Unveiling the carbon footprint of True Neapolitan Pizza: paving the way for eco-friendly practices in pizzerias

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Abstract

This study investigated the environmental ramifications in the production and consumption of pizza. The PAS 2050 standard methodology was used to quantify the cradle-to-grave carbon footprint of a typical medium-sized Neapolitan pizzeria offering both table service and takeaway in cardboard boxes. A spectrum of sustainable practices capable of mitigating the greenhouse gas (GHG) emissions of pizzerias was analyzed. By accounting for consistent GHG emissions across specific life cycle phases—such as energy consumption, refrigerant gas leakage, detergent production, and wastewater treatment—it was possible to estimate the cradle-to-grave carbon footprint of different iterations of the True Neapolitan Pizza. For instance, the Marinara pizza had a carbon footprint of approximately 1.7 kg CO_{2e}/kg while the Margherita pizza topped with mozzarella cheese registered roughly twice that figure. Moreover, garnishing the Margherita with buffalo mozzarella increased its carbon footprint to 4.2 kg CO_{2e}/kg. This difference in environmental impact can be chiefly attributed to the condiments of vegetable or animal origin, with variations in protein and fat content significantly influencing the energy value of each pizza variant. These findings emphasized the importance of informed decisions for a greener culinary future, highlighting the critical role of ingredient choices in shaping the sustainability profile of pizza offerings.

Keywords: carbon footprint; life cycle analysis; PAS 2050 standard method; True Neapolitan Pizza; typical pizza restaurant

Introduction

There has been a drastic increase in greenhouse gas (GHG) emissions over the last century due to global population explosion and the adoption of more intensive production and consumption patterns. Numerous studies have found that the total emissions from the food system range from 14 to 22 Pg CO_{2e}/year (Crippa *et al.*, 2021; IPCC, 2019; Rosenzweig *et al.*, 2020; Tubiello *et al.*, 2021), accounting for approximately 30–34% of the total anthropogenic emissions. Within the food sector, GHG emissions associated with the production of animal-derived foods (particularly red meat and dairy) is the major contributor (about 60%), while plant-based products contribute around 30%, and the remaining agricultural products (such as fibers) account for 13% (Xu *et al.*, 2021). The sources of these emissions vary widely and include methane produced from enteric fermentation in the stomachs of ruminants like cattle and sheep, as well as anaerobic fermentation of their manure, and nitrous oxide (N_2O) from agricultural soil fertilization and animal waste management.

These emissions also encompass pre- and postproduction agricultural activities, including the manufacturing of fertilizers and packaging, transportation of raw-materials and finished products, food preparation, retail sales, domestic consumption, food waste, and waste disposal. These emissions are significant: in 1990, they accounted for 25% of the total food-related emissions while in 2019 they increased to 37%. In contrast, emissions related to land conversion decreased from 35% to 22% during the period 1990–2018, primarily due to reduced deforestation. During the same period, emissions associated with the agricultural phase remained nearly constant, accounting for 40% of total emissions (Tubiello *et al.*, 2022). The increasing emissions from activities beyond the farm gate suggest that these activities will become the most prominent component of total food system emissions in the decades to come (Tubiello *et al.*, 2022).

These estimates solely refer to the indicator of climate change. Currently, although there is no unanimous international consensus, the overall environmental impact is assessed by standard methods such as IMPACT World$^+$ (Bulle *et al.*, 2019), Product Environmental Footprint (EC, 2021), and ReCiPe 2016 (Huijbregts *et al.*, 2017), which consider 16–18 environmental impact categories. For example, Weidema *et al.* (2008) demonstrated that the agricultural phase has the greatest impact in dairy and meat production. Kim *et al.* (2013) assessed the environmental impact of mozzarella and cheddar for nine impact categories and found that the agricultural phase was responsible for over 60% of the total environmental impact for seven of them. For the other two impact categories, such as cumulative energy demand and human toxicity, over 50% of the total impact was attributed to subsequent phases, with a significant contribution from production and consumption phases for human toxicity. Other studies have identified the agricultural phase as having the greatest environmental impact for other products as well, including meat (Dijkman *et al.*, 2018), cheeses (Bava *et al.*, 2018), bread (Roy *et al.*, 2009), dry pasta (Cimini *et al.*, 2020, 2022), dried legumes (Moresi and Cimini, 2024), and olive oil (Espadas-Aldana *et al.*, 2019). Some of these products are important ingredients in pizza, as specified for the two types of True Neapolitan Pizza (Marinara and Margherita) included in the list of traditional specialties guaranteed (STG) by European Commission Regulation No. 97/2010 (EC, 2010).

In this work, the environmental impact of consuming a True Neapolitan Pizza in a typical medium-sized pizzeria, which offers table service and takeaway in cardboard boxes, will be evaluated using the climate change indicator, known as the carbon footprint. It is worth noting that such an indicator is strongly correlated with other impact categories, such as acidification, eutrophication, photochemical ozone formation, and fossil resource use (Huijbregts *et al.*, 2006, 2010).

