	Organic Fraction of Municipal Wastes	-
PCR	Product Category Rule	-
REF	Reduction of Expired Food chains	-
RMB	Chinese	RMB
Q	Average procapita production of FW	t
QR	Heat of pyrolysis reaction	kJ
RECIPE	Impact assessment method developed from the collaboration between RIVM, Radboud University Nijmegen, Leiden University and PRé Sustainability.	-
VRP	Vehicle Routing Problem	-
WH	Working Hours	h

1. Introduction

China accounts for almost 20% of the world's population, while its arable land is reduced (see Larson [1]). Meanwhile, a large amount of food is not consumed along the food value chain. Currently, China has nearly 250 million small farmers and the agricultural sector is based on small-scale production (see Zhao et al. [2]). This system often causes low efficiency in postharvest handling and postharvest food losses, due to inadequate infrastructure, lack of adequate storage facilities, knowledge and technology (see Parfit [3] and UNEP [4]). To address this great concern (see Li et al. [5]), the research team from the Institute of Geographic Sciences and Natural Resources Research (Beijing, China) has collected the Food Waste production during 2011 to 2015. Their work demonstrated that the amount of food waste in China's catering industry is approximately 17 to 18 Mt per year (about 20% of total food losses), which is equivalent to 30 million to 50 million person-year rations. In this framework is inserted also the Chinese “Clean Plate” campaign, which was launched in 2020 (see BBC [6]). It is also important to consider that the total consumption of catering industry in China has reached 1 trillion Yuan, which is equivalent to about 10% of GDP (Cheng et al. [7]). Since ten years ago, China has implemented a number of policies and laws, promoting the comprehensive utilization of food waste (De Clerq et al. [8]). In May 2010, the National Development and Reform Commission, the Ministry of Housing, the Ministry of Environmental Protection and the Ministry of Agriculture jointly issued the “Organized Development of Municipal Food Waste Resource Utilization and Safe Disposal Pilot Project” work notice. As a result, China's National Development and Reform commission has currently ratified 100 pilot cities in five batches over 2011 to 2015, to implement food waste treatment projects. According to the 12th five-year plan, by 2015 there will be 242 food waste treatment facilities in the country, and cities will achieve a 50% waste separate collection rate. Due to dedicated project investment funds of 10.9 billion RMB, the total food waste treatment capacity in China should reach 30,000 t per day (Song et al. [9]).

Anaerobic digestion appears to be the most successful technology to convert non edible food waste into a resource. About 80% of the food waste treatment projects in the aforementioned pilot cities will integrate some forms of AD technology, whether as a stand-alone treatment method or connected with other waste-to-resource processes such as composting and biodiesel production. More recently China is developing a new law on the prevention of food waste (see the Guardian [10]). On the other hand universities appear still at a global level not efficient in food waste reduction and valorization, see recent publications (Leal Filho et al. [11]).

For the above said reasons, it is very important to understand clearly which is the environmental impact of these new bioenergy chains (especially in the small scale). Xu et al. [12] performed a Life Cycle Assessment with the ReCiPe method, to evaluate the environmental effects of three FW-based biogas generation scenarios in China. The functional unit in this study is the management of 1 t volatile solid (VS). The work studies three scenarios: the anaerobic digestion of FW and sludge; the anaerobic digestion of only FW and FW disposal to landfill. Jin et al. [13] performed an LCA study using the data of an already existing biogas plant, located in Suzhou, Jiangsu Province, in Eastern China. They used the CML method to evaluate: Global Warming Potential, Acidification, Eutrophication and Toxicity for humans and ecosystem. Woon et al. [14] performed a consequential LCA comparing different uses of biogas obtained from food waste anaerobic digestion in Hong Kong. The production of electricity and heat, city gas and biomethane is taken into account.

To the best of the authors' knowledge few works are focused on the use of food waste in university campuses to produce biogas. On the other hand, university campuses represent a particularly favorable location to implement the collection of a highly concentrated waste and its valorization. These activities assume particular interest also in the light of the i-REXFO LIFE16 project managed by the University of Perugia in Italy on food waste reduction. The project deals with the development of two types of chains: Expired Food Reduction chains (which aim at the reduction of the production of food waste through communication and awareness campaigns and initiatives promoted at the level of the organized distribution) and Expired Food Energy chains (which aim at the production of energy with the food waste which is not edible). The i-REXFO project wants to promote a business model in which the REF chains are partially or totally co-funded from the income generated by the EFE chains. This has brought already to the development of some studies on the LCA of food waste tailored to the Italian situation (as reported in the publications of the Sustainable Energy Systems (SES) lab at the department of Engineering of the University of Perugia [15-17]). The i-REXFO project has demonstrated that the feasibility of the EFE chains is linked with the possibility of using the digestate obtained from the anaerobic digestion of the food waste as a fertilizer but this is not always allowed by the law. For this reason, in this study the possibility to treat digestate with pyrolysis is tested to find more promising ways to use the digestate. Before spreading it into the soil the digestate should be anyway pretreated with pasteurization, to avoid proliferation of unwanted microbes in the soil. Other possible digestate treatments, which are alternative to pyrolysis are represented by composting, but this has been already analyzed on a previous paper [18], in which it was demonstrated that the aerobic treatment of digestate has an unfavorable energy balance. Besides this the University of Bath, School of Management has developed logistic tools to solve the Vehicle Routing Problem, which can be favorably applied to the case of food waste collection in the university campus area (Erdoğan [19]). In fact, this represents a novelty of this study: the VRP solver is firstly applied to food waste collection.

The aim of this study is to assess the technical and environmental feasibility of producing energy from non-edible food waste, through LCA. Two technical scenarios will be compared: anaerobic digestion coupled with the use of the digestate in the soil and anaerobic digestion coupled with pyrolysis of the digestate, to produce a further amount of energy and biochar.

For the above-mentioned reasons, this paper is organized as follows:

- description of materials and methods of the LCA study, comprising the goal and scope of the study and the inventory analysis with detailed calculations of the optimized food waste collection path and also of the optimized heat integration in the biogas CHP plant. Two layouts of the anaerobic digestion plant are proposed: one is only based on biogas production and conversion in an engine; the other contains also a pyrolysis plat coupled to the anaerobic digestor, to avoid the problem of digestate disposal. The methodology for the Life Cycle Impact Assessment (LCIA) is also explained in section 2 of this paper;
- in the section number three the main results are explained. The impact of the two plants layouts are compared referring to the impact categories: Climate Change; Eutrophication; Photochemical Oxidation; Acidification.

The importance of the work is given by the fact that it demonstrates that small scale biogas plants tailored to big Chinese University campuses can efficiently reduce the environmental impact of food waste management. These results can be extended to all the universitycampuses in the world.

2. Materials and methods

In this section the main assumptions of the LCA analysis will be illustrated, starting from the goal and scope of the study; then describing the inventory analysis and finishing with the Life Cycle Impact Assessment (LCIA).

In the paragraph on the inventory analysis the following aspects are taken into consideration: the Canteen Food Waste (CFW) availability; the biogas plant mass and energy balances; the coupled anaerobic digestion and pyrolysis plant mass and energy balances; the scenario on the reuse of the digestate through soil application and the scenario on the pyrolysis of the digestate.

