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Carbon Footprint of a Typical Neapolitan Pizzeria

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Abstract: Neapolitan pizza is very popular worldwide and is registered on the traditional specialties guaranteed (TSG) list. This study was aimed at identifying the cradle-to-grave carbon footprint (CF) of a medium-sized pizza restaurant serving in situ or takeaway true Neapolitan pizzas conforming to the Publicly Available Specification (PAS) 2050 standard method. An average CF of ~4.69 kg CO_{2e}/diner was estimated, about 74% of which was due to the production of the ingredients used (with buffalo mozzarella cheese alone representing as much as 52% of CF). The contribution of beverages, packaging materials, transportation, and energy sources varied within 6.8 and 4.6% of CF. The percentage relative variation of CF with respect to its basic score was of about +26%, +4.4%, and +1.6% or +2.1%, provided that the emission factor of buffalo mozzarella, fresh cow mozzarella (fiordilatte), Grana Padano cheeses, and electricity varied by +50% with respect to each corresponding default value, respectively. The specific carbon footprint for Marinara pizza was equal to ~4 kg CO_{2e}/kg, while for Margherita pizza, it was up to 5.1, or 10.8 kg CO_{2e}/kg when topped with fresh cow or buffalo mozzarella cheese. To help pizza restaurant operators select the most rewarding mitigation strategy, we explored how CF was affected by more sustainable buffalo mozzarella cheese production, lighter and reusable containers for beer, mineral water, and main fresh vegetables, newer diesel-powered vans, less air-polluting electric ovens instead of traditional wood-fired ovens, as well as renewable electricity sources.

Keywords: carbon footprint; life cycle assessment; standard method PAS 2050; Neapolitan pizza restaurant; pizza; sensitivity analysis; mitigation strategy

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1. Introduction

The annual sales of the global pizza market are currently around USD 145 billion, including USD 54.4 billion in Western Europe, USD 50.7 billion in North America, USD 16.8 billion in Latin and South America, and USD 11.2 billion in Asia Pacific and Oceania [1]. In the US, the pizza market gave rise to USD 47 billion in revenue in 2019, with the typical price for a large plain pizza ranging from USD 7.25 for a medium pie in Alaska to USD 14 in North Dakota. Thus, at an average price of USD 11.23 per pizza, about 4.1 billion pizzas were sold in 2019 [1]. In the United States, there are currently about 77,000 pizzerias employing more than 1 million people [1]. The regular and thin-crust pizza types are the most popular, being preferred by 33% and 29% of US consumers, while the most frequently selected pizza toppings are, in descending order, pepperoni, sausage, cheese, pineapple, and anchovies.

The per capita consumption of pizza ranges from 13 kg/yr in the US to 7.6 kg/yr in Italy, 4.2–4.3 kg/yr in France, Germany, and Spain, and 4 kg/yr in the UK [2].

In Italy, about 127,000 companies with pizzeria activities are currently operating with the help of circa 100,000 employees, with this number approximately doubling on weekends. In total, 8.3×10^6 pizzas are consumed daily, with a turnover of EUR 15 billion, their price ranging from EUR 5 to EUR 10 each [3]. About eight out of ten Italians (78.8%) choose the margherita, marinara, or capricciosa pizza type. The production activities of artisanal pizza in restaurants, pizzerias, bars, delicatessens, and takeaway restaurants cover about 80% of pizza sales, the remaining 20% being related to frozen pizza [3].

The worldwide interest in this food product has become focused with particular attention on its ideotype, the Neapolitan pizza, a very popular food in the region of Campania in South Italy. European Commission Regulation no. 97/2010 [4] entered the name Pizza Napoletana in the register of traditional specialties guaranteed (TSG) of Class 2.3 (confectionery, bread, pastry, cakes, biscuits, and other baked items) to define and thus preserve its original characteristics, as requested by the Associazione Verace Pizza Napoletana (Naples, Italy. https: //www.pizzanapoletana.org/en/ (accessed on 1 March 2022)). In 2017, the United Nations Education, Scientific and Cultural Organization (UNESCO) inscribed the art of the Neapolitan pizza maker (Pizzaiuolo) on the Representative List of the Intangible Cultural Heritage of Humanity [5].

In brief, the Pizza Napoletana TSG consists of a circular 0.4-centimeter-thick base with a diameter no greater than 35 cm and a rim 1–2 cm thick, which is garnished in the central area. Just two garnishing sets are accounted for by Neapolitan Pizza, namely the Marinara (enriched with tomato, table salt, extra-virgin olive oil, oregano, and garlic) and Margherita (garnished with tomato, table salt, mozzarella and grated cheeses, extra-virgin olive oil, and basil). In this way, all the numerous toppings, including meat and dairy products, seafoods, and vegetables, were excluded, despite their widespread use around the world to provide consumers with a broad variety of sensory properties. Moreover, the Pizza Napoletana TSG is baked exclusively in wood-fired ovens for as long as 60–90 s. Such ovens consist of a base of tuff and fire bricks covered by a circular cooking floor, over which is built a dome made of refractory materials to minimize heat dispersion. Their appropriate geometric dimensions (i.e., an oven mouth with a width of 45–50 cm and a height of 22–25 cm, a cooking floor diameter of 105–140 cm, and a vault height of 40–45 cm) allow the temperature of the cooking floor and dome to be kept at about 430 °C and 485 °C, respectively, thereby ensuring the baking quality of the Pizza Napoletana.

All the production steps (i.e., dough preparation, dough rising process, dough ball shaping, garnishing, baking, and conservation), as well as the main mistakes and defects, of Neapolitan Pizza processing were fully described by Masi et al. [6].

As reported by EC regulation [4] and required by the international requirements to obtain the Verace Pizza Napoletana brand [7], the use of wood-fired ovens is, on one hand, a prerequisite for assuring the main sensory characteristics of the Neapolitan pizza. On other hand, it is the Achilles' heel of this food product. In fact, wood burning is a significant source of air pollutants (namely, carbon monoxide, polycyclic aromatic hydrocarbons, sulfur dioxide, nitrogen oxide, black carbon, and particulate matter, PM), as observed in several metropolitan areas [8,9]. Ambient air pollution was estimated to cause 4.2 million premature deaths worldwide per year in 2016 as a consequence of exposure to small particles with an aerodynamic diameter not greater than 2.5 μm, which causes cardiovascular and respiratory disease, and cancers [10]. For example, the burning of wood logs or briquettes in pizzerias was found to be a major source of black carbon and $PM_{2.5}$ within the Metropolitan Area of São Paulo (Brazil), one of the largest megacities in the world with more than 20 million inhabitants, 8 million vehicles, and 8000 pizzerias [8]. Furthermore, in San Vitaliano, a town with a population of 5000 people located near Naples (Italy), the use of wood-fired ovens was banned in restaurants and bakeries during the cold season unless their chimneys were equipped with light pollution filters [11]. In these circumstances, the Associazione Verace Pizza Napoletana would allow the use of an alternative oven, such as the so-called Scugnizzo Napoletano electric oven (Izzo Forni, Naples, Italy. https://www.izzoforni.it/izzonapoletano/ (accessed on 1 March 2022)) since this oven succeeded in a series of physical and sensory tests. Nevertheless, many traditionalists, and especially the members of another opposing association, the Associazione Pizzaioli Napoletani, were skeptical about this type of oven and disapproved of its use, insisting that the True Neapolitan Pizza must be cooked in wood-fired ovens [12].

Relatively few studies have been so far carried out to measure the environmental impact of mixed or highly processed foods, such as home- or restaurant-made pizza, and ready-to-cook pizza. For instance, Stylianou et al. [13] estimated the carbon footprint of pizza in the US diet deconstructing such a mixed dish into its basic components using life cycle inventory databases from Ecoinvent v. 3.2 and World Food LCA Database v. 3.1, and three methods accounting for the different food pattern categories, food commodities, and food ingredients. By deconstructing pizza into 18–69 components, mainly vegetables, grains, and cheese, the resulting scores varied from 2.5 to 3.5 kg of carbon dioxide equivalents (CO_{2e}) per kg.

Hofmann and Gensch [14] estimated that the greenhouse gas (GHG) emissions associated with the production and consumption of deep-frozen, chilled, and home-made salami pizzas varied in the ranges of 5.6–6.1, 5.5–5.9, and 5.7–5.8 kg CO_{2e}/kg, respectively. Such GHG emissions were also influenced by the choice of toppings (meat vs. vegetarian) and, especially, by the consumer behavior (i.e., shopping trip, storage in the private household, preparation, and dishwashing), which amounted up to 33% of the overall GHG emissions [14]. According to WRAP [15], the carbon footprint of frozen and chilled pizzas ranged from 3.4 to 5.2 kg CO_{2e}/kg. Moreover, another cradle-to-grave carbon footprint study referred to a functional unit consisting of a 120-g portion of a cheese-based Sorrento pizza (intended for air catering and obtained from partial frying of a leavened dough with wheat flour, salt, yeast, water, sucrose, malted wheat flour, sunflower oil, and trehalose, variously stuffed with tomato pulp, a mixture of cheeses, basil, etc.) was about 4.63 kg CO_{2e}/kg [16].