Environmental Impact of Pizza: State-of-the-Art

In the culinary world, pizza is defined as an Italian dish consisting of a round flat base of cooked dough, topped with tomato sauce and cheese, often enriched with anchovies, sliced sausage, mushrooms, and other vegetables (https://www.dictionary.com/browse/pizza). This definition is also supported by Luca Cesari (2023), who attributes the birth of pizza as we know it today to the opening of the first Neapolitan pizzeria (*Pizzeria Lombardi*) at 531/2 Spring Street in New York in 1905. The highest per capita consumption of pizza is currently recorded in the United States, with an average of 13 kg per year, while in Italy it stands at about 7.6 kg per year (UDiCon, 2020). In the United States, in addition to a preference for meat toppings, the most popular pizza toppings include pepperoni, sausage, cheese, pineapple, and anchovies (Kuscer, 2024).

The environmental impact of homemade pizza, restaurant-made pizza, or ready-to-cook pizza has been relatively understudied. For example, Stylianou *et al.* (2018) analyzed the composition of pizza consumed in the United States, identifying between 18 and 69 different ingredients, mainly vegetables, cereals, and cheese. Using databases such as Ecoinvent v. 3.2 and World Food LCA Database v. 3.1, they estimated a carbon footprint ranging from 2.5 to 3.5 kg CO_2 equivalent (CO_{2e}) per kilogram. In another study, Hofmann and Gensch (2012) examined GHG emissions associated with the production and consumption of salami pizzas, both industrial (frozen or refrigerated) and homemade. Their estimates indicated values ranging from 5.6 to 6.1 kg CO_{2e}/kg, from 5.5 to 5.9 kg CO_{2e}/kg, and from 5.7 to 5.8 kg CO_{2e}/kg, respectively. Interestingly, depending on the ingredients of animal or plant origin and consumer behavior regarding purchase, storage in freezer or refrigerator, preparation, and dishwashing, the carbon footprint could vary by ±33% from the average value.

Recently, Cortesi *et al.* (2022) conducted a study on the environmental impact of 80 types of pizza representative of the French retail market in 2010. They adopted 1 kg of ready-to-eat pizza as the functional unit (FU) and the Product Environmental Footprint (PEF) method to characterize the impact. The findings indicated that ingredient production had the greatest environmental impact during the pizza production process, while production and distribution methods had a lesser impact. In particular, Bolognese pizza, containing beef, was found to have a significantly higher environmental impact than other variants. Overall, the environmental impact was positively correlated with the cheese content. For example, the carbon footprint of Bolognese pizza was estimated at 5.45 kg CO_{2e}/kg, while that of Margherita pizza was approximately 2.1 kg CO_{2e}/kg. These results are in contrast to the data of Stylianou *et al.* (2018), who had assessed only the ingredient production stage, estimating values ranging from 1.3 to 3.2 kg CO_{2e}/kg for vegetarian pizzas and from 4.0 to 5.2 kg CO_{2e}/kg for those containing meat. Overall, Cortesi *et al.* (2022) reported an average of 3.2 ± 1.0 kg CO_{2e}/kg for the examined pizzas, with a minimum–maximum range of 2–6 kg CO_{2e}/kg and an overall eco-indicator of 530 ± 170 μPt/kg with a minimum and maximum of 267 and 1135 μPt/kg, respectively. In addition, the analysis showed that, depending on the type of pizza, the ingredient production stage accounted for an average of 74.8% of the total impact for the climate change indicator, with a minimum–maximum range between 41 and 92%. Following in decreasing order were the packaging stage (minimum, average, and maximum values of 2.0, 7.7, and 19.6%), pizza transportation (2.7, 6.1, and 11.2%), use (1.6, 5.6, and 13.6%), processing (0.1, 3.0, and 11.1%), and distribution (1.2, 2.9%, and 5.7%). For other impact categories of the PEF method, ingredient production was the most impactful stage (Cortesi *et al.*, 2022).

These results are consistent with those reported by Jazbec *et al.* (2022), where scenarios for reducing GHG emissions and resource use in Australia were examined. To reduce meat consumption, predominant in the country (OECD, 2023), scenarios were proposed to replace 25–100% of meat-based menu options with plant-based options in fast-food outlets. It was hypothesized that such interventions could significantly reduce the climate and environmental footprint of fast-food outlets. It is important to note that pizza, representing 16% of the turnover of fast-food and takeaway services in Australia, has a significant carbon footprint, especially due to the use of cheese. Substituting mozzarella with tofu, for example, could significantly reduce the environmental impact of pizza (Quantis, 2016).