2.1 Goal and scope

The study is based on the LCA methodology, as defined in the norms: ISO 14044 and the ISO 14040. In particular for this study, the PCR “Electricity, steam and hot/cold water generation, UN-CPC groups 171 and 173” has been considered. It is available in the website of the International EPD System (Environdec).

To perform the study the OpenLCA software was used. The scope of the LCA includes system boundaries and functional unit determination. As above said the goal of the work is to calculate the environmental impact of producing 1 kWh of electricity (i.e the functional unit), reusing food waste in an anaerobic digestion pant by means of an

LCA analysis. The system boundaries illustrated in Figure 1 determine which unit processes shall be included within the LCA. In the specific case the processes contained inside the system boundaries can be classified in three main categories: upstream, core and downstream. The upstream processes are represented by the collection of the food waste from each of the 29 canteens. A logistics optimization tool was used to calculate a minimum cost collection route. Core processes are represented by the small-scale anaerobic digestion plant operation. Assuming an average composition of the food waste the mass and energy balances of the plant were calculated and modeled. Then the downstream processes are represented by: digestate application in soil for nutrient release; transport of dismantled construction material to recycling facilities, and electricity distribution. It is assumed that the digestate will be used as fertilizer in gardening operations inside the University campus. Some studies (see Lijó [20]) assume that the digestate can substitute the use of other commonly used fertilizers (nitrogen nitrate for example).

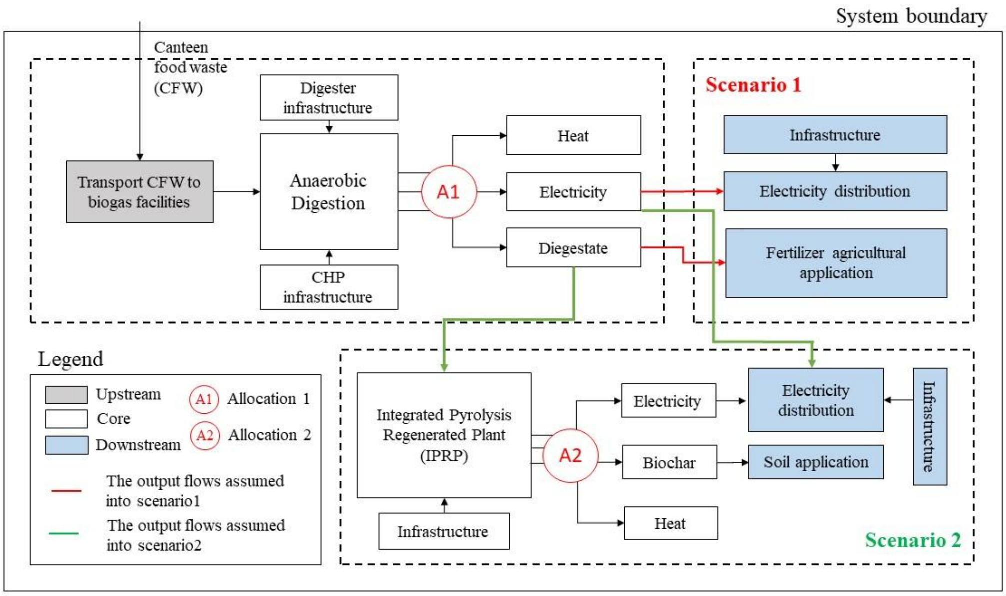

Figure 1: LCA of biogas produced from canteen food waste (FU=1kWhe)

From Figure 1 it can be seen that 2 cases of allocation are encountered:

1. the first in correspondence of the Combined Heat and Power production from biogas;

2.the second in correspondence of the Combined Heat and Power production from pyrogas.

For this reason, two approaches are adopted for allocation and lately compared in a sensitivity analysis: economic allocation and allocation performed with system expansion.

2.2 Inventory analysis

2.2.1 Canteen food waste availability

This paper uses HUST (Huazhong University of Science and Technology), as an example of university campus in China. HUST is situated in Wuhan, a city with 9 million inhabitants located between Beijing and Shanghai. HUST is a national key university directly under the administration of the Ministry of Education of P.R. China. The campus covers an area of over 1,153 acres and has 72% greenery coverage.

HUST has a number of students equal to 61,700 and over 3000 teachers (of which 900 are professors). The canteens are frequently used by the students and professors (three times per day: breakfast, lunch and dinner). There are altogether 29 canteens in the HUST campus. The coordinates of the canteens used in this study are listed in Table S1 of the supplementary material.. The estimate of Canteen Food Waste production is based on the equation:

$$CFW = Q \times n \tag{1}$$

Where CFW denotes the total quantity of canteen food waste. Q represents the average per capita production of food waste in Chinese canteens (expressed in kg/d/person), while n is the number of students and teachers. According to De Clercq et al. 2016 [8], Q is 51 kg /year/person and n is 64,700, so the total available CFW equals to about 3,300 t.

To solve the VRP (Vehicle Route Problem) associated with the CFW collection, the VRP Spreadsheet Solver developed by prof. Erdoğan at Bath University (UK) [19] was used, and the shortest route is shown in Figure 2. It is assumed to start the collection from the Depot (or the biogas plant installation), which in this case is coincident with canteen number 11.

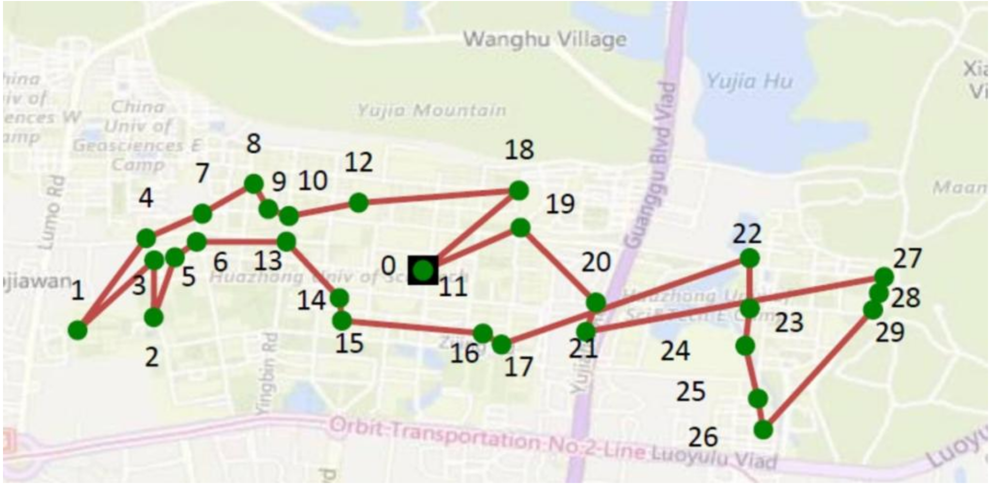

Figure 2: Optimized food waste collection path

The length of the optimized route is shown in Table 1, where the path is divided step by step, indicating the distance from one canteen to another.

According to the Table 1, the total transport distance is 17.37 km. The route is repeated daily. If we consider that the total quantity to be transported is equal to 3300 t per year, we can infer that the total transport quantity is 109,725 t*km (on an annual basis, considering that on holidays the collection is not performed). The process to simulate the impact of the transport phase is “Market for transport, freight lorry 16-32 metric tons, EURO 4 GLO” taken from the database Ecoinvent 3.5.