The environmental impacts of the foodservice and food retail industries are regarded as relevant and are classified into three categories: (i) direct environmental impacts deriving from the service provision and involving energy use for cooking (nearly a third of the total), refrigeration, lighting, and space heating, air and water emissions, and solid waste generation; (ii) upstream environmental impacts associated with the food supply chain; (iii) downstream environmental impacts related to the disposal of food and packaging (i.e., corrugated cardboard, paper, plastics, steel, aluminum, glass, and wood) wastes, and wastewaters, these being usually discharged into the municipal solid waste stream and sanitary sewer systems, respectively [17]. The Carbon Footprint of restaurants appears to be high for several reasons related to high fraction of food and energy wasted, the latter through excess heat and noise from inefficient heating equipment, ventilators, air conditioning systems, lights, and refrigerators. As an example, a study conducted by Origin Climate estimated an annual carbon footprint for a Chinese restaurant of the order of 600 Mg CO_{2e}, even if the overall number of meals served was not given [11].

Another aspect that is currently under debate is the increasing use of takeaway food packaging associated with online meal deliveries. In 2018, the disposal of single use packaging from online food orders in Australia led to 5600 Mg of CO_{2e}, which are expected to increase by more than 15% each year [18]. These emissions resulted to be maximum for a burger meal (0.29 kg CO_{2e}), which included a paper bag, paper boxes, plastic straw, liquid paperboard cup with plastic lid and cardboard cup holder. A Thai meal, which comprised a plastic container and a paper bag, gave rise to 0.23 kg CO_{2e}, while a pizza contained in a cardboard box to 0.20 kg CO_{2e} [18]. This clearly asks for more environmentally friendly packaging options to reduce single-use packaging emissions.

The results of the above LCA studies are hardly comparable since they differed for several aspects, namely the pizza type and quantity, its preparation (i.e., frozen, chilled, or home-made), and the appliance used. Since it was reported that the water footprint of two typical Italian foods (i.e., semolina dry pasta and pizza margherita) is responsible for the Italian overall water footprint (~2330 m^3 per capita per year), about the double of the world one [19], it is therefore necessary to assess accurately the cradle-to-grave environmental impact of a traditional food as the True Neapolitan Pizza.

The primary aim of this study was to identify the cradle-to-grave GHG emissions associated to the operation of a medium-sized pizza-restaurant with 22 tables baking averagely 275 Neapolitan Pizzas per day to be eaten either in situ or packed in a cardboard box and taken away, in compliance with the Publicly Available Specification (PAS) 2050 standard method [20], as well as the main hotspots of this foodservice to suggest a series of more sustainable practices to reduce the restaurant carbon footprint. Final aim was to compare the GHG emissions associated with the production of the two types (i.e., the Marinara and Margherita types) of Neapolitan Pizza (TSG) recognized by the European Commission Regulation no. 97/2010 [4].

2. Methodology

This work was compliant with the Life Cycle Assessment procedure (ISO 14040 [21]; ISO 14044 [22]) according to the guidelines established by the Publicly Available Specification (PAS) 2050 standard method [20].

2.1. Goal and Scope Definition

The purpose of this study was to assess the cradle-to-grave carbon footprint (CF) of a typical Neapolitan pizzeria (functional unit) and thus to derive the carbon footprint of the Neapolitan pizza (TSG) of the Marinara or Margherita type as specified by the European Commission Regulation no. 97/2010 [4].

The system boundary for this study is shown in Figure 1. Three different life cycle processes were included. More specifically, the upstream processes consisted of:

(U1) Production of raw and auxiliary materials, and ingredients.
(U2) Production of packaging materials.
(U3) Transport of raw, auxiliary, and packaging materials, ingredients, and firewood from their production sites (PS) or regional distribution centers (RDC) to the restaurant gate (RG).

The core processes involved:

(C1) Chilled and ambient storage, as well as processing, of raw materials and ingredients.
(C2) Disposal of wastes and by-products generated during pizza preparation and cooking.
(C3) Use of electricity and firewood.

Finally, the following downstream processes were included:

(D1) Table serving of pizza, including the provision of all eating utensils (plates, cutlery, glasses, tablecloths, and napkins) and beverages.
(D2) Takeaway serving of each pizza as stored in a corrugated cardboard box.
(D3) End-of-life processes of pizza, table setting and cardboard wastes, and wastewaters.

The manufacture of capital goods (refrigerators, mixers, oven, etc.) and their disposal (Section 6.4.4 in [20]), as well as personnel travel, and transport of consumers to and from the restaurant gate (Section 6.5 in [20]), were not included in the system boundary.

In accordance with Section 7.2 in [20], the following was stated:

- The carbon footprint assessment was referred to the year 2019 when the pizza restaurant under study had been fully operative, the first cases of the coronavirus pandemic having been detected in Italy on 31 January 2020 [23].
- The process technology used in this study was characteristic of the Pizza restaurants in the city of Naples (Italy) in the reference year.
- The primary data were provided by the restaurant *La Notizia* (Naples, Italy) and referred to the management of production and logistics of raw, auxiliary, and packaging materials, including that of catering wastes after pizza consumption.

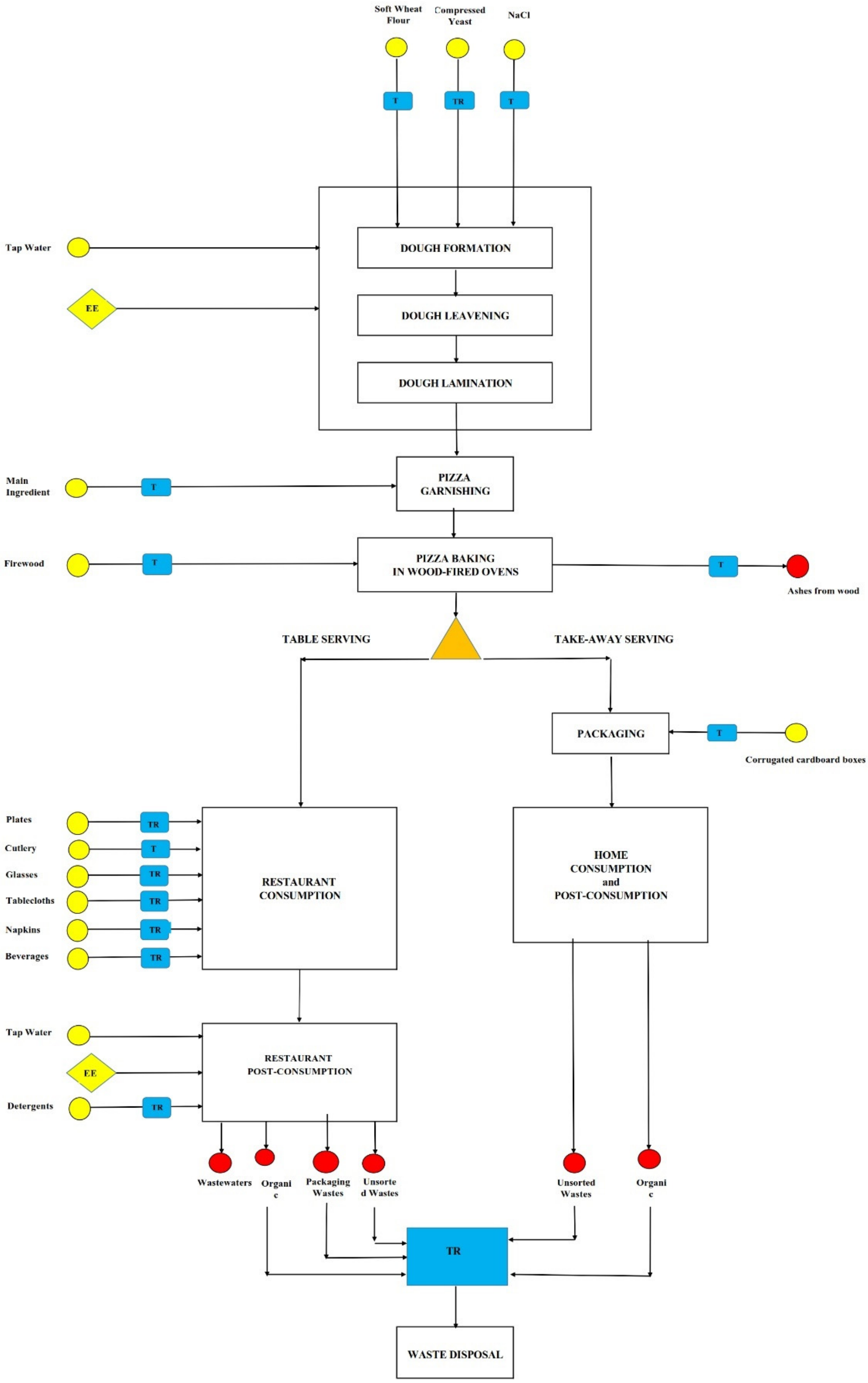

Figure 1. System boundary of the study carried out to assess the carbon footprint of a typical Neapolitan Pizza restaurant: EE—electric energy; TR—transportation.

2.2. Life Cycle Inventory Analysis

Inventory analysis was performed to assess material, water, and energy consumption, as well as waste production.

2.2.1. Pizza Preparation

At the Neapolitan pizzeria, pizza preparation was segmented into the following subsequent stages, namely ingredient mixing to form the dough, which was then leavened, laminated, garnished, and finally baked. In particular, the pizza dough was prepared using the so-called direct method, this involving the sequential addition of water, table salt, yeast and flour under continuous mixing followed by 3 to 5 min resting to allow the development of a continuous gluten network entrapping starch granules. To this end, a 0.75-kW fork mixer with the hook and bowl rotating at 36 and 9 rev/min, respectively, was used to prepare batchwise 32-kg dough lots in about 20 min according to EC [4].