The restaurant sector is known for its high environmental impact, particularly regarding water, food, and energy waste (Singh and Highway, 2016). According to the Food and Agriculture Organization (FAO, 2019), restaurants contribute significantly to food waste, which not only squanders resources but also adds to the carbon footprint through methane emissions from decomposing food in landfills. Furthermore, the energy used in cooking, refrigeration, ventilation, air conditioning, and lighting in restaurants contributes substantially to GHG emissions. Inefficient energy use not only increases operating costs but also results in higher emissions of CO_2 and other GHGs. According to the U.S. Environmental Protection Agency (EPA, 2022), restaurants use about five to ten times more energy per square meter than office buildings and retail stores, as most commercial kitchen appliances are very energy intensive. Several sustainable practices involving energy and water efficiency, as well as sustainable policies, were examined to measure restaurants' performance factors such as market share, cost advantage, and stakeholders' satisfaction (Jang, 2016). In addition, an eco-inefficiency formula was developed to verify the cost of the economic, environmental, and social impact of waste in food services (Lins *et al.*, 2021). To mitigate these impacts, many restaurants are implementing energy-efficient appliances and practices. To this end, it is essential to analyze the sector through three main impact categories identified by Davies and Konisky (2000). These categories include service provision, the food supply chain, and food and packaging disposal as municipal solid waste (MSW). Examining the restaurant sector through these categories allows for a more comprehensive understanding of its environmental impact and helps identify areas for intervention to promote more sustainable practices and reduce overall environmental impact.

Finally, a critical aspect to consider is the excessive use of packaging in the takeaway food sector, especially in online meal deliveries. In 2018, the disposal of single-use packaging from online food orders in Australia resulted in 5600 Mg of CO_{2e}, with a growth trend of +15% per year (Crawford, 2021). For example, emissions associated with just the packaging of a takeaway hamburger meal amounted to 0.29 kg CO_{2e}, as each package included a paper bag, paper boxes, plastic straws, a cardboard cup with a plastic lid, and cardboard cup holders. For a pizza in a cardboard box, a carbon footprint of 0.20 kg CO_{2e} was estimated (Crawford, 2021). It is therefore important to adopt more sustainable single-use packaging to reduce emissions associated with their production.

In conclusion, studies on the environmental impact of pizza vary in results due to various factors, such as the type and quantity of pizza consumed and preparation and consumption methodologies. However, they are essential for making the restaurant sector more sustainable.

Environmental Impact of Ingredients in *True Neapolitan Pizza*

To determine the carbon footprint of the two variants of *True Neapolitan Pizza* (i.e., Marinara and Margherita), the ingredients specified in the production regulations (EC, 2010) were considered.

Table 1 presents the minimum and maximum quantities of each generic ingredient used to season the two variants of the *true Neapolitan pizza* (TSG: traditional specialty guaranteed), along with their respective carbon footprints (CF_i). For further details, please refer to the work of Falciano *et al.* (2022). It is worth noting that the carbon footprint of the various ingredients was primarily

Table 1. Minimum and maximum quantities of ingredients used to season True Neapolitan Pizza (TSG) in Marinara and Margherita variants (EC, 2010), along with their carbon footprint (CF_i).

Pizza Ingredient [g]	Marinara		Margherita		CF_i
	min	max	min	max	[kg CO_{2e} kg^{-1}]
Wheat flour type 0 or 00	150	170	150	170	0.61±0.23
Compressed yeast	0.03	0.3	0.03	0.3	0.82±0
Water	100	100	100	100	0.0003±0
Peeled tomatoes	70	100	60	80	1.28±0.04
PDO buffalo mozzarella cheese	–	–	80	100	12.0±1.4
Fresh cow mozzarella cheese	–	–	80	100	8.5±1.4
Grana Padano cheese	–	–	5	7	14.3±2.8
Table salt	5	5	5	5	0.16±0
Extra virgin olive oil	6	8	6	8	3.8±2.9
Oregano	0.5	0.5	–	–	1.60±0
Basil leaves	-	–	2	3	1.60±0
Garlic	3	3	–	–	0.67±0.07
Total mass [g]	*335*	*387*	*408*	*473*	–

obtained from the SU-EATABLE LIFE database, which collects GHG emissions associated with the production of various categories of fresh foods, based on a meta-analytical analysis conducted by Petersson *et al.* (2021).

In a previous work (Falciano *et al.*, 2022), the carbon footprint of buffalo mozzarella was initially derived from a life cycle assessment (LCA) study conducted by Berlese *et al.* (2019), which reported values ranging from 29 to 34 kg CO_{2e} per kilogram of buffalo mozzarella, depending on the (economic or physical) allocation method used. Such a high carbon footprint was attributed to the low productivity of buffalo milk in the six livestock farms that were examined in Northeast Italy. Berlese *et al.* (2019) hypothesized that, by increasing farm productivity to national averages, the carbon footprint could be reduced by at least 40%. In support of this hypothesis, a significantly lower carbon footprint (8.2 kg CO_{2e}/kg), similar to that of mozzarella cheese (Table 2), was calculated for organic mozzarella produced with buffalo milk in Brazil (Alves *et al.*, 2019). More recently, Rossi *et al.* (2023) assessed the environmental impacts, from milk production to consumption, of the buffalo mozzarella supply chain in the production district of Amaseno (FR, Italy), an area suitable for labeling mozzarella as protected designation of origin (PDO) under EC Regulation No. 1107/96 (EC, 1996). With reference to this production district, where buffalo farming accounts for a total of 23,043 head, approximately 5.5% at the national level, a carbon footprint of 12.0 ± 1.4 kg CO_{2e}/kg of PDO buffalo mozzarella was estimated.