Table 1: Results of the calculation of the shortest path between the 29 canteens

Location name	Distance travelled (km)
Depot	0
C19	0.63
C20	1.68
C21	1.86
C27	4.64

C28	4.74
C29	4.83
C26	6.29
C25	6.50
C24	7.08
C23	7.21
C22	7.48
C17	9.00
C16	9.19
C15	9.86
C14	10.15
C13	10.60
C6	11.05
C5	11.22
C2	11.63
C3	11.95
C1	13.40
C4	14.34
C7	14.85
C8	15.16
C9	15.38
C10	15.47
C12	15.87
C18	16.60
C11	17.37
Depot	17.37

In HUST the daily availability of food waste is about 11 tons and it is concentrated on a limited area; considering that during the holidays there is no production, it is assumed that the collection will take place only during 300 days per year. So, it has been assumed that the food waste will be collected daily by a truck of a maximum capacity of 20 t.

2.2.2 Biogas plant mass and energy balances

As stated above, the annual quantity collected in HUST campus canteens is equal to 3,300 t. The composition of this quantity is taken from Liu [21]. Each component has been cooked separately and then mixed in the proportions reported by Liu [21], the mixture has been analyzed at the laboratories of the Biomass Research Center at the University of Perugia, obtaining the data reported in Table S2 of the supplementary material. Data about the working conditions of the plant have been derived using the modeling software BioWin, released by Envirosim Canada, as reported in [16].

The mass of the digestate is obtained by multiplying the daily production calculated by the software BioWin for the total number of days obtained from the following equation:

$$ND = WH/24 \qquad (2)$$

Where ND represents the number of days; WH represents the working hours (assumed to be 7,000 hours).

The Anaerobic digestion plant layout is shown in figure 3 and derives from a previous study realized by Huiru et al. [16]. The study was done in collaboration between the University of Perugia and ICARE (Institute for Clean and Renewable Energy) located in Huazhong University of Science and Technology (HUST) in Wuhan. The results have shown that the project has an interesting economic performance and so a deeper analysis was needed on the environmental performance of the whole chain. That layout is based on the information which was provided by a Chinese company producing anaerobic digestion plants, named Puxin Technology Co. Ltd.

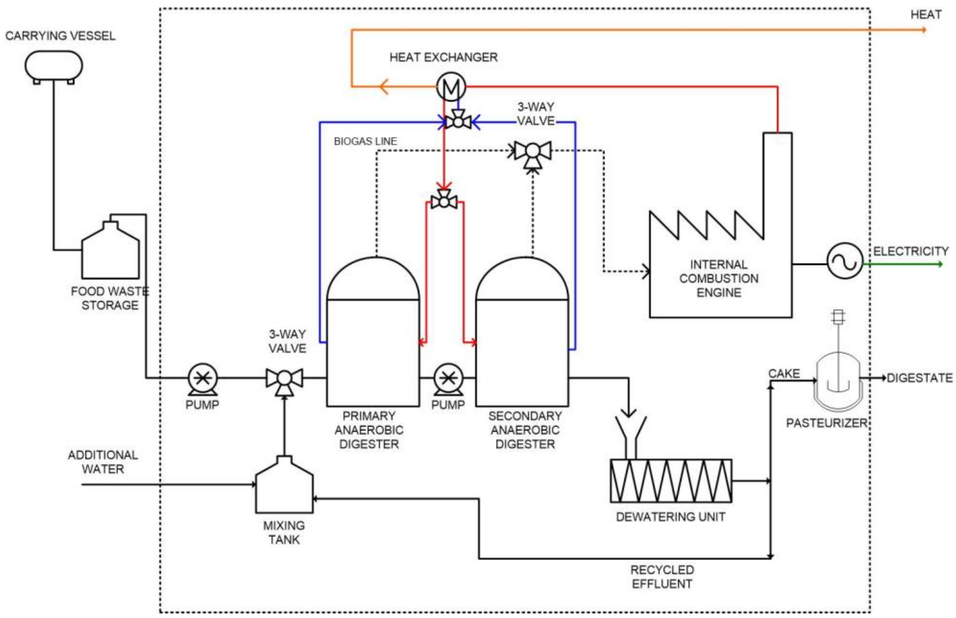

Figure 3: Scenario 1, layout of the anaerobic digestion plant with digestate pasteurization to use it into the soil, adapted from [16]

Each of the two digesters (primary and secondary) has a volume of 1,260 m^3. The digesters are two Continuously Stirred Reactors (CSTR), which are operated in fed-batch mode. Wet anaerobic digestion (with an average substrate moisture content of 69%) is performed at 35°C. Total available volume is about 2,500 m^3. The digester is modeled using the process: “Anaerobic digestion plant, agricultural |RoW| construction| Alloc Rec, U” taken from the Ecoinvent 3.3 Database. This process is referred to a volume of the digester which is equal to 500 m^3. So the impact should be multiplied for 5 times, given that the total volume of the digesters in this case study is about 2500 m^3. The life cycle of the plant is assumed to be about 20 years, according to Gebrezgabher [22], hence the annual coefficient to assess the impact of the anaerobic digestion infrastructure is about 0.25. Details on the anaerobic digestion infrastructure are listed in Table 2. The electrical consumption of the biogas plant is reported in table S12 in the supplementary material.

Table 2: Anaerobic digestion plant infrastructure

Materials/fuels	Unit	Values
Concrete, normal {RoW}| market for | Alloc Rec, U	m^3	120
Polyethylene, high density, granulate {GLO}| market for | Alloc Rec, U	kg	170
Reinforcing steel {GLO}| market for | Alloc Rec, U	kg	10800
Glued laminated timber, for outdoor use {GLO}| market for | Alloc Rec, U	m^3	80
Polystyrene, high impact {GLO}| market for | Alloc Rec, U	kg	570
Polyvinylidenchloride, granulate {GLO}| market for | Alloc Rec, U	kg	330
Copper {GLO}| market for | Alloc Rec, U	kg	250
Synthetic rubber {GLO}| market for | Alloc Rec, U	kg	1200
Steel, chromium steel 18/8 {GLO}| market for | Alloc Rec, U	kg	1300
Heat and power co-generation unit, 160kW electrical, common components for heat+electricity {GLO}| market for | Alloc Def, U	Items	0.046
Heat and power co-generation unit, 160kW electrical, components for heat only {GLO}| market for | Alloc Def, U	Items	0.046
Heat and power co-generation unit, 160kW electrical, components for electricity only {GLO}| market for | Alloc Def, U	Items	0.046

The disposal of the waste construction material was not considered, assuming that it was recycled. Only the transport to the recycling facility was considered.

For each kWh of electricity produced an amount of 3,91E-8 of CHP plant facility is required, assuming a life cycle of the plant of about 20 years (see Gebrezgabher [22]). The processes that are used to simulate the impact of the CHP plant belong to the

Ecoinvent 3.3 Database. They are indicated in the unit of measure “items”, which implies that we allocate the CHP facility based on time and we consider 1 year out of 20 years of total life of the plant, calculating also the maintenance hours during which the plant is stopped (the same unit is used for the anaerobic digestion facility which is based on 2 digesters).

Electricity production and distribution are calculated by multiplying the net power capacity for the working hours. Table 3 reports the mass and energy balances, as they have been calculated and then inserted in the OpenLCA software. The details of the calculations are reported in the supplementary materials.