As the dough was extracted from the mixer, it was placed on a table, covered with a damp cloth to avoid its surface hardening, and left resting for 2 h. Then, it was portioned using a spatula and manually shaped in 180- to 250-g near spherical loaves [4], which were then left rising in a cupboard at 25 °C and 70–80% relative humidity to limit water dehydration for 4 to 6 h to hydrolyze enzymatically fractions of starches and proteins to obtain a more extensible and digestible structure. The end of this process was revealed by about 100% increase in the initial loaf volume. By using a spatula, the Pizzaiolo placed each pizza loaf over the pizzeria counter, sprinkled it with a pinch of flour, and started to laminate it under the pressure of both hands' fingers from the center outwards by turning the resulting disc several times. According to EC [4], the final thickness of the raw pizza base was not greater than 4 mm in the center and equal to 10–20 mm on the edges. Its basic garnishing consisted of crushed, peeled tomatoes dressed with table salt, oregano, garlic, and extra-virgin olive oil in the case of the Marinara pizza type. Alternatively, in the case of the Margherita pizza type it was seasoned with sliced mozzarella cheese produced using cow or water buffalo milk, table salt, grated Grana Padano cheese, fresh basil leaves, and extra-virgin olive oil [4]. Other pizza toppings were also used. Then, the Pizzaiolo collected each garnished pizza using a wooden baker's peel and laid it on the baking floor of a wood-fired oven. This type of oven assures the characteristic quality of the Neapolitan Pizza TSG [4]. Figure S1 in the electronic supplement shows that the typical radial temperatures of the oven floor from the pizza base towards the mouth oven or burning wood logs, which, respectively, approach 350 °C or 504 °C, as measured using a non-contact thermal imaging camera FLIR E95 with 42° interchangeable lens (FLIR Systems, Wilsonville, OR, USA). In such baking conditions, the Pizzaiolo continuously turned each pizza towards the fire using a metal peel on the same area of the baking floor for as long as 60–90 s. In this way, the pizza disc had a limited chance of being burned by contacting incidentally other floor areas at higher temperatures. The floor area of the wood-fired oven, where the pizza base had been laid over, reduced its temperature from 453 ± 10 °C to 302 ± 14 °C in just 75 s.

2.2.2. Pizza Serving

The pizza restaurant operated 312 days during 2019. About 83.3% of the pizzas baked by the restaurant (i.e., 71,500 pizzas/year) were served at the restaurant tables, while the remaining 16.7% (i.e., 14,300 pizzas/year) was packed in 168-g pizza boxes (see Figure S2 in the electronic supplement) and taken away. Of the overall number of pizzas served (i.e., 85,800 pizzas/year), 25% of which was of the Margherita type, 10% of the Marinara one, and the remaining 65% of other types. Each one of the 22 restaurant tables was provided with a paper tablecloth, and a few paper napkins, ceramic plates, stainless-steel cutlery, and glasses. Each pizza box was 330-mm wide, 330-mm large, and 38-mm high. It was made of recycled corrugated cardboard, which was internally coated with an aluminum layer (its overall surface and weight being of 0.2925 m^2 and 11.1 ± 0.6 g, respectively) and a 12-µm polyethylene terephthalate (PET) layer to be suitable for food contact applications.

The PET coating avoided oil leakage, and prevented pizza from tasting of cardboard, as well as kept pizza warm for longer.

All the input energy sources and raw, auxiliary, and packaging materials consumed in 2019 are listed in Table 1, together with the amount of table sets broken or disposed of throughout the annual activity of the pizza restaurant and replaced by new items. No information about the main components of the liquid detergents used for dish, floor, glass-window, and toilet washing was available in the Ecoinvent v. 3.7 database. Several detergent ingredients used by Procter and Gamble and detergent industry are incorporated in nowadays obsolete databases, such as Boustead 1992, Buwal 250, and ETH 1994 [24]. Thus, the GHG emissions associated to their production were estimated by accounting for the different components considered by Martin et al. [25], as well as the estimations carried out by Koehler and Wildbolz [26], as reported in the electronic supplement (Table S1).

Table 1. Inventory of all the input/output sources of the pizza restaurant in 2019 and specific yield factors per each pizza baked.

Input/Output Sources	Overall Consumption	Unit	Specific Yield Factor	Unit
Utility sources				
Electricity	37,600	kWh	0.44	kWh/pizza
Tap water	2930	m^3	34.15	L/pizza
Firewood	31,900	kg	0.37	kg/pizza
Refrigerant recharging	0.5	kg	6.1	mg/pizza
Input materials				
Ingredients				
Soft wheat flour type 00 or 0	17,090	kg	199.18	g/pizza
Compressed yeast	10	kg	0.12	g/pizza
Peeled tomatoes	11,200	kg	130.54	g/pizza
Fresh tomatoes	858	kg	10.00	g/pizza
Mozzarella di Bufala Campana PDO	6390	kg	74.48	g/pizza
Fresh cow mozzarella cheese TSG	4198	kg	48.93	g/pizza
Grana Padano cheese	930	kg	10.84	g/pizza
Ricotta cheese	80	kg	0.93	g/pizza
Provola cheese	248	kg	2.89	g/pizza
Pecorino Romano cheese	108	kg	1.26	g/pizza
Naples salami	100	kg	1.17	g/pizza
Baked ham	160	kg	1.86	g/pizza
Boneless pressed dry-cured ham	120	kg	1.40	g/pizza
Cracklings	24	kg	0.28	g/pizza
Baby artichokes	24	kg	0.28	g/pizza
Mushrooms	48	kg	0.56	g/pizza
Rucola leaves	25	kg	0.29	g/pizza
Escarole	40	kg	0.47	g/pizza
Eggplant	144	kg	1.68	g/pizza
Peppers	64	kg	0.75	g/pizza
Fresh cleaned broccoli	80	kg	0.93	g/pizza
Table salt	624	kg	7.27	g/pizza
Extra-virgin olive oil	720	L	8.39	g/pizza
Oregano	7	kg	0.08	g/pizza
Garlic	93	kg	1.08	g/pizza
Basil leaves	96	kg	1.12	g/pizza
Beverages				
Mineral water	10,600	L	0.15	L/pizza
Beer in 75-cL GBs	15,120	L	0.21	L/pizza
Beer in 33-cL GBs	5900	L	0.08	L/pizza
Coca-Cola	3700	L	0.05	L/pizza
Coca-Cola Zero	470	L	0.01	L/pizza
Fanta	2600	L	0.04	L/pizza

Table 1. *Cont.*

Input/Output Sources	Overall Consumption	Unit	Specific Yield Factor	Unit
Packaging materials				
Corrugated cardboard pizza boxes	2531	kg		
Table setting replacement				
Ceramic plates	23.6	kg	0.33	g/pizza
Stainless steel cutlery	1.3	kg	0.02	g/pizza
Drinking glasses	21.4	kg	0.30	g/pizza
Paper tablecloths	1136	kg	15.89	g/pizza
Paper napkins	728	kg	10.18	g/pizza
Detergents				
Dishwashing liquid detergent	220	L	2.56	mL/pizza
Floor washing liquid detergent	160	L	1.86	mL/pizza
Glass window cleaner detergent	120	L	1.40	mL/pizza
Toilet detergent	50	L	0.58	mL/pizza
Restaurant wastes				
Organic waste	2222	kg	25.9	g/pizza
Paper & Cardboard waste	112	kg	1.3	g/pizza
Plastic waste	622	kg	7.2	g/pizza
Glass waste	19856	kg	231.4	g/pizza
Iron waste	1996		23.3	g/pizza
Aluminum waste	140	kg	1.6	g/pizza
Wood waste	244	kg	2.8	g/pizza
Unsorted waste	1889	kg	22.0	g/pizza
Ashes from wood	570	kg	6.6	g/pizza
Takeaway pizza wastes				
Organic waste	434	kg	30.4	g/pizza
Unsorted waste	2402	kg	168.0	g/pizza

2.2.3. Transportation Stage

All raw materials and ingredients, as well as auxiliary and packaging materials and firewood, were differently packed and transported from the production sites (PS) to the firm gates (FG), regional distribution centers (RDC) or restaurant gate (RG) using heavy (HRT), or light (LRT) rigid trucks, or light commercial vehicles (LCV). All processing and foodservice wastes or post-consumer organic and packaging wastes from RG or consumers' houses (CH), respectively, were transported to the waste collection center (WCC) by road using 21-Mg municipal waste collection service lorries (MWCSL). Table 2 shows the logistics of the input raw and packaging materials and output wastes together with the packaging types and masses and means of transport used (MT) and delivery distances travelled (D) from the production sites (PS), factory gates (FG) or regional distribution centers (RDC) to the restaurant gate (RG), and from RG or consumers' houses (CH) to the waste collection center (WCC).

Table 2. Logistics of input raw and packaging materials, output wastes with indication of the packaging and means of transport (MT) used for their delivery from the production sites (PS) or factory gates (FG) or regional distribution centers (RDC) to the restaurant gate (RG) and from RG or consumers' houses (CH) to the waste collection center (WCC) and distance (D) travelled.