From the data reported in Table 1, it is evident that the contribution to GHG emissions solely from the ingredients used to prepare the Marinara pizza ranges between 208 and 266 g CO_{2e}. In contrast, emissions associated with the preparation of the Margherita pizza range between 945 and 1190 g CO_{2e} when seasoned with fresh cow mozzarella cheese and between 1227 and 1543 g CO_{2e} when seasoned with PDO buffalo mozzarella from Campania.

By referring to the same quantity of product, the indicator of climate change impact varies from 0.6 to 0.7 kg CO_{2e} per kg of Marinara pizza, while for Margherita pizza, it ranges from 2.3 to 2.5 kg CO_{2e}/kg with mozzarella cheese or from 3 to 3.3 kg CO_{2e}/kg with PDO buffalo mozzarella. As expected, the absence of cheese in Marinara pizza results in a significantly lower carbon footprint compared to Margherita pizza, especially when seasoned with PDO buffalo mozzarella from Campania.

Of course, the environmental impacts mentioned do not account for other crucial phases of the pizza's life cycle. These include:

1. The packaging and transportation of individual ingredients to the pizzeria.

2. The methods of preparation and baking of the pizza, which determine energy consumption and GHG emissions associated with the production of each pizza.

3. The modes of consumption on-site or at home, which can involve the formation of disposable packaging or the use of additional energy for transportation and heating of the pizza in household ovens.

Table 2. GHG emissions of the different life cycle stages associated with the operation of the pizzeria under study in 2019, when using a wood-fired or electric oven of equal capacity, when referred to each pizza prepared for table service or takeaway.

GHG emissions Life Cycle Phase	Wood-fired oven		Electric oven	
	[g CO_{2e}/pizza served]	[%]	[g CO_{2e}/pizza served]	[%]
Ingredient production	1·916	60.86	1·916	60.07
Beverage production	318	10.10	318	9.97
Table setting production	35	1.13	35	1.11
Detergent production	5	0.17	5	0.16
Packaging material manufacture	302	9.60	302	9.47
Transportation	267	8.48	229	7.19
Electricity use	198	6.29	293	9.18
Firewood use	15	0.48	–	–
Refrigerant leakage	24	0.76	24	0.75
Wastewater treatment	16	0.52	16	0.51
Waste disposal	51	1.61	51	1.59
Carbon Footprint (CF)	*3·149*	*100.00.*	*3·190*	*100.00*

4. The management of waste generated during the preparation and consumption of the pizza, including packaging and any food waste.

Therefore, while it is crucial to consider the carbon footprint of ingredients in the pizza production phase, it is equally essential to evaluate and reduce the environmental impact of other phases of the life cycle to obtain a comprehensive and accurate understanding of the overall impact of pizza on the environment.

Therefore, the contribution of these phases will be highlighted with reference to the environmental impact of a typical Neapolitan pizzeria.

Environmental Impact of a Typical Neapolitan Pizzeria

The GHG emissions associated with the operation of a typical Neapolitan pizzeria (i.e., La Notizia, Naples) during the year 2019, prior to the outbreak of the coronavirus pandemic, were identified. The pizzeria in question is of medium size, equipped with 22 tables. In 2019, it operated for 312 days, with an average production of 275 pizzas per day. Approximately, 83.3% of these pizzas were consumed on-site, while the remaining 16.7% were taken away in cardboard boxes. These boxes, measuring 330 mm in width, 330 mm in length, and 38 mm in height, were manufactured from recycled corrugated cardboard. They were internally coated with a layer of aluminum and a layer of polyethylene terephthalate (PET) to ensure their suitability for contact with food.

To assess the carbon footprint of the pizzeria, a business-to-consumer study was conducted in accordance with the LCA procedure defined by ISO norms 14040 (ISO, 2006a) and 14044 (ISO 2006b), encompassing the following stages: goal and scope definition, inventory analysis, impact assessment, and interpretation of results.

The selected FU was a pizza served at the pizzeria's tables or taken away in cardboard boxes. The system boundary diagram depicting the life cycle from cradle to grave for each pizza is illustrated in Figure 1. Three distinct life cycle processes were considered. Specifically, upstream processes included:

- U1 Production of raw materials, auxiliaries, and ingredients.
- U2 Production of packaging materials.
- U3 Transportation of raw materials, packaging, ingredients, and firewood from their production sites or regional distribution centers to the restaurant.

Core processes involved:

- C1 Refrigerated storage, as well as processing of raw materials and ingredients.
- C2 Disposal of waste and by-products generated during the preparation and baking of the pizza.
- C3 Use of electricity and firewood.

Finally, the following downstream processes were included:

- D1 Table service of pizza, including the provision of all tableware (plates, cutlery, glasses, tablecloths, and napkins) and beverages.