Table 3: Final mass and energy balance of the biogas plant

Items	Amount	Unit
Inputs		
Digester	0.092	Items
Electricity distribution	1.23E+6	kWh/year
Flue gases	9.465E+6	kg/year
Heat and power co-generation unit,	0.046	Items
Food Waste	3,300	t/year
Electricity consumption for pasteurizer	75,000	kWh/year
Output		
Electricity biogas plant	1.23E+6	kWh/year
Heat	0.343E+6	kWh/year
Digestate	3,300	t/year

It can be seen from table 3 that the digestate produced is equal to only 3300 t/year, given that after the solid-liquid separation only the cake is used in the soil, while the liquid fraction (equal to about 12,140 t/year of effluent) is recirculated inside the digester to dilute the food waste. The digestate characteristics are reported in table S3 of the supplementary material. From the plant the following quantities of biogas are produced:

- 7.71 m^3/h biogas (64% concentration of CH_4) in the second digester;
- 84.13 m^3/h biogas (62% concentration of CH_4) in the first digester.

2.2.3 Coupled Anaerobic Digestion and Pyrolysis Plant mass and energy balances

According to what has been presented in Figure 1, the paper assumes that two scenarios can be adopted for the treatment of digestate:

1. pasteurization of digestate and its use in the soil;

2. drying of the digestate and its pyrolysis.

In this last case the layout of the plant will be modified into that shown in Figure 4.

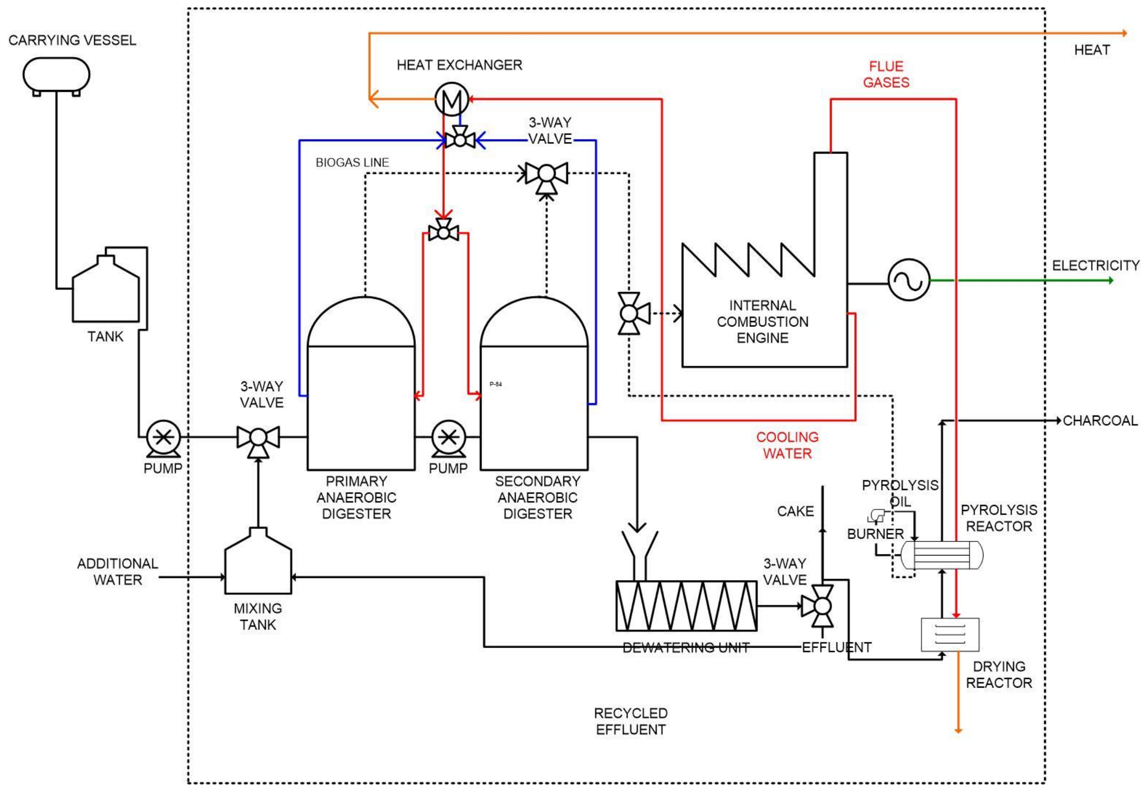

Figure 4: Scenario 2, layout of the coupled anaerobic digestion and pyrolysis plant

From Figure 1S of the Supplementary material it can be seen that the following yields have been obtained from the pyrolysis tests performed on digestate (at the final temperature of 600°C):

- charcoal mass yield: 36 wt%;
- pyrolysis oil mass yield: 18 wt%;
- pyrogas mass yield: 46 wt%.

These yields have been obtained performing slow pyrolysis tests at the facility of the Biomass Research Centre of the University of Perugia, see [23, 24]. The tests have been performed with a heating rate of about 5°C/min and a final pyrolysis temperature of 550°C. The temperature and pressure trends inside the batch reactor are reported in Figure 2S of the supplementary material. The characterization of the digestate and the charcoal, obtained after pyrolysis, are reported respectively on tables 3S and 4S of the supplementary material. Syngas composition is reported in Figures S.3 and S.4. The LHV at 550°C can be approximated to 16.6 MJ/kg. the average LHV of pyrolysis oils is 21 MJ/kg, given that they contain also about 40% water.

Table 4: Final mass and energy balance of the biogas plant when coupled with the pyrolysis plant

Items	Amount	Unit
Inputs		
Digester	0.25	Items
Pyrolysis unit	676,168*	kWh/year
Electricity distribution	1.906E+6	kWh/year
Flue gases	16.069E+6	kg/year

Heat and power co-generation unit	0.046	Items
Food Waste	3,300	t/year
Electricity consumption for drying the digestate	324,219	kWh/year
Output		
Electricity biogas plant	1.906E+6	kWh/year
Heat	0.419E+6	kWh/year
Charcoal	383	t/year

*the pyrolysis plant, which is an input of the analysis is considered as an infrastructure, its amount is expressed in kWh because it is the reference unit reported also in [25].

As it can be seen from Table 4, the pyrolysis plant impact is estimated through the values reported in Bartocci et al. [25]. These represent the impact of the materials used to construct the plant, which are referred to 1 kWhe produced by the plant. For this reason, the impact of the plant is expressed referring it to the electrical production capacity. Considering that about 85 kWe can be produced using the pyrogas generated through pyrolysis a total electricity production of 676,168 kWhe/year can be obtained (this will be added to the electricity produced from the biogas plant, see table 3, giving the total sum of 1,906,128 kWhe). It is assumed that the pyrogas obtained from the plant will be mixed together with biogas and converted in the same engine used for the anerobic digestion plant. So only the materials used to build the pyrolysis reactor are considered.

Table 5: Composition of cake and effluent (derived from BioWin simulation)

Parameter	Amount	Unit
Cake		
TSS	32.2	%

VSS as % of TSS	67.00	%
N as % of TSS	4.38	%
P as % of TSS	0.45	%
pH	7.31	-
TSS	967.08	kg/d
VSS	647.91	kg/d
Effluent		
Flow	37.04	m^3/d
Ammonia N	3882.88	mgN/L
Filtered TKN	3978.38	mgN/L
Total N	3999.42	mgN/L
Total P	140.17	mgP/L
TS	669.52	mg/L
COD	6125.41	mg/L
Total carbonaceous BOD	30.28	mg/L
pH	7.31	-

The mass of charcoal is calculated considering the product yields of the pyrolysis process reported in Figure S1 of the Supplementary material and the composition of the digestate (in particular moisture content) reported in Table 5. This has been calculated using the software BioWin.