Input Sources	Packaging		Ingredient				Packaging				Packed Ingredient			
	Type	Mass §	From	To	D #	MT	From	To	D #	MT	From	To	D #	MT
Firewood	0.8-Mg pallet	25000	PS	FG	300	HRT	-	-	-	-	FG	RG	20	LCV
Soft wheat flour	25-kg paper bag	115.0	PS	FG	300	HRT	PS	RDC	300	LRT	RDC	RG	9	LCV
Compressed yeast	25-g multilayer	1.0	PS	FG	-	-	FG	RDC	500	LRT	RDC	RG	13	LCV
Peeled tomatoes	400-g metal can	70.0	PS	FG	200	HRT	PS	FG	200	LRT	FG	RG	53	LCV
Fresh tomatoes	5-kg wood cassette	1190	PS	FG	100	HRT	PS	FG	100	LRT	FG	RG	32	LCV

Table 2. *Cont.*

Input Sources	**Packaging**		**Ingredient**				**Packaging**				**Packed Ingredient**			
	Type	**Mass §**	**From**	**To**	**D #**	**MT**	**From**	**To**	**D #**	**MT**	**From**	**To**	**D #**	**MT**
Buffalo mozzarella cheese PDO	3-kg PST tray	161.0	PS	FG	50	LCV	PS	FG	200	LRT	FG	RG	69	LCV
Fresh mozzarella cheese TSG	1-kg PE bag	1.0	PS	FG	50	LCV	PS	FG	50	LRT	FG	RG	47	LCV
Grana Padano cheese	2-kg PE bag	3.0	PS	RDC	650	LRT	PS	RDC	650	LRT	RDC	RG	38	LCV
Ricotta cheese	1.5-kg paper foil	9.4	PS	FG	50	LCV	PS	FG	200	LRT	FG	RG	69	LCV
Provola cheese	1.0-kg PE bag	4.8	PS	FG	50	LCV	PS	FG	200	LRT	FG	RG	69	LCV
Pecorino Romano cheese	2-kg PE bag	3.0	PS	RDC	300	LRT	PS	RDC	650	LRT	RDC	RG	38	LCV
Naples salami	0.6-kg piece	1.8	PS	RDC	200	LRT	PS	RDC	200	LRT	RDC	RG	13	LCV
Baked ham	4-kg PE bag	100.0	PS	RDC	200	LRT	PS	RDC	200	LRT	RDC	RG	13	LCV
Raw ham	10-kg PE bag	300.0	PS	RDC	200	LRT	PS	RDC	200	LRT	RDC	RG	13	LCV
Greaves	1-kg PE bag	20.8	PS	RDC	201	LCV	PS	RDC	200	LCV	RDC	RG	13	LCV
Baby artichokes	1-kg glass jar	400.0	PS	FG	30	LRT	PS	FG	100	LRT	FG	RG	42	LCV
	Metal lid	15.0	-	-	-	-	PS	FG	100	LRT	FG	RG	42	LCV
Mushrooms	1-kg glass jar	400.0	PS	FG	30	LCV	PS	FG	100	LRT	FG	RG	32	LCV
	Metal lid	15.0	-	-	-	-	PS	FG	100	LRT	FG	RG	32	LCV
Rucola leaves	100-g bunch	2.0	PS	FG	30	LCV	PS	FG	100	LCV	FG	RG	32	LCV
Escarole	0.6-kg wood cassette	600.0	PS	FG	30	LCV	PS	FG	100	LCV	FG	RG	32	LCV
Eggplant	15-kg PP box	2000.0	PS	FG	30	LCV	PS	FG	100	LCV	FG	RG	32	LCV
Peppers	15-kg PP box	2000.0	PS	FG	30	LCV	PS	FG	100	LCV	FG	RG	32	LCV
Broccoli	2.5-kg PE bag	5.0	PS	FG	30	LCV	PS	FG	100	LCV	FG	RG	32	LCV
Table salt	1-kg cardboard box	33.0	PS	RDC	300	LRT	PS	RDC	300	HRT	RDC	RG	13	LCV
Extra-virgin olive oil	5-L metal can	232.0	PS	FG	50	LCV	PS	FG	300	LRT	FG	RG	102	LCV
Oregano	1-kg plastic jar	186.0	PS	FG	30	LCV	PS	FG	300	LRT	FG	RG	53	LCV
Garlic	100-g plastic net	1.0	PS	FG	30	LCV	PS	FG	300	LRT	FG	RG	32	LCV
Basil leaves	300-g plastic tray	597.0	PS	FG	30	LCV	PS	FG	300	LRT	FG	RG	32	LCV
Mineral water	0.75-L glass bottle	430.0	PS	RDC	100	LRT	PS	RDC	200	LRT	RDC	RG	18	LCV
Beer	0.75-L glass bottle	370.0	PS	RDC	100	LRT	PS	RDC	200	LRT	RDC	RG	46	LCV
Beer	0.33-L glass bottle	230.0	PS	RDC	100	LRT	PS	RDC	200	LRT	RDC	RG	46	LCV
Coca-Cola	0.33-L glass bottle	195.0	PS	RDC	100	LRT	PS	RDC	200	LRT	RDC	RG	13	LCV
Fanta	0.33-L aluminum can	15.0	PS	RDC	100	LRT	PS	RDC	200	LRT	RDC	RG	13	LCV
Coca-Cola Zero	0.33-L aluminum can	15.0	PS	RDC	100	LRT	PS	RDC	200	LRT	RDC	RG	13	LCV
Corrugated cardboardpizza box	multilayer box	168.0	-	-	-	-	PS	FG	300	LRT	FG	RG	29	LCV
Ceramic plates	-	1180.0	-	-	-	-	PS	RDC	300	LRT	RDC	RG	40	LCV
Stainless steel cutlery	-	56.0	-	-	-	-	PS	RDC	300	LRT	RDC	RG	14	LCV
Drinking glasses	-	214.0	-	-	-	-	PS	RDC	300	LRT	RDC	RG	13	LCV
Paper tablecloths	-	16.0	-	-	-	-	PS	RDC	300	LRT	RDC	RG	46	LCV
Paper Napkins	-	7.0	-	-	-	-	PS	RDC	300	LRT	RDC	RG	18	LCV
Dishwashing liq. detergent	20-L plastic tank	697.0	PS	RDC	697	LRT	PS	RDC	1000	LRT	RDC	RG	13	LCV
Floor washing liq. detergent	1-L plastic bottle	100.0	PS	RDC	300	LRT	PS	RDC	500	LRT	RDC	RG	13	LCV
Glass window cleaner detergent	0.5-L plastic bottle	60.0	PS	RDC	300	LRT	PS	RDC	500	LRT	RDC	RG	13	LCV
Toilet detergent	1.5-L plastic bottle	140.0	PS	RDC	300	LRT	PS	RDC	500	LRT	RDC	RG	13	LCV
All wastes from RG and CH	-	-	-	-	-	-	-	-	-	-	RG	WCC	50	MWCSL

§ g; # km. Heavy rigid truck (HRT) 7.5–16 Mg–Euro5 (EF = 0.212 kg CO_{2e} Mg^{-1} km^{-1}). Light rigid truck (LRT) 3.5–7.5 Mg–Euro 5 (EF = 0.506 kg CO_{2e} Mg^{-1} km^{-1}). Light Commercial Vehicle (LCV) (EF = 1.83 kg CO_{2e} Mg^{-1} km^{-1}). Municipal waste collection service lorry (MWCSL) 21 Mg (EF = 1.27 kg CO_{2e} Mg^{-1} km^{-1}).

2.2.4. Energy Sources

Pizza production might be regarded as an energy-intensive process, especially in the baking phase. The energy resources used to manage the pizza restaurant under study were electricity and firewood. Electricity was used to drive dough fork mixers, refrigerators and freezers, dishwashers to automatically clean dishware and cutlery, etc., while Forest Stewardship Council (FSC)-certified oak logs were used to bake the Neapolitan Pizza TSG in a 4-pizza wood-fired oven having a floor diameter of 120 cm, dome height of 45 cm and consuming about 4 kg/h of logs. Each log was approximately long 250 $\pm$ 20 mm with a diameter smaller than 5 cm, being characterized by moisture and ash contents of 5.67 $\pm$ 0.17 and 2.9 $\pm$ 0.7% (w/w), respectively, and a lower heating value of about 5 kWh/kg. The oak logs were assembled in 800-kg European Pallet Association (EPA) wooden pallets, each one weighing 25 kg. In 2019, the electricity used by the restaurant in question was absorbed from the Italian low-voltage grids.

2.2.5. Fugitive Emissions of Refrigerant Gases

The pizza restaurant was provided with 9 refrigerators having an overall nominal power of about 3 kW. These were equipped with an overall amount of ~10.5 kg of a non-toxic and non-flammable ternary refrigerant blend (R404a) consisting of (44 ± 2) % pentafluoroethane (R-125), (52 ± 1) % 1,1,1-trifluoroethane (R143a) and (4 ± 2) % 1,1,1,2-tetrafluoroethane (R134a) [27]. Although R404a is largely used in commercial refrigerators/freezers, in vending and ice machines, in refrigerated transport, etc. with a Global Warming Potential of 3922 kg CO_{2e}/kg and a zero Ozone Depletion Potential, its use is now prohibited in new equipment and restricted in pre-existing equipment, its reclaiming being permitted till 2030 for servicing equipment already running on R404a [27]. Despite no refrigerant has been recharged over the latest two years, the expected leakage of refrigerant was assumed to be of the order of 5% per year [28].