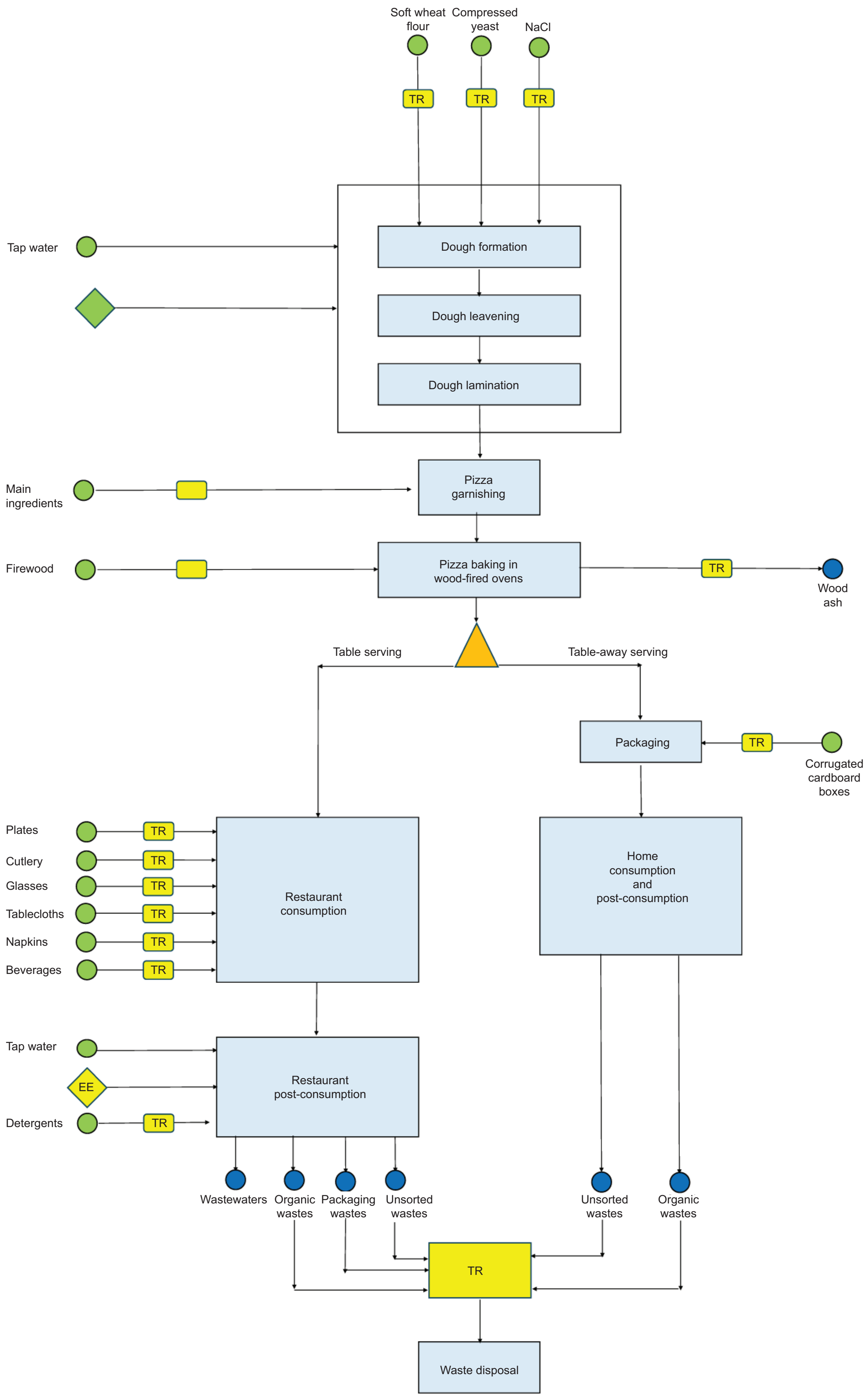

Figure 1. System boundary of the LCA study performed to evaluate the carbon footprint of a typical Neapolitan pizzeria: EE, electricity; TR, transportation.

D2 Takeaway service of pizza in cardboard boxes.

D3 End-of-life processes for pizza, retrieval of disposable tablecloths and napkins and packaging waste, as well as wastewater.

The manufacture and disposal of capital goods (refrigerators, mixers, ovens, etc.) as outlined in Section 6.4.4 of PAS 2050 (BSI, 2011), along with personnel travel and consumer transport to and from the restaurant (Section 6.5) (BSI, 2011), were excluded from the system boundary. Regarding data quality rules (Section 7.2: BSI, 2011), the carbon footprint assessment was based on the year 2019, a pre-COVID-19 pandemic year when the pizza restaurant examined was fully operational. The process technology used was typical of pizza restaurants operating in Naples, Italy, during the reference year. Primary data were provided by the restaurant La Notizia (Naples, Italy) and covered the management of production and logistics of raw, auxiliary, and packaging materials, including the handling of catering waste post-pizza consumption.