2.2.4 Reuse of digestate: soil application versus pyrolysis

Dealing with the reuse of the digestate, it is assumed that this will be used as compost and soil amendment in gardening operations inside the campus. The distribution into the soil is assumed to be manual for the cake. Spreaders will be used for the liquid effluent. Once the digestate is inside the soil, the nitrogen contained in it will be transformed by soil microbia, generating air emissions (eg. dinitrogen oxide). When the digestate is mineralized into nitrates and nitrites, it will also undergo leaching. These phenomena are simulated using the PCR (Product Category Rules) of arable crops, available in the Environdec website (i.e. the website of the International EPD® System). The International EPD® System is a global programme for type III environmental declarations operating in accordance with ISO 14025. The PCR contained in the Environdec website are very useful to standardize the LCA results. The methods used for the calculation of air and water emissions are shown in Table 6.

Table 6: Methods used for the calculation of air and water emissions, based on the PCR on Arable Crops

	Emission	Paragraph	Source
Emission in air	Ammonia	8.4.1	[26-28]
	N_2O, NO- direct emission	8.4.2	[29]
	N_2O, -indirect emission	8.4.2	[27]
Emission in water	Nitrates	8.4.4	[28]
	Phosphorus	8.4.5	[30]

Instead of using the cake and part of the effluent as a soil amendment, the residue of the anaerobic digestion can be dried and then pyrolysed. This treatment has the following advantages:

- the emissions to air and water, released by the degradation of the nitrogen and phosphorus contained in the digestate are avoided. This is true also when the solid product of pyrolysis (charcoal) is applied into the soil, because nitrogen and phosphorus in that case are contained in more stable forms (see Liu et al. [31] and Case et al. [32]);

- the carbon fraction of charcoal (see Fang et al. [33]) is also more stable than that of digestate (see Monlau et al. [34]), once it is inserted in the soil. In fact, the carbon fraction of charcoal can remain stable for more than 100 years (see Singh et al. [35]) and represents for this reason a storage of carbon ;
- charcoal can have benefits on the soil, decreasing the leaching of pollutants (see Si et al. [36]) and increasing elements absorption in crops (see Namgay et al. [37] and Yao et al. [38]), as well as water retention in the soil (see Baiamonte et al.[39] and Hussain et al. [40])
- from the volatile part of the digestate pyrogas and pyrolysis oil (see Bartocci et al. [23]) can be produced. Those products can be used to produce electricity and also heat, to complete the drying of the digestate.

The advantage on soil of using charcoal or biochar are not considered in this study, because they could not be assessed experimentally.

2.3 Life cycle impact assessment

Dealing with the Impact Assessment phase, the CML method has been used. Among the CML impact categories, the following were chosen: Climate Change, Freshwater eutrophication, Photochemical oxidant formation and acidification.

The software used in the analysis is OpenLCA. Dealing with allocation two approaches are chosen:

1. allocation based on economic values of electricity, heat and digestate;

2. allocation based on system expansion, considering as avoided products: the electricity produced by the Chinese electricity mix; the heat produced inside the campus using heat pumps; urea (which is substituted by digestate on the basis of the nitrogen concentration).

Dealing with the economic allocation, the coefficients shown in Table 7 have been used. They have been calculated according to the following equation:

$$EAC = \frac{PrSb_i * QSb_i}{\sum_i^n PrSb_i * QSb_i} \quad (3)$$

Where $PrSb_i$ is the price of the subproduct I; QSb_i is the quantity of the subproduct i. The quantitative data reported in table 7 are the outputs reported in tables 4 and 5.

Table 7: Economic allocation factors

		SCENARIO 1		
	Quantity	Unit	Income (RMB)	Coefficient
Heat	343,000	kWh	64,313	0.06
Electricity	1,230,000	kWh	738,000	0.69
Digestate	3,300	t	261,130	0.25
		SCENARIO 2		
	Quantity	Unit	Income (RMB)	Coefficient
Heat	419,000	kWh	78,563	0.04
Electricity	1,906,000	kWh	1,608,600	0.91
Charcoal	383	t	84,000	0.05

Calculations of the allocation factors for the scenario number 1 are based on the following assumptions:

- price of electricity in China: 0.6 RMB/kWh (according to CEIC [41] and CEIC [41]);

- price of heat (if heat is produced through electricity is the same of the electricity, the efficiency of the heat pump is estimated to be about 3.2);
- price of urea is about 1820 RMB/kg, according to CEIC [42] data.

Calculations of the allocation factors for the second scenario are based on the following assumptions:

- the digestate which is pyrolyzed has a total dry matter equal to 1063 t;
- the product yields are those reported in figure S1 of the supplementary material;
- gas LHV is correspondent to what reported in figure S4 of the supplementary material;
- gross electric power of the plant is about 85 kWe;
- price of electricity in China: 0.6 RMB/kWh (according to CEIC [41] web site);
- price of heat (if heat is produced through electricity is the same of electricity, the efficiency of the heat pump is estimated to be about 3.2).

The input data for the allocation based on system expansion are reported in tables 8 and 9. Table 8 shows for each of the multiple products obtained by the process “Combined Power and Heat generation” in both cases of the anaerobic digester and of the combined anaerobic digester and pyrolysis plant, the corresponding avoided products. Table 9 for each avoided product identifies which are the most important impacts in the considered impact categories.

Table 8: Impacts of the avoided products, according to CML impact method (data taken from SimaPro database and OpenLCA database)

Impact category	Reference unit	Urea /kg	Phosphate fertilizer /kg	Electricity /kWh
Climate change	g CO_2eq	3287.42	1863.59	1126.29
Eutrophication	g P_2O_5eq	0.00406	0.00862	0.00085
Photochemical Oxidation	gC_2H_2	0.00091	0.00093	0.00023
Acidification	gSO_2eq	0.02197	0.02183	0.00579

Table 9: Avoided products

Product	Value	Unit	Alternative	Value	Unit
Digestate	1	t	Urea	30,76	kg
			Phosphate fertilizer	3,16	kg
Heat	3.2	kWh	Electricity	1	kWh
Electricity	1	kWh	Electricity	1	kWh
Biochar	1	t	Urea	73,91	kg

To calculate the rate of substitution shown in table 9 the following input data have been considered:

- the composition of digestate shown in table S3;
- the composition of biochar reported in table S4;
- the COP of the heating plants used in Huazhong University of Science and Technology campus (retrieved by the students and based on the heating apparatus datasheets).

Allocation is not used when the impact is expressed based on the tons of canteen food waste which are disposed. In that case the final impact is calculated based on the following equation:

$$I\_CFW = I\_El*EP/EAC \qquad (4)$$

Where I_CFW identifies the impact referred to the ton of Canteen Food Waste (CFW) which is produced; I_EI represents the impact referred to the production of 1 kWhe, EP is the total electricity production for the scenario and EAC is the allocation factor for the electricity.