2.2.6. Home Pizza Consumption Phase

At home the pizza boxes supplied by the pizza restaurant are generally used as dinner plates. Thus, for the sake of simplicity, no cleaning of plates, knives, forks, and glasses, as well as no other use of pizza leftovers, was accounted for. The post-consumer wastes were assumed to be formed by used pizza boxes and pizza wastes. Since the percent waste of the latter is currently unknown, it was assumed to be as practically coincident with the average one (~6% of total pizza mass) collected from the restaurant tables at the end of the meal on a year-basis.

2.2.7. Management of the Pizza Restaurant Wastes

All wastes produced by the pizza restaurant, as listed in Table 1, were differentially collected in differently colored bins according to the curbside collection of Municipal Solid Waste (MSW), namely:

- Raw ingredients discarded during the preparation of pizza topping, as well as raw or baked pizza wastes, were collected in the bins for the organic fraction of MSW. The pizza waste collected from the restaurant tables was systematically weighted in different months of the year and referred to the initial amount of pizza served. The average percentage was equal to (5.8 ± 0.6) %.
- Cardboard pizza boxes refused during pizza takeaway packaging (0.5%), as well as paper and cardboard primary packages of input materials, were amassed in the bins for paper and cardboard waste.
- Empty glass bottles and broken glasses were collected in the bins for glass waste, while empty tomato, soft-drink, and olive oil metal cans in the bins for metal waste.
- Empty plastic boxes, packs, and jars were gathered in the bins for plastic waste.
- Used tablecloths and napkins, as well as mixed and undifferentiated materials, were amassed in the bins for unsorted waste.
- Wastewaters from flush toilets, sinks, and dishwashers were disposed of in the municipal sewer system, their volume being assumed as equal to that of the overall tap water consumption (Table 1).

All food, kitchen, and packaging wastes, as well as the post-consumer organic and packaging wastes, were disposed of according to the overall Italian management scenarios of MSW in 2019 [29], as listed in Table 3. Specifically, the organic fraction is the most polluting one of MSW, even if it might be converted into compost (soil amendment) or into biofuel for heat and electricity generation or the automotive sector and digestate for soil amendment [30]. In 2019, 21% of such a fraction was landfilled, 18% incinerated, and 51% recycled [31,32]. Demichelis et al. [33] noted that the organic fraction of MSW underwent biological treatment (38–72%), incineration with energy recovery (16–52%) and anaerobic digestion (7–32%). Thus, the recycling aliquot was assumed to be mainly composted (42.5%) and the remaining 8.5% anaerobically digested. Finally, unsorted municipal solid waste is mainly landfilled (52.6%) and incinerated (47.4%), as estimated by Legambiente [34].

Table 3. Overall Italian waste management scenarios for packaging and organic wastes in 2019, as derived from the processing, distribution, and consumer phases of all the input/output sources of the pizza restaurant in 2019 and specific yield factors per each pizza baked.

Waste Management Scenarios	Landfill [%]	Recycling [%]	Incineration [%]	References
Organic wastes	31	51	18	[31,32]
Paper and cardboard wastes	11.6	80.8	7.6	[29]
Wood wastes	34.8	63.1	2.1	[29]
Plastic wastes	7.4	45.6	47.0	[29]
Glass wastes	22.7	77.3	0.0	[29]
Metal wastes	17.9	82.1	0.0	[29]
Aluminum wastes	24.4	69.5	6.1	[29]
Unsorted MSW	52.6	0.0	47.4	[34]

2.3. Carbon Footprint Assessment

The cradle-to-grave carbon footprint (CF) of the functional unit chosen was assessed by summing up all the GHG emissions associated to the production of raw and packaging materials, and detergents, all transport stages, consumption of woodfire and electricity, and waste disposal:

$$CF = \sum_{i} (\Psi_i\ EF_i), \quad (1)$$

where Ψ_i is the entity of any activity parameter (expressed in mass, energy, mass-km basis), and EF_i its corresponding emission factor. Since any activity datum was referred to the functional unit mentioned above, the resulting carbon footprint was related to the activity of the pizza restaurant in 2019 and expressed as kg CO_{2e} and then referred to each Neapolitan pizza baked.

To avoid including the subsystems related to the cultivation of raw materials (e.g., soft wheat, tomatoes, olives, garlic, oregano, basil, etc.), and production of selected ingredients (i.e., mozzarella and Grana Padano cheeses, extra-virgin olive oil, table salt, etc.) and beverages (such as beer, Coca-Cola and Fanta soft-drinks, and mineral water), the mean and standard deviation of the carbon footprint values of such products were extracted from the SU-EATABLE LIFE database [35], which was the result of a meta-analysis carried out by Petersson et al. [36] to combine the results of multiple scientific studies on the greenhouse gases emitted by different fresh food categories, including a previous review by Clune et al. [37], and provided a solid basis for evaluating the impact of dietary shifts on global environmental policies, including climate mitigation through greenhouse gas emission reductions. Other carbon footprint scores for pork meat products [38], herbs and spices [39,40], mineral water [41,42], and soft drinks [43] were retrieved from the literature. Similarly, the carbon footprint scores of the packaging (i.e., cardboard pizza boxes, glass bottles, caps, and labels, metal cans, etc.), and auxiliary materials (e.g., detergents, tablecloths, napkins, cutlery, plates, and glasses) were extracted from the Ecoinvent v. 3.7 database with the cut-off system model [44] and Agribalyse v. 3.0.1 database, both embedded in the LCA software SimaPro 9.2 (PRé Consultants, Amersfoort, NL), or appropriately estimated using the same LCA software and 100-year time-horizon global warming potentials [45]. For illustrative purposes, Tables S2 and S3 show the LCA models used to estimate the carbon footprint of the 168-g cardboard pizza box and 5-L metal can containing extra-virgin olive oil using the software SimaPro and aforementioned databases. According to the cut-off system model, each producer is fully responsible for the disposal of its wastes and does not receive any credit for the provision of any recyclable materials. Thus, all CO_{2e} credits potentially deriving from the recycling of renewable and non-renewable materials were excluded. All the emission factors used are listed in Table S1 in the electronic supplement.

2.4. Sensitivity Analysis

Firstly, the sensitivity of the LCA model defined by Equation (1) was assessed by using the emission factors characterizing the recycling of all post-consumer wastes, as retrieved from the EcoInvent v. 3.7 database when using the Allocation at the point of substitution (APOS) system model [37] and listed in Table S1. According to this model, recyclable materials are linked to the input side of the activities producing them with a negative sign, this being equivalent to a CO_{2e} credit.

Secondly, it was assessed how the different sources of uncertainty in the emission factors EF_i of any activity parameter affected the output of the above LCA model of CF. To this end, CF was differentiated with respect to the generic i-th independent variable (EF_i) while keeping all the other variables (EF_j) constant for $j \neq i$:

$$\left.\frac{\partial CF}{\partial EF_i}\right|_{EF_{j\neq i}} = \Psi_i \tag{2}$$

Then, each partial derivative ($\partial CF/\partial EF_i$) was used to estimate the relative variation (ΔCF) of CF with respect to a reference value (CF_R) by resorting to a 1st-degree Taylor polynomial and assuming a given degree of relative variation for the i-th emission factor ($\Delta EF_i/EF_{iR}$), as follows:

$$\left.\frac{\Delta CF}{CF_R}\right|_{EF_{j\neq i}} = \frac{1}{CF_R} EF_{iR} \left(\frac{\Delta EF_i}{EF_{iR}}\right) \Psi i \tag{3}$$

With,

$$\Delta EF_i = EF_i - EF_{iR} \tag{4}$$

In addition to,

$$\Delta CF = CF - CF_R \tag{5}$$

where EF_{iR} is the reference value of the generic i-th emission factor.

In this specific case, the sensitivity of CF of the Neapolitan pizzeria was evaluated by changing the emission factor (EF_i) of each i-th activity by ±50% with respect to the default condition.

3. Results and Discussion

3.1. Specific Yield Factors for a Generic Pizza Baked

Table 1 shows the specific yield factors for the average pizza baked at the restaurant under study. The energy needs were of the order of 2.3 kWh per each pizza baked, 80.9% of which being supplied by the wood-fired oven and the remainder absorbed from the Italian electricity grid mix. The water use was around 34.2 L/pizza, while the amount of ingredients used to prepare a single pizza was approximately equal to 507 g. The beverages consumed during pizza eating at the restaurant summed up to about 0.54 L/pizza, 54.76% of which being made of beer, 27.61% of bottled mineral water, 10.86% of the main Coca Cola varieties and 6.77% of Fanta. The table setting contribution was near to 26.7 g/pizza, 97.6% of which being made of paper tablecloths and napkins, while the specific use of detergents to ~6.4 mL/pizza. As resulting from the operating activity of the pizza restaurant under study, glass wastes (231 g/pizza served) were about 10 times greater than organic (26 g), iron (23 g), and unsorted (22 g) ones. On the contrary, the unsorted wastes deriving from the takeaway pizza consumption were as high as 168 g/pizza, these being made of used pizza boxes. These, being generally soiled with cheese, grease, and other food residues, cannot be reutilized to avoid contaminating paper and cardboard recycling chain.

Figure 2 shows how each pizza disc is garnished, as well as the minimum and maximum amounts of the ingredients useable for preparing the Pizza Napoletana TSG of the Marinara or Margherita type according to the EC Regulation no. 97/2010. 4 About five leaves of basil are generally used to garnish each Margherita pizza, each one weighing 0.4 ± 0.2 g.