Details regarding the collection of all inventory data concerning pizza preparation, serving, and consumption, along with the logistics of sourcing the raw and packaging materials used, were reported by Falciano *et al.* (2022) and are briefly summarized here.

The great majority of raw, auxiliary, and packaging materials, and ingredients were transported to the restaurant gate using light commercial vehicles (LCV). All processing and foodservice wastes or postconsumer organic and packaging wastes were transported from the restaurant gate or consumers' houses to the waste collection center by road using 21-Mg municipal waste collection service trucks. Table 2 by Falciano *et al.* (2022) shows their logistics together with the means of transport used and delivery distances travelled.

The energy resources used to operate the pizzeria include electricity and firewood. Electricity, sourced from the national low-voltage electrical grid, was used to power dough mixers, refrigerators, freezers, and dishwashers. To bake the True Neapolitan Pizza TSG, a wood-fired oven fueled with certified oak logs with a lower calorific value of about 5 kWh/kg was used.

The pizzeria's refrigerators had a total nominal power of 3 kW and were loaded with approximately 11 kg of a nontoxic and nonflammable ternary mixture (R404a), with a global warming potential of 3922 kg CO_{2e}/kg and virtually zero ozone depletion potential (Falciano *et al.*, 2022). A refrigerant gas leakage rate of around 5% annually was assumed.

All wastes produced by the pizza restaurant, as listed in Table 1 by Falciano *et al.* (2022), were collected in differently colored bins according to the curbside collection of MSW, namely:

- Green bins: organic waste, such as ingredient scraps and pizza leftovers.
- Blue bins: paper and cardboard packaging.
- Yellow bins: empty glass bottles, broken glasses, and empty tomato, soft-drink, and olive oil metal cans.
- Red bins: plastic packaging and jars.
- Black bins: undifferentiated waste, such as used tablecloths, napkins, and other materials.

Waste generated from household pizza consumption (i.e., used cardboard boxes and pizza leftovers) was also disposed of according to the norms of the Italian MSW management in 2019 (Ronchi & Nepi, 2020). Specifically, the percentage of leftovers was assumed to be the same as that observed at the end of the meal in the pizzeria, equivalent to 6% of the total weight of pizza served at the tables (Falciano *et al.*, 2022). The organic fraction was recycled at 51%, incinerated at 18%, and landfilled at 21%. Unsorted waste was mainly landfilled (52.6%) or incinerated (47.4%). Wastewater from sinks and dishwashers was discharged into the municipal sewer system. We assumed that the wastewater production coincided with the overall tap water usage during the pizzeria's operations in 2019, as derived from all related bills. This assumption was made because there were no significant sources of water input or loss other than tap water usage.

The impact assessment was conducted using emission factors from the Intergovernmental Panel on Climate Change (IPCC, 2019) database, the Ecoinvent v. 3.7 database applying the cut-off system model (Ecoinvent, n.d.), and the SU-EATABLE LIFE database (Petersson *et al.*, 2021). The SU-EATABLE LIFE database facilitated a detailed analysis by providing specific emission factors for the cultivation of raw materials such as wheat, tomatoes, garlic, oregano, and basil, as well as for the production of main ingredients like mozzarella, grated cheese, extra virgin olive oil, and kitchen salt. Although the PAS 2050 standard method considers not only the total GHG emissions caused directly and indirectly throughout the product life cycle but also GHG removals due to reforestation, soil carbon sequestration, or carbon capture and storage, no processes or activities sequestering GHGs from the atmosphere were identified in this study focused on the pizza life cycle. Thus, the impact assessment included only the total GHG emissions.

Table 2 shows the GHG emissions associated with the main life cycle phases (i.e., production of ingredients, beverages, detergents, packaging materials, and tableware to be replaced; transportation of ingredients, packaging materials, and wood logs; electricity use; refrigerant gas losses; wastewater treatment; and waste disposal) associated with the operation of the pizzeria under study.

Considering that the pizzeria served a total of 85,800 pizzas in 2019, the overall GHG emissions amounted to approximately 270 Mg CO_{2e}. Of these, the production of all ingredients accounted for about 61%, while the contributions from beverages, packaging, and transportation covered 10.1%, 9.6%, and 8.5%, respectively. Regarding emissions associated with ingredients, PDO buffalo mozzarella represented 46.6%, followed by mozzarella cheese (21.6%) and grated Grana Padano cheese (8.1%). Overall, the emission contribution of all the cheeses used by the pizzeria amounted to 79.4% of the emissions associated with the use of various toppings, confirming the significant environmental impact of cheeses on pizza (Cortesi *et al.*, 2022; Jazbec *et al.*, 2022), even in a typical Neapolitan pizzeria.

Electricity consumption was approximately 0.44 kWh per pizza and accounted for 6.3% of total emissions. In spite of the high energy consumption of the wood-fired oven (1.86 kWh per pizza), the abiotic CO_2 emissions resulting from the combustion of oak logs covered only 0.5% of total emissions because biogenic CO_2 emissions were not calculated, being equivalent to the CO_2 photosynthetically absorbed during the growth of the forest biomass burned in the pizza oven.