3. Results

3.1 Impact analysis: comparison between the first and the second scenario

The results for every impact category have been listed in Table 10. It can be seen that the coupling of pyrolysis and anaerobic digestion has in general a lower impact compared to the scenario 1 in which only anerobic digestion is performed. Scenario 2 has lower impact in the categories: Climate Change, Eutrophication and Acidification; which are the most important. On the other hand, the scenario 2 has a higher impact in the category Photochemical oxidation, this is due to the increased production of electricity, which implies higher emissions of C_2H_2 from the CHP plant.

Table 10: LCA analysis results for scenario 1 and 2 – Economic allocation

Impact category	Reference unit	Results-scenario 1	Results-scenario 2
Climate change	g CO_2-eq/kWh	62.17±1.12	27.07±0.75
Eutrophication	g PO_4^{3-}-eq/kWh	1.10±0.05	0.24±0.01
Photochemical oxidation	g C2H2-eq/kWh	0.01±2.51E-3	0.06±1.96E-3
Acidification	g SO_2-eq/kWh	3.00±0.27	0.88±0.41

3.2 Sensitivity analysis on allocation

The results of the LCA analysis based on allocation on system expansion are proposed in table 11.

Table 11: Sensitivity analysis on allocation, results of the system expansion approach

	Climate change (gCO_2eq/kWh)	Freshwater eutrophication ($gPO_4^{3-}eq/kWh$)	Photochemical oxidation (gC_2H_2/kWh)	Terrestrial acidification (gSO_2eq/kWh)
Scenario 1	-367.52	1.5795	0.0926	4.33
Scenario 2	-189.27	0.240	0.06	0.0004

If we compare the results shown in Table 11 with those shown in Table 10, we see that the value of the impact in the category Climate Change passes from positive to negative. This is due to the fact that the avoided products prevail. Avoided heat, electricity and fertilizers have big impacts, that bring the total results to a negative value. This is a typical result, which can be achieved also with a consequential approach. In particular the final results has been calculated with the following equation:

$$El\_I = I\_EA/EAC-AI\_Heat-AI\_Fert \quad (5)$$

Where El_I is the impact of electricity production; I_EA is the impact obtained with economic allocation (which is shown in table 10); EAC is the economic allocation coefficient (which is reported in equation 3); AI_Heat is the avoided impact of heat production (obtained by multiplying the mass of avoided natural gas for the impact of its production and combustion); AI_Fert is the avoided impact of fertilizer production (obtained by multiplying the quantity of avoided fertilizer for the impact of its production). From equation 5 it can be seen that the avoided fertilizer explains the difference between the impacts of Scenario 1 and 2. In this case the results obtained from the economic allocation scenarios are inverted. In our opinion the economic allocation is preferable in this case because they are closer to reality (if we consider in fact the total quantity of food waste which is treated, as shown in table 12, the second scenario appears to be more convenient). We have also to consider that the use of digestate as a fertilizer is not always possible and could lead to pollution of the soil, when it is derived from food waste (eg. by spreading microplastics in the soil).

The second scenario in this case has an impact which is always lower than the first scenario, given that biochar reduces much of the negative impact of digestate, when applied in the soil. On the other hand, biochar substitutes a quite irrelevant amount of fertilizer, on the contrary of digestate, this explains why the performance on the Climate Change category is better for the digestate.

3.3 Results expressed on the ton of treated food waste

If we multiply the final results shown in table 10 for the total produced electricity and we divide for the total amount of treated food waste we can express the final impact on the ton of treated food waste (see table 12). This is equal to: 20.04 kgCO_2eq/t CFW for the first scenario and 14.53kgCO_2eq/t CFW in the second scenario. These values are in agreement with that presented in Jin et al. [13] and even lower. We see here that if allocation is completely avoided the most promising scenario becomes the second one.

The other impacts in the categories of Photochemical Oxidation, Eutrophication and Acidification are: 2.01E-3 kgC_2H_2eq/t CFW and 0.03kgC_2H_2eq/t CFW; 0.35$gPO_4^{3-}eq/t$ CFW and 0.13$gPO_4^{3-}eq/t$ CFW; 0.97$kgSO_2eq/t$ CFW and 0.47kg SO_2eq/t CWF, respectively for the Scenario 1 and the Scenario 2 (see table 12).

Table 12: Results expressed on the ton of treated food waste

Impact category	Reference unit	Results-scenario 1	Results-scenario 2
Climate change	$kgCO_2$-eq/tCFW	20.04±2.71	14.53±0.98
Eutrophication	$kgPO_4^{3-}$-eq/tCFW	0.35±0.11	0.13±0.08
Photochemical oxidation	kgC2H2-eq/tCFW	2.01E-3±5.41E-4	0.03±0.01
Acidification	$kgSO_2$-eq/tCFW	0.97±0.22	0.47±0.08

4. Discussion

4.1 Comparison with other works

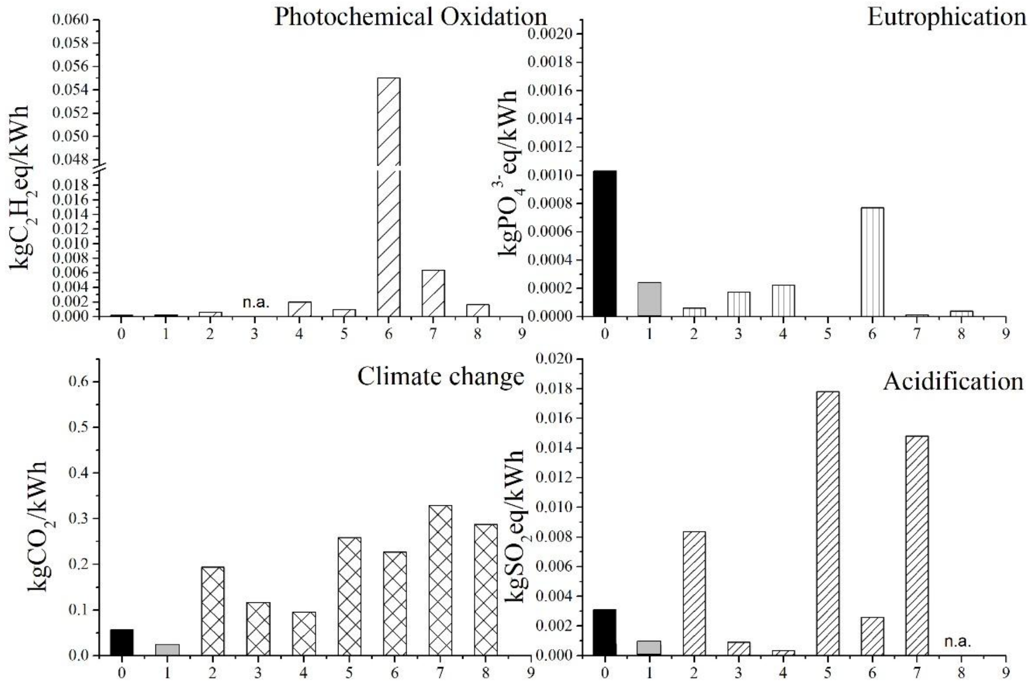

Figure 5: Comparison of the results fort the two scenarios with literature. Scenario 1 is indicated with the number 0 (it corresponds to the analysis of anaerobic digestion and use of digestate as a fertilizer, performed in this study) and it is colored in black, scenario 2 is indicated with the number 1 (which corresponds to the analysis of anaerobic digestion followed by pyrolysis, performed in this study) and it is colored in grey, literature scenario number 2 refers to the analysis presented in Lijó et al. [20] the substrate in this case is represented by maize, pig slurry Organic Fraction of Municipal Wastes (OFMW) and food waste (food waste contributes to 41% of the mass input), literature scenario 3 refers to the analysis presented in Boulamanti et al. [43] the substrate is manure it is assumed that the digestate is stored on a closed storage, literature scenario 4 refers to the analysis presented in Fantin et al. [44] the plant is fed with a mixed feedstock which is composed by: maize silage, sorghum, triticale, cow slurry, pressed sugar beet pulps, winery waste,