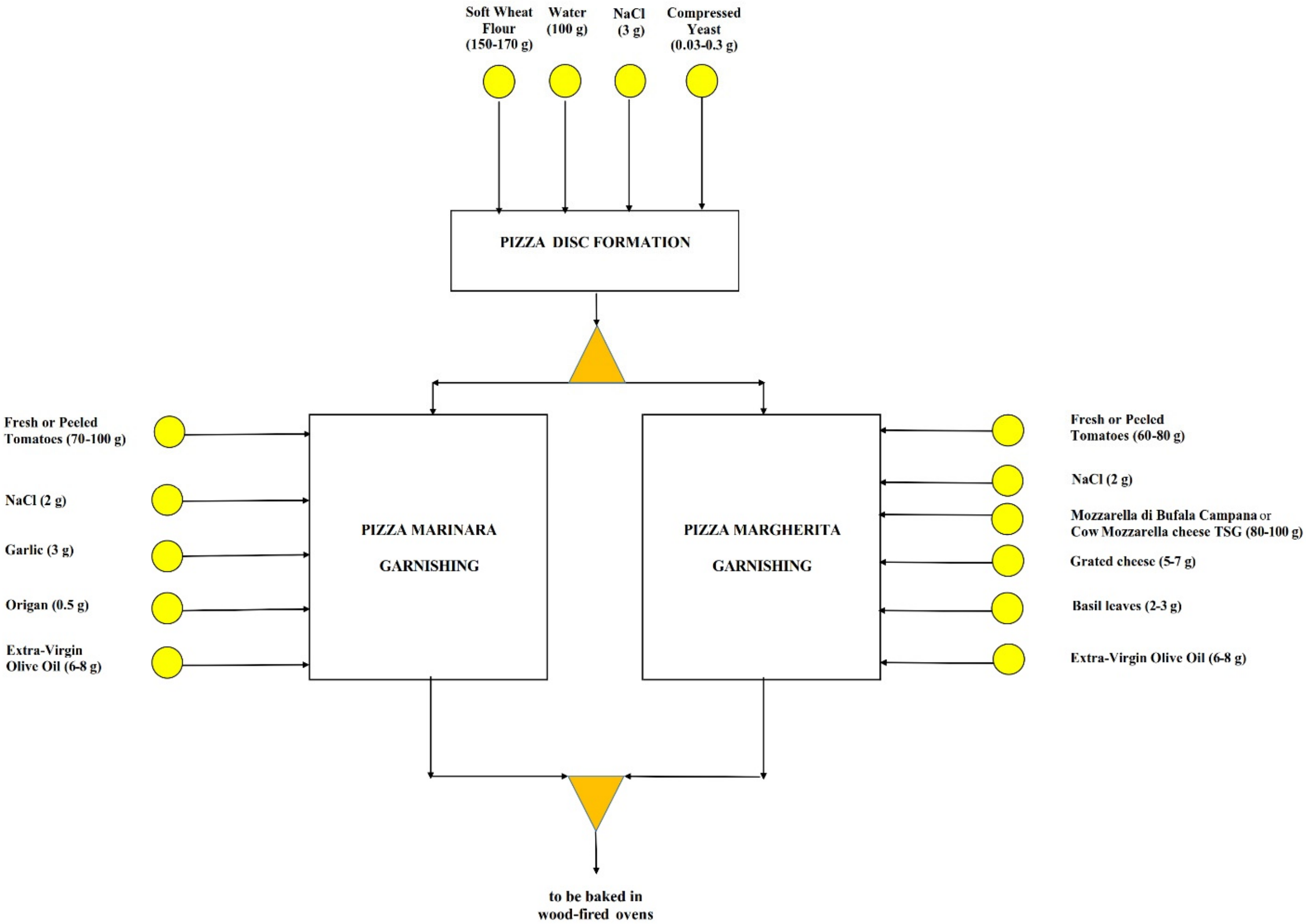

Figure 2. Minimum and maximum quantities of the ingredients needed to garnish the Pizza Napoletana (TSG) of the Marinara or Margherita type according to the EC Regulation no. 97/2010 [4].

3.2. Carbon Footprint of a Meal Dined at the Pizza Restaurant

Table 4 shows the GHG emissions associated to the main life cycle phases (i.e., production of ingredients, beverages, detergents, packaging materials, and table settings to be replaced; transportation of ingredients, packaging materials and wood logs; energy source use, refrigerant leakage; wastewater treatment and waste disposal) associated to the operation of the pizza restaurant under study.

The annual carbon footprint (CF) of the pizza restaurant amounted to about 402 Mg CO_{2e}. While the contribution of beverages, packaging materials, and transportation covered 6.8, 6.4, and 5.7% of CF, respectively; the production of all ingredients used embodied about 74% of CF. Of such a great contribution (296.7 Mg CO_{2e}), the only use of buffalo mozzarella cheese PDO represented 51.9% of CF. The energy consumption corresponded to just 4.55% of CF, about 93% of which being related to the electricity consumed by refrigerators, lights, air conditioning systems, and electric equipment. Despite the prevailing thermal energy supplied by the wood-fired oven (1.86 kWh/pizza), the abiogenic GHG emissions resulting from wood log burning were as small as 0.3% of CF, while the biogenic ones practically equaled the carbon dioxide captured from the atmosphere during the growth of the forestry biomass itself.

Table 4. Contribution of the different life cycle phases to the GHGs emitted during the operation of the pizza restaurant under study in 2019 or specifically referred to each pizza baked to be served or taken away when using a woodfired (WFO) or electric (EO) oven of the same pizza capacity.

LCA Phase	Overall GHG Emissions [kg CO_{2e}/yr]		Specific GHG Emissions [g CO_{2e}/Diner]		Percentage [%]	
	WFO	EO	WFO	EO	WFO	EO
Ingredient production	296,696		3458.0		73.73	73.00
Beverage production	27,299		318.2		6.78	6.72
Production of used table setting	3040		35.4		0.76	0.75
Detergent production	447		5.2		0.11	0.11
Packaging material production	25,932	25,920	6.44	6.38	6.44	6.38
Transportation	22,907	19,673	5.69	4.84	5.69	4.84
Electricity use	16,995	25,583	4.23	6.29	4.23	6.29
Firewood use	1295	0	0.32	0	0.32	0
Refrigerant leakage	2059		24.0		0.51	0.51
Wastewater Treatment	1395		16.3		0.35	0.34
Waste Disposal	4349		50.8	50.7	1.08	1.07
Carbon Footprint (CF)	**402,424**	**406,400**	**4690**	**4737**	**100.00**	**100.00**

Quite limited inventories for the GHGs emitted by restaurants have been so far published, generally in non-peer reviewed sources [46]. For instance, the inventory undertaken by Origin Climate reported that the annual carbon footprint for a Chinese restaurant was of the order of 600 Mg CO_{2e} [11], while that carried out by Zero Foodprint for the Noma (Copenhagen, Denmark) and Frankies 457 (Brooklyn, New York, USA) restaurants yielded 24.7 and 8.5 kg CO_{2e} per diner, respectively [47]. Moreover, the ingredients and electricity used in the Noma restaurant covered about 60 and 29% of CF, respectively; while the ingredients, electricity and gas consumed in the Brooklyn restaurant embodied near 68, 12, and 18% of CF, respectively [46].

By assuming that each diner would eat one of the pizzas baked in the restaurant examined, its carbon footprint would amount to near 4.7 kg CO_{2e}. Thus, a meal based on pizza would definitively have a smaller impact than that in the restaurants mentioned above, mainly because it included no meat cuts of bovine origin [48].

By referring to the min-max quantities of the ingredients used to prepare a Neapolitan Pizza TSG of the Marinara or Margherita type shown in Figure 2 and to their corresponding emission factors (see Table S1), it was for the sake of simplicity assumed that the specific contribution of all the other LCA phases coincided with that shown in Table 4. In the circumstances, the GHG emissions associated to a meal based on a Marinara pizza would range from 1.39 to 1.42 kg CO_{2e}, while those pertaining to a meal based on a Margherita pizza would vary from 2.13 to 2.36 kg CO_{2e} or from 4.07 to 4.78 kg CO_{2e} if such pizza was garnished with fresh cow or buffalo mozzarella cheese, respectively.

To assess their specific carbon footprint per unitary mass, several pizzas were weighted as these entered or exited from the wood-fired oven, or served on a plate, their masses being shown in Table S4 in the electronic supplement. The average mass of the raw Marinara (350 $\pm$ 4 g) or Margherita (417 $\pm$ 6 g) pizza fell within the range of 335–387 g or 408–473 g, respectively, prefixed by the Neapolitan Pizza production disciplinary [49] and summarized in Figure 2.

Thus, the cradle-to-grave carbon footprint of the Marinara pizza would range from 3.97 to 4.06 kg CO_{2e}/kg, while that of a Margherita pizza would vary from 4.6 to 5.7 kg CO_{2e}/kg or from 9.8 to 11.5 kg CO_{2e}/kg when it was topped with fresh cow or buffalo mozzarella cheese, respectively. Such different GHG emissions mainly derived from the choice of toppings (cheese vs. vegetarian).

Obviously, such scores included all the GHG emissions generated by processes that occurred both directly and indirectly in the operation of the pizza restaurant under study, as well as those deriving from the restaurant supply chain. For these reasons, the estimated cradle-to-grave scores were by far higher than those (2.5–3.5 kg CO_{2e}/kg) calculated by Stylianou et al. [13] by accounting for the diverse ingredients used only, as well as those (3.4–6.1 kg CO_{2e}/kg) estimated by Hofmann and Gensch [14] or WRAP [15] in the case of deep-frozen, chilled, and home-made pizzas.