On average, a pizza meal resulted in a footprint of 3.15 kg CO_{2e}, which is significantly lower compared to meals served in restaurants studied by Zero Foodprint (Ying and Freed, 2016), which amounted to 24.7 kg CO_{2e} at Noma restaurant (Copenhagen, Denmark) and 8.5 kg CO_{2e} at Frankies 457 restaurant (Brooklyn, New York, USA). In the former case, ingredient and electricity contributed to about 60% and 29% of total emissions, while in the latter case, ingredients, electricity, and gas accounted for approximately 68%, 12%, and 18% of total emissions, respectively (Messier, 2016).

For the typical pizzeria under study, as well as for the two aforementioned restaurants, the emissions from ingredients played a predominant role, accounting for 60 to 68% of the total. However, it is worth noting that in the case of the pizzeria, electricity usage was minimal, around 6.3%, as the energy needed for cooking is sourced from the combustion of renewable biomass.

The sensitivity of the carbon footprint of the Neapolitan pizzeria was then estimated by varying the emission factor of the generic i-th ingredient or energy source by ±50% with respect to the corresponding reference value (Table 1). Table 3 shows the corresponding relative percentage change in the carbon footprint (CF) compared to the reference value ($\Delta CF/CF_R$).

Compared to the main ingredients of the true Neapolitan pizza, the carbon footprint of the pizza typically served by the pizzeria showed greater sensitivity, registering an increase of approximately +9.5% when the emission factor of buffalo mozzarella was increased by +50%. This sensitivity then decreased to +4.4%, +1.8%, +1.6%, +1.3%, or +0.3% for a +50% variation in the emission factors of mozzarella cheese, peeled tomatoes, grated Grana Padano cheese, soft wheat flour, or extra virgin olive oil. Similarly, a relative variation of ±50% in the emission factors of electricity, beer or mineral water in 75-cL glass bottles resulted in a relative carbon footprint variation of +2.1%, +1.3%, or +0.8% (Table 3).

Referring to the data presented in Table 3, it is possible to mitigate the overall GHG emissions generated by the pizzeria's activities by mainly addressing the impact of some selected ingredients. It is advisable to focus on reducing the impact of PDO buffalo mozzarella, followed in decreasing order by mozzarella and Grana Padano

Table 3. Percentage relative change in the cradle-to-grave carbon footprint (CF) of the Neapolitan pizzeria compared to the reference value ($\Delta CF/CF_R$) as referred to a ±50% relative change in the emission factor (EF_i) of each generic i-th ingredient or energy source compared to the corresponding reference value (EF_{iR}).

Energy or Ingredient Source	($\Delta CF/CF_R$) [%]
Electricity	±2.11
Woodfire	±0.16
Tap water	±0.10
Soft wheat flour	±1.30
Compressed yeast	±0.001
Peeled tomatoes	±1.77
Fresh tomatoes	±0.05
Buffalo mozzarella PDO	±9.53
Fresh cow mozzarella cheese	±4.42
Grana Padano cheese	±1.65
Table salt	±0.01
Extra virgin olive oil	±0.34
Oregano	±0.001
Garlic	±0.01
Basil leaves	±0.02
Mineral water (75-cL glass bottles)	±0.82
Beer (75-cL glass bottles)	±1.30
Beer (33-cL glass bottles)	±0.58
Coca-Cola (33-cL glass bottles)	±0.50
Coca-Cola Zero (33-cL aluminum cans)	±0.03
Fanta (33-cL aluminum cans)	±0.17

cheeses. For these products, it is necessary to reduce the impacts of the agricultural phases, focusing mainly on reducing methane emissions, improving manure management, and adopting optimal fertilization techniques.

As a second priority, it is necessary to address the environmental impact of the beverages served at the pizzeria, such as beer and mineral water packaged in 75-cL glass bottles (Table 3). Following the suggestion to reduce the contribution of packaging materials to the carbon footprint of beer by replacing the currently used single-use glass bottles with lighter, reusable, or recycled containers (Cimini and Moresi, 2021), the pizzeria could avoid serving beer in glass bottles or aluminum cans, by replacing it with beer in 30-L stainless steel kegs, with a carbon footprint approximately half of that of beer packaged in 66-cL glass bottles (Cimini and Moresi, 2016), or with beer in 30-L KeyKegs, made from 100% recycled polyethylene terephthalate (Cimini and Moresi, 2021). This choice could also significantly reduce the impact of the transportation phase.

Thirdly, the contribution of packaging to the carbon footprint could be reduced by replacing single-use containers (wooden crates for fresh tomatoes, polystyrene trays for buffalo mozzarella, etc.) with reusable and recyclable containers. To further support this option, it is important to note that the distance these empty containers need to travel for cleaning and reuse is generally less than 50 km, and the amount of detergent required is quite limited.