literature scenario 5 refers to the analysis of Fusi et al. [45] in which the feedstock is mainly represented by maize silage, literature scenario 6 refers to the analysis presented in Iordan et al. [46] in which the feedstock is represented by sewage sludge, fats from food industry, sludge from septic tanks and other biological wastes, which are pretreated with thermal hydrolysis, literature scenario 7 refers to the analysis presented in Kompogas [47] where the feedstock is represented by green and organic waste, literature scenario 8 refers to the analysis presented in Van Stappen et al. [48] where the feedstock is represented by: beet tails, downgraded potatoes, cereal middlings, mown lawn grass and starch from fries cleaning; in this case the consequential LCA analysis is adopted, instead of attributional LCA

To understand fully the results reported in table 10 these have to be compared with other LCA studies on biogas plants, which are available in the literature. Regarding the literature data reported in figure 5, it has to be taken into account that in the study of Lijó et al. [20], two scenarios are compared: a biogas plant fed with cultivated maize (scenario A) and a biogas plant in which part of the maize is substituted by food waste (scenario B). The data reported in Figure 5 are referred to scenario B. In Lijó et al. [20] it is demonstrated that substituting energy crops with food waste basically can reduce the impact of biogas production. Our study demonstrates that if biogas is produced only using food waste the impact can be further reduced. This study in fact has impacts which are always lower than those obtained by Lijó et al. [20]. The only exception is the eutrophication impact. This is due to the used of digestate and the fact that in the study of Lijó et al. [20] the substituted inorganic fertilizer is considered inside the boundaries of the LCA.

The work of Boulamanti et al. [43] proposes an LCA study on different scenarios for producing biogas. The case study reported in Figure 6 represents a biogas plant fed with animal manure when the digestate is stored in a closed environment. Also in this case the literature study has a lower value of eutrophication, while the other impacts are definitely higher. In the work of Fantin et al. [44] an LCA of a biogas plant fed with energy crops, cow slurry and agro-industrial residues, in co-digestion. The impact of acidification cannot be compared with that of our study because it was calculated with another method. The impact for the eutrophication category also in this case is lower than in our study.

In the work of Fusi et al. [45] the feedstock which is used in the anaerobic digestion plant is represented by maize and so the impact is generally always higher than this study, which uses food waste. The impact assessment methods which are used are similar to those used in this study. The work of Iordan et al. [46] deals with the LCA of biogas production from sewage sludge, fats, sludge from septic tanks and other biological substrates. Since the heat and the digestate are not sold the impact is assigned only to electricity production and no avoided products are taken into account. It can be seen that for the impact categories of acidification, climate change and photochemical oxidation the case study when the obtained digestate is applied to the soil. In the study of the Kompogas [47] facility, which has been downloaded in the Environdec website the impacts are always higher, except for the categories of acidification and eutrophication. In this EPD the methodologies used to calculate emissions during digestate use are not explained in detail. Besides these emissions depend on the composition of the waste which is digested. The Kompogas plant works with OFMW, which can have slightly lower content of nitrogen and phosphorus. The impact on Photochemical Oxidation is missing in the Kompogas [47] LCA analysis.

The study of Van Stappen et al. [48] is clearly a consequential LCA. So this reference was considered to see which is the difference between the results of an attributional LCA and a cLCA. The lower impact of cLCA is generally due to the fact that several avoided products are inserted in the boundaries of the system. This choice often is not easy to justify and to standardize. In particular in Van Stappen et al. [48] different scenarios are examined, which differ for the final use of the produced biogas. In Figure 5 it is reported the scenario which displaces electricity produced with natural gas.

We can conclude that the higher impact on eutrophication is quite significant, but we have to take into consideration also that in many literature case-studies (see 2,3,4,8,9) the eutrophication is divided in two subcategories: terrestrial and maritime and the units of measure are slightly different respect to the one adopted in CML, so this can explain the difference, at least partially. The literature case study 7 has values of eutrophication which are quite comparable and this makes the results of this study quite significant because this case study is the only which has been certified and is based on a Product Category Rule. Product Category Rules are useful to standardize LCA methodology and the presentation and communication of results, they are mainly used for Environmental Products Declarations (EPD) in which the main considered impacts are: acidification, eutrophication, photochemical oxidation and climate change. For this reason, these were chosen also in this study.

4.2 Scale up of the results of the analysis to a global level: the potential reduction of GHG emissions

Starting from the data shown in table 12, which show the impact of treating 1 t of CFW, we can consider that the final impact of the proposed technology should be evaluated also considering the following aspects:

- the negative impacts deriving from the avoided products, which are considered to be: the fertilizer (avoided by the digestate and the biochar use in the soil); the heat (avoided by the heat produced from the CHP plant); the electricity (avoided by the electricity produced by the CHP plant) and the landfill disposal (avoided by the anaerobic digestion plant).
- the avoided impacts due to landfill disposal are estimated based on what reported in [49].

In this way in Figure 6 we can see the total impacts referred to 1 ton of CFW treated with anaerobic digestion coupled with pyrolysis and also how much is the reduction of the impact, due to the treatment of the above-mentioned food waste.

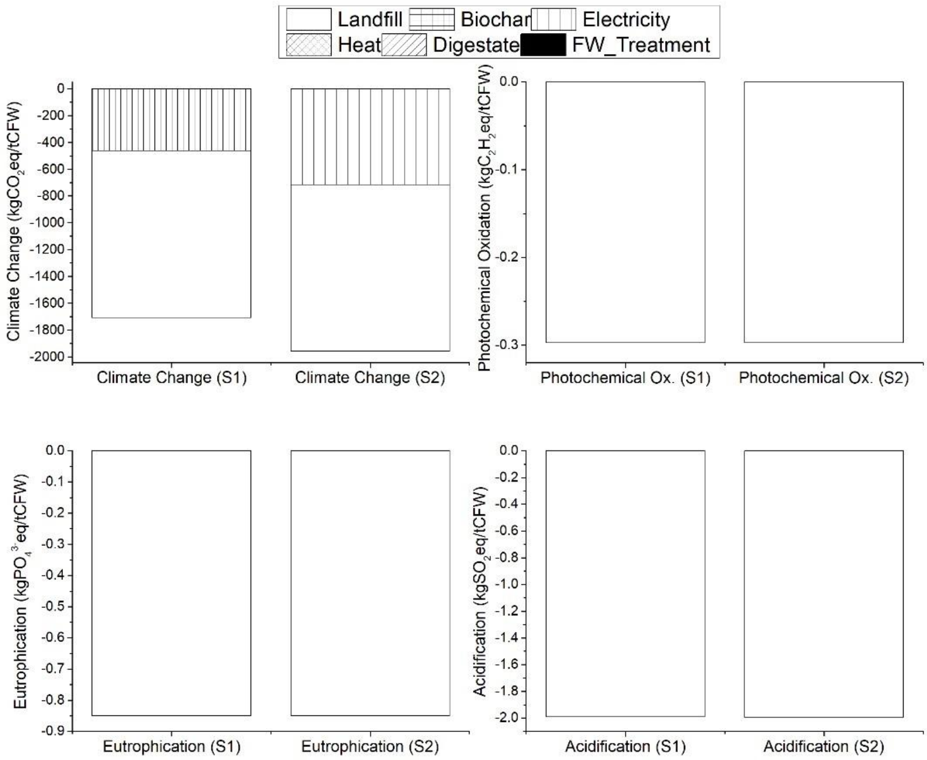

Figure 6: Total impact reduction due to CFW treatment with anaerobic digestion followed by pyrolysis, considering also the avoided impact of landfill disposal