3.3. Sensitivity Analysis

3.3.1. Sensitivity to the CO_{2e} Credits from Packaging Material Recycling

By assuming that all the restaurant and takeaway post-consumption wastes were disposed of according to the average Italian waste management scenarios shown in Table 3 and that their corresponding emission factors were extracted from the EcoInvent v. 3.7 database using the cut-off system model (Table S1), the contribution of waste disposal to the overall GHGs emitted was positive and equaled to ~51 g CO_{2e}/diner (Table 4). To account for all CO_2e credits potentially deriving from the recycling of waste materials, the above LCA model was newly run by accounting for the emission factors extracted from the EcoInvent v. 3.7 database when using the APOS system model (Table S1). In the circumstances, recycling of post-consumption wastes would give rise to credits of near 20.4 Mg CO_{2e} (namely, ~238 g CO_{2e}/diner), this lowering the overall GHG emissions of the pizza restaurant examined from 402.4 to 377.7 Mg CO_{2e}/year and the cradle-to-grave carbon footprint of a meal from about 4.7 to 4.4 kg CO_{2e}.

3.3.2. Sensitivity to the Uncertainty in the Emission Factors of Selected Input Materials

The sensitivity of CF of the Neapolitan pizzeria was estimated by varying the emission factor (EF_i) of the i-th ingredient by ± 50% with respect to the corresponding default value (Table S1). Table 5 shows the percentage relative variation of CF ($\Delta CF/CF_R$) as the emission factor EF_i of each ingredient or energy source was varied by ± 50% with respect to its basic score (EF_{iR}).

It can be noted that CF exhibited the largest increase (about +26%) as the emission factor of the water buffalo mozzarella cheese was increased by +50%. The CF increment reduced to +4.4%, +2.1%, +1.8%, +1.6%, +1.3% or 0.8% for a +50% variation in the emission factor of fresh cow mozzarella cheese, electricity, peeled tomatoes, Grana Padano cheese, beer in 0.75-cL glass bottles (GB) and soft wheat flour, or mineral water in 0.75-cL GBs, respectively. A relative variation of ± 50% in the emission factor of any other ingredient, as well as woodfire, with respect to the corresponding default one gave rise to a relative variation of CF by far smaller than ± 0.5% (Table 5).

Table 5. Percentage relative variation ($\Delta CF/CF_R$) of the cradle-to-grave carbon footprint (CF) of the Neapolitan pizza restaurant examined with respect to the reference score (CF_R) as referred to a ±50% relative variation ($\Delta EF_i/EF_{iR}$) of the emission factor EF_i of each energy source or ingredient used. Data in bold type represent the parameters most effective on CF.

Energy Source or Ingredient	**($\Delta CF/CF_R$) [%]**
Electricity	**±2.11**
Woodfire	±0.16
Tap Water	±0.10
Soft wheat flour	±1.30
Compressed Yeast	±0.001
Peeled tomato	**±1.77**
Fresh tomato	±0.05
Buffalo mozzarella cheese	**±25.96**
Fresh mozzarella cheese	**±4.42**
Grana Padano cheese	**±1.65**
Ricotta cheese	±0.03
Provola cheese	±0.33
Pecorino Romano cheese	±0.25
Naples salami	±0.14
Baked ham	±0.21

Table 5. *Cont.*

Energy Source or Ingredient		(ΔCF/CF$_R$) [%]
Deboned pressed dry-cured ham		±0.19
Cracklings		±0.001
Baby artichokes		±0.001
Mushrooms		±0.01
Rucola leaves		±0.001
Escarole		±0.002
Eggplants		±0.02
Peppers		±0.01
Broccoli		±0.01
Table salt		±0.01
Extra-virgin olive oil		±0.34
Oregano		±0.001
Garlic		±0.01
Basil leaves		±0.02
Mineral water	(75 cL)	**±0.82**
Beer	(75 cL)	**±1.30**
Beer	(33 cL)	±0.58
Coca-Cola	(33 cL)	±0.50
Coca-Cola Zero	(33 cL)	±0.03
Fanta	(33 cL)	±0.17
Dishwashing liquid detergent		±0.02
Floor washing liquid detergent		±0.12
Glass window cleaner detergent		±0.01
Toilet detergent		±0.02

3.4. Potential Mitigation Strategy

To mitigate the overall GHG emissions resulting from the operation of the pizzeria under study, two different approaches can be taken.

By considering the only impact category of climate change, as in this case, Morawicki [50] proposed to improve firstly food processing plant efficiencies for energy, water, and raw and packaging material consumption, secondly to replace fossil energy usage with renewable one by purchase or self-generation, thirdly to reduce the GHG emissions associated with the transportation of input materials, and finally to minimize the impact of the post-consumer waste disposal, as well as food loss. Alternately, the mitigation actions should be ranked starting from the life cycle stages more highly affecting the carbon footprint score [51,52].

By referring to Table 4, the primary aim would be that of reducing the impact of some selected ingredients, especially water buffalo mozzarella cheese PDO followed, in decreasing order, by fresh cow mozzarella cheese TSG, peeled tomatoes, and Grana Padano cheese. As observed by Berlese et al. [53], the great majority of the GHG emissions associated to the production of buffalo mozzarella cheese (32.7 ± 0.1 kg CO_{2e}/kg) derived from a significantly lower productivity of buffalo milk than the Italian average one. By increasing buffalo milk production up to national averages, the GHG emissions might be cut by as much as 40%. Furthermore, any further increase in buffalo meat utilization would improve the sustainability of such an ingredient of the Margherita pizza [53].

The secondary aim should be directed to lessen the environmental impact of the beverages available for purchase at the pizzeria, namely beer and mineral water packed in 75-cL glass bottles (Table 5). In previous work [54], it was suggested to reduce the contribution of the packaging materials to the carbon footprint of beer by replacing the one-way containers currently in use (i.e., glass bottles) with lighter, reusable, or recycled ones. In this specific case, the restaurant might stop serving the most popular beer package formats (i.e., glass bottles and aluminum cans) and start using returnable 30-L stainless-steel kegs, the carbon footprint of kegged beer having been found to be almost half of that of beer packed in 66-cL glass bottles [55], or 30-L KeyKegs, made from 100% recycled PET (https://www.keykeg.com (accessed on 1 March 2022)) [54]. The latter's choice might also significantly reduce the impact of the transportation stage.

Thirdly, the contribution of packaging materials to CF might be lessened by substituting the one-way containers (i.e., wooden cassettes for fresh tomatoes or escarole, polystyrene trays for buffalo mozzarella cheese, and polypropylene boxes for eggplants and peppers) with returnable and reusable ones. To substantiate further the suitability of such an option, it is worth underlining that the road distance such empty containers should travel for being cleaned and refilled is generally shorter than 50 km, and the amount of cleaning detergents needed quite small.

Fourthly, the contribution of the transportation stage to CF mainly derived from the delivery of the great majority of packed ingredients by using light commercial vehicles (Table 2) having an emission of 1.83 kg CO_{2e} Mg^{-1} km^{-1} according to the EcoInvent v. 3.7 database (Table S1). Even if such vehicles were not replaced by electric vehicles, just the use of new diesel-powered vans meeting the EU 2020/21 CO2 emission performance target of 95 g CO_{2e}/km [56] would lower their corresponding emission factor to as low as 79 kg CO_{2e} Mg^{-1} km^{-1}, provided that their average payload was about 1210 kg. In the circumstances, the GHG emissions from transport would reduce by near 33%, that is from about 22,9 to 15.1 Mg CO_{2e}/yr.

Fifthly, since the electricity used by the restaurant in question in 2019 was withdrawn from the Italian grid mix (which uses about 52% fossil sources, mainly natural gas, and 37.6% renewable ones, mainly hydroelectric and wind power) [57], the contribution of electricity to CF might be lowered by shifting to a quasi-zero carbon alternative for electricity generation such as hydropower or wind electricity, their emission factor being equal to 0.00594 or 0.0293 kg CO_{2e}/kWh, respectively (Table S1). In the circumstances, the main household electric cookstoves exhibited the minimum overall environmental impact, as previously estimated using the well-known ReCiPe 2016 and Product Environmental Footprint standard methods [58]. In this specific case, the GHG emissions associated to electricity consumption would be lessened from about 17 Mg CO_{2e} to 1.1 or 0.2 Mg CO_{2e} if wind- or hydro-power electricity was alternatively supplied to the pizza restaurant examined here.

Finally, to limit the environmental impact of fugitive emissions, the restaurant refrigerators equipped with the refrigerant blend R404a might be replaced with new refrigeration appliances charged for instance with propane (R290), that is a refrigerant gas having a negligible ozone depletion potential and quite a lower global warming potential of ~3 kg CO_{2e}/kg [59]. In this way, the fugitive emissions might be reduced from about 2.1 Mg CO_{2e}/yr to as low as 1.6 kg CO_{2e}/yr. Furthermore, the higher energy efficiency of such appliances would in addition reduce the restaurant electricity consumption too.

Similar to the guideline suggested by Messier [46], Tables 4 and 5 are useful to identify the most significant hot-spot emissions sources and might help pizza restaurant operators establishing targeted reduction strategies.