Fourthly, the transportation phase significantly contributes to the carbon footprint, primarily due to the delivery of most packaged ingredients by LCVs. These vehicles emit approximately 1.83 kg CO_{2e} per metric ton-kilometer according to the EcoInvent v. 3.7 database. The use of new diesel vans, compliant with the emission target of 95 g CO_{2e}/km set by EU Regulation 2019/631 (EC, 2019), would result in a reduced emission factor of 79 g CO_{2e} per ton-kilometer. Under these conditions, GHG emissions from transportation would be reduced by approximately 33% (Falciano *et al.*, 2022).

Fifthly, it's noteworthy that in 2019, the electricity utilized by the pizzeria was supplied by the Italian electricity grid. Approximately, 52% of this grid's energy stemmed from the combustion of fossil sources, primarily natural gas, while 37.6% was derived from renewable sources like photovoltaic, hydroelectric, and wind energy (Terna, 2022). To notably diminish the contribution of electricity to the carbon footprint, installing photovoltaic panels or procuring energy from green energy suppliers could be highly effective strategies.

Finally, to mitigate the environmental impact of fugitive emissions, it is advisable to replace the refrigerators in the restaurant that currently use the R404a refrigerant with new ones loaded with propane (R290). Propane is a refrigerant gas with virtually zero ozone depletion potential and a low global warming potential of approximately 3 kg CO_{2e}/kg. This substitution could result in a reduction of the impact of fugitive emissions by at least three orders of magnitude. In addition, the higher energy efficiency of such appliances would contribute to lower the restaurant's electricity consumption.

An important environmental concern arises from the significant formation of fine particulate matter ($PM_{2.5}$) resulting from the combustion of wood in pizza ovens. Buonanno *et al.* (2010) reported concentrations ranging from 12 to 368 mg/m^3, with an average value of 95 mg/m^3, significantly exceeding the average level (15 μg/m^3) recommended by the World Health Organization (WHO, 2021) for indoor settings within a 24-h period. It is noteworthy that Falciano *et al.* (2022) measured a $PM_{2.5}$ concentration of 12.7±2.4 mg/m^3 at the chimney exit of the pilot wood-fired oven. This highlights the importance of equipping wood-fired pizza ovens with flue gas and soot purification systems capable of filtering and purifying smoke, thereby removing all soot particles released from the chimneys through water sprays.

To mitigate air pollution inside pizzerias, the *Associazione Verace Pizza Napoletana* (https://www.pizzanapoletana.org/it/) currently allows the replacement of traditional wood-fired ovens with certified gas or electric ovens, such as for instance the so-called *Scugnizzonapoletano* electric oven.

The pizzeria under study used a wood-fired oven fueled with approximately 4 kg/h of oak logs, generating a combustion power of 20 kW. The corresponding electric oven employs nickel-chromium electric resistors distributed on the vault and floor of the oven, delivering respective electric powers of 8 and 3 kW. Considering that the pizzeria operates on average for 5 h per day, the electric oven is turned on at least 2 h before, adjusting the power to the maximum level to bring the vault and floor to the appropriate pizza baking temperatures. In the following 5 h, the electric resistors of the vault or the floor are modulated between the zero and maximum power levels. The latter level is maintained, respectively, for 7 s every 10 s, or for 3 s every 10 s. This results in an electricity consumption of approximately 55 kWh/day, equivalent to an annual consumption of around 18 MWh.

Table 2 shows the GHG emissions associated with the main life cycle phases of the pizzeria when using an electric oven with the same pizza production capacity as the wood-fired oven.

The carbon footprint associated with serving a pizza by the pizzeria increased by 1.3%, from approximately 3149 to 3190 g CO_{2e}. This increase is mainly attributable to the increased contribution of electricity consumption from 6.3% to 9.2%, partially offset by the decrease in the contribution of the transportation phase from 8.5% to 7.2%, due to the elimination of oak log procurement and wood ash disposal. In spite of a slight increase in the carbon footprint, using an electric oven for pizza would have the advantage of avoiding the emission of fine particles into the air, significantly reducing air pollution levels both inside and outside the pizzeria. Of course, the adoption of renewable electricity could further reduce the environmental impact of the pizzeria.

In conclusion, in accordance with the guidelines proposed by Messier (2016), Tables 2 and 3 are useful tools for identifying the most relevant emission sources, providing pizzeria operators with valuable information that can be used to develop targeted reduction strategies.

Cradle-to-Grave Environmental Impact of the *True Neapolitan Pizza*

To calculate the cradle-to-grave carbon footprint of the various variants of the True Neapolitan Pizza, in accordance with the PAS 2050 standard method, the emission contributions of certain lifecycle phases, such as energy consumption, refrigerant gas leaks, detergent production, and wastewater treatment, were assumed to be the same as those found in the case of the typical pizzeria mentioned above, while the emission contribution of the ingredients actually used and their respective packaging were *ad hoc* recalculated.

Table 4 presents both the quantity (SUM) of each ingredient present in its sales unit and the type and mass (PM) of the respective packaging, highlighting the contribution of packaging materials per unit of ingredient used.

The impact of the raw material logistics, as detailed by Falciano *et al.* (2022), was recalculated considering the transport of all raw materials and packaging from