The final impacts reduction is the following (if we consider the treatment with biogas plus pyrolysis):

- Climate Change: 2.0E+03 kgCO_2eq/t CFW;
- Photochemical Oxidation: 3.0E-01 kgC_2H_2eq/t CFW;
- Eutrophication: 8.5E-01 kgPO_4^{3-}eq/tCFW;
- Acidification: 2.0E+00 kgSO_2eq/tCFW.

If we scale up the results shown in table 11 to the quantity of treated food waste, we can obtain a total reduction of GHG emissions equal to: 2.0E+03 kgCO_2eq/t CFW. If we consider that the technology tested in this study (especially anaerobic digestion coupled with pyrolysis) is applied to University canteens at a global level, we can achieve the potential reduction of GHG emission indicated in figure 7. The detail of the calculations shown in figure 7 are reported in Table 13, where the University student population is reported in the biggest countries in the world and together with this also the food waste produced per capita, according to [50]. The total number of the university students population has been evaluated recently by the UNESCO to be more than 200 million [51] and it is forecasted to grow to 262 million in 2025 [52]. The total amount of GHG which could be reduced by properly treating the CFW generated in all the world amounts at more than 20MtCO_2/year.

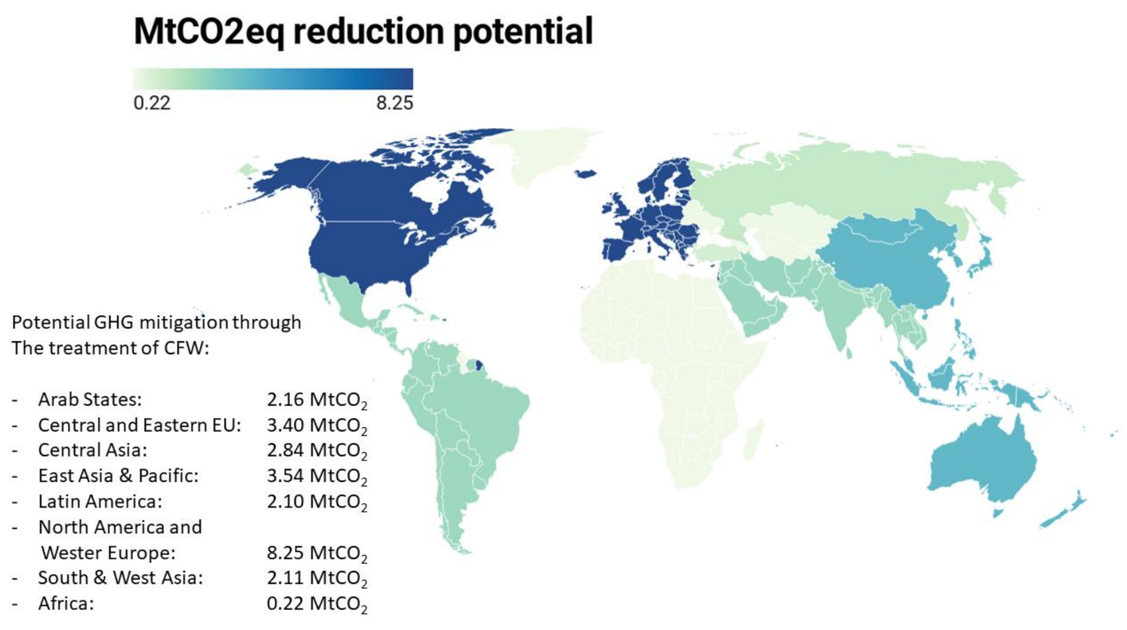

Figure 7: Potential reduction of GHG emissions at continent level

If we consider the sum of the data reported in figure 7. This value is equal to about 0.7% of the total emissions released by the food waste generated in the world. Inf fact, as it is reported in [53], the estimated emissions released by the food wastes worldwide amount to 3.3 GtCO_2eq. If we consider that in the i-REXFO LIFE16 project it has been demonstrated that with the earnings coming from biogas activity communication and awareness campaigns can be founded and that the students will lead the future generation given the training and the education they have received, it can be assumed that this reduction can almost double due to the increase awareness and knowledge on the benefits of avoiding food waste.

Table 13: Food waste generated by students in the main countries in the world

	Students (millions)	kg FW/ capita	CFW (t)	CO2 avoided (t)	Source
India	34.6	25	865000	1,730,000	[54]
China	30.3	70	2,121,000	4,242,000	[55]
South America	20	40	800,000	1,600,000	[56]
USA	19.6	110	215,6000	4,312,000	[57]
EU-27	17.5	110	1,925,000	3,850,000	[58]
Middle East	13	100	1,300,000	2,600,000	[59]
Africa sub-Saharian	5.3	15	79,500	159,000	[60]
Russian Confederation	5.2	25	130,000	260,000	[61]
Indonesia	4.4	25	110,000	220,000	[62]
Phylippines	3.2	25	80,000	160,000	[63]
Japan	2.91	110	320,100	640,200	[64]
Canada	2.12	110	233,200	466,400	[65]
Thailand	2	25	50,000	100,000	[66]
South Korea	2	70	140,000	280,000	[67]
Vietnam	1.77	25	44,250	88,500	[68]
Australia	1.5	110	165,000	330,000	[69]

Malaysia	1.3	25	32,500	65,000	[70]
Northern Africa	1.28	15	19,200	38,400	[71]
Bangladesh	1	25	25,000	50,000	[72]

The data shown in table 13 cover about 169 millions of students equal to about 85% of the total world university students population.

5. Conclusions

This work has presented a detailed impact analysis of the production of biogas using food waste collected in a University campus. The study has been performed based on ISO 14040 and ISO 14044 norms. It was also based on a Product Category Rule: “Electricity, steam and hot/cold water generation”. This was made to grant high reliability to the results. The open-source software OpenLCA was used to perform the LCA analysis, integrating the available databases with Ecoinvent 3.5 processes. This study has shown that the integration of pyrolysis and anaerobic digestion, if compared with anaerobic digestion only, can bring to a decrease of the impact on Climate Change of 27%. The impact on eutrophication can be reduced of 64% and the impact on acidification can be reduced of 51%, referring to the unit of disposed food waste. The integration of pyrolysis has advantages on the final use of digestate which is transformed into biochar (i.e. a more stable soil amendment) and also on the final energy production, which increases from 224 kWhe/t of food waste treated to 487 kWhe/t of food waste treated. Pyrolysis can be also a good solution for the countries, like Italy, in which the use of digestate produced from food waste as a soil fertilizer is not currently allowed.

6. Acknowledgments

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