3.5. Electric Versus Wood-Fired Ovens

The wood-fired ovens are worldwide used in restaurants, bakeries, and rotisserie shops. According to Lima et al. [60], the average $PM_{2.5}$ concentration at the exit of the chimney of three pizzerias in São Paulo city (Brazil), burning eucalyptus timber logs or wooden briquettes, was found to be quite high (6171.2 μg/m^3), while in indoor areas it was around 68 μg/m^3. The noxious effect of such emissions, being generally released close to the ground level, is regarded as much higher than that from industrial emissions from by far taller chimneys, especially during cold months with stable atmospheric conditions [8]. By investigating the physical properties of aerosols in 15 Italian pizzerias, Buonanno et al. [61] measured that the indoor $PM_{2.5}$ concentration ranged from 12 to 368 μg/m^3 with an average value of 95 μg/m^3. Similarly, grilling different foods on a gas stove gave rise to indoor $PM_{2.5}$ concentrations varying from 78 and 389 μg/m^3, while frying chips using different oils on a gas stove or an electric fryer to 60–118 μg/m^3 or 12–27 μg/m^3, respectively [62]. In such pizzerias, the indoor $PM_{2.5}$ concentrations definitively exceeded the indoor 24-h mean level of 15 μg/m^3 recommended by WHO [10]. To limit $PM_{2.5}$ emissions, in Delhi (India), it was proposed the replacement of coal- with electric or gas-fired appliances in all restaurants with a greater seating capacity than 10 people [9].

By referring to an average emission factor for $PM_{2.5}$ of 0.38 g per kg of wood burned [60], the pizza restaurant under study, consuming about 32 Mg/year of wood as fuel (Table 1), would emit an overall amount of particulate matter of ~12.1 kg/year, equivalent to about 47% of the global normalization factor for $PM_{2.5}$ emissions of the ReCiPe 2016 standard method, as derived from the annual impact score of 25.58 kg $PM_{2.5}$ per each average world inhabitant [63].

To limit indoor air pollution, the Associazione Verace Pizza Napoletana would allow the replacement of the traditional wood-fired oven with the aforementioned *Scugnizzo Napoletano* electric oven, even if other electric ovens for pizza baking are commercially available. Whereas the wood-fired oven installed in the pizzeria under study could simultaneously bake four pizzas by consuming about 4 kg/h of logs, equivalent to a combustion power of 20 kW, the electric counterpart had its vault and floor equipped with 8- and 3-kW nickel-chrome electric resistances, respectively (Izzo Forni, personal communication). Since the pizza restaurant examined is averagely operating for about 5 h/day, it was assumed that the electric oven was set at its maximum power level for about two hours to heat its vault and floor at their proper pizza baking temperatures, while for the subsequent 5 h the electric resistances of the dome or floor were averagely switched on for 7 s or 3 s out of 10 s, respectively (Izzo Forni, personal communication). Thus, the electric energy consumed on a day- or year-basis would be as follows:

$$11 \times 2 + (8 \times 0.7 + 3 \times 0.3) \times 5 = 54.5 \text{ kWh/day}$$

Or,

$$54.5 \times 312 = 17{,}004 \text{ kWh/year}$$

By rounding off the annual electricity consumption to about 19 MWh, the estimated electricity consumption would be as small as 11.9% of the combustion heat released annually in the wood-fired oven (159.5 MWh).

Table 4 shows the GHG emissions associated to the main life cycle phases of the pizzeria when using an electric oven with the same pizza capacity of the wood-fired one.

Consequently, the annual carbon footprint (CF) of the pizzeria increased by 1.0%, that is from near 402 to 406.5 Mg CO_{2e}/yr. This was mainly due to the increase in the contribution of electricity consumption from 4.2% to 6.3% of CF, which was partly compensated by the decrease in the contribution of the transportation stage from 5.69% to 4.84%, being needless the supply of oak logs, as well as the disposal of residual wood ashes.

Concurrently, the specific cradle-to-grave carbon footprint increased from about 4.69 to 4.74 kg CO_{2e}/diner. Thus, despite just a slight increase in CF, the use of the electric pizza oven would have the advantage of avoiding the emission to air of nearly 12 kg of $PM_{2.5}$/year, this significantly reducing the in- and out-door air pollution levels. Obviously, by resorting to hydropower or wind electricity, the contribution of electricity would reduce from circa 25.6 Mg CO_{2e} to as low as 0.34 or 1.66 Mg CO_{2e}, and the specific CF score to 4.43 or 4.46 kg CO_{2e}/diner, respectively.

As concerning the specific energy cost per single pizza served, it is worth noting that the oak logs used by the pizzeria costed about €0.12/kg while the electricity price (including taxes) was about 0.21 ± 0.07 €/kWh, as directly derived from the invoices for the purchase of wood logs and electricity bills during the reference period examined. In the circumstances, the energy cost of any single pizza baked in an electric oven (c€13.9 ± 4.6) would averagely be 1% greater than that baked in a wood-fired oven one (c€13.7 ± 3.1).

4. Conclusions

The carbon footprinting study presented here showed that the cradle-to-grave carbon footprint (CF) of a typical Neapolitan pizza restaurant was of the order of 4.69 kg

CO_{2e}/diner. It was also estimated that the CF of the Marinara pizza, as prepared in agreement with the True Neapolitan Pizza disciplinary, would be of the order of 4 kg CO_{2e}/kg, while that of the Margherita pizza would be around 5.1 kg CO_{2e}/kg or 10.8 kg CO_{2e}/kg if topped with fresh cow or buffalo mozzarella cheese, respectively. Whatever the pizza type, about 74% of CF was represented by the production of all ingredients, of which the only buffalo mozzarella cheese PDO represented 51.9% of CF. The contribution of beverages, packaging materials, transportation, and energy sources varied from 6.8 to 4.6% of CF, respectively.

Despite the data used to carry out this study were characterized by a high level of technological-, geographical-, and time-representativeness, their main limitation stemmed from the lack of information about the production of all the ingredients used to prepare the Neapolitan pizza, some of them being bought from suppliers without having control or influence on the agricultural raw materials production and sourcing. Even if the input data were derived from energy bills, receipts and invoices and the quantity of output waste for disposal from random measuring, the carbon footprint score was affected by the uncertainty in the emission factors accounted for. More specifically, the percentage relative variation of CF with respect to its basic score was of about +26%, +4.4%, or +1.6% provided that the emission factor of buffalo mozzarella, fresh cow mozzarella, or Grana Padano cheese was varied by +50%, respectively. The sensitivity of CF to electricity emission factor was about 2.1%.

It was also evaluated the effect of a few actions regarding the use of more sustainable buffalo mozzarella cheese production, lighter and reusable containers for beer, mineral water, and fresh vegetables, newer diesel-powered vans meeting the EU 2020/21 CO_2 emission performance target for light commercial vehicles, and renewable electricity from hydro- or wind-power plants to help pizza restaurant operators adopting the most rewarding mitigation strategy.

Finally, as an attempt to limit in-door and out-door air pollution it was assumed to replace the traditional wood-fired oven with its electric counterpart, this resulting in quite a small increase in the specific cradle-to-grave carbon footprint from 4.69 to 4.74 kg CO_{2e}/diner. Despite the specific energy cost augmented by circa +1% (c€ 13.9 vs. c€ 13.7 per single pizza baked), as many as 12 kg of $PM_{2.5}$ emissions to air per year were avoided.

Further work is still needed to carry out a multi-environmental issue LCA to determine the overall environmental performance of the True Neapolitan Pizza TSG and further corroborate the mitigation actions suggested here.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/su14053125/s1, Figure S1: Radial profiles of the temperature of the wood-fired oven floor; Figure S2: Pictures of the cardboard pizza box used; Table S1: Emission factors used to assess the cradle-to-grave carbon footprint of a typical Neapolitan pizzeria; Tables S2 and S3: Details of the LCA models used to estimate the carbon footprint of the cardboard pizza box and metal can for extra-virgin olive oil; Table S4: Mass of several raw and baked Marinara and Margherita pizza types.

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Abbreviations

APOS	Allocation at the point of substitution
CF	Cradle-to-grave carbon footprint of the functional unit, as defined by Equation (1) [kg CO_{2e}]
CH	Consumers' house
CO_{2e}	Carbon dioxide equivalent
D	Delivery distance [km]
EC	European Community
EE	Electric energy
EF_i	Generic i-th emission factor [kg CO_{2e} per kg, kWh, or Mg km]
EPA	European Pallet Association
FG	Factory gate
GB	Glass bottles
GHG	Greenhouse gas
HRT	Heavy rigid truck
LCA	Life Cycle Assessment
LCV	Light commercial vehicle
LHV	Lower heating value [kWh/kg]
LRT	Light rigid truck
MSW	Municipal Solid Waste
MT	Means of transport
MWCSL	Municipal waste collection service lorry
PAS	Publicly Available Specification
PDO	Protected Designation of Origin
PE	Polyethylene
PET	Polyethylene terephthalate
PM	Particulate Matter
$PM_{2.5}$	Inhalable particles with diameters $\leq$2.5 mm
PP	Polypropylene
PS	Production site
PST	Polystyrene
R404a	Hydrofluorocarbon refrigerant blend
RDC	Regional distribution centers
RG	Restaurant gate
TR	Transportation phase
TSG	Traditional Specialities Guaranteed
WCC	Waste collection center
ΔCF	Relative variation of CF, as defined by Equation (5)
ΔEF_i	Relative variation for the i-th emission factor EF_i, as defined by Equation (4)
Ψi	Entity of the i-th activity parameter [kg, kWh, or kg km]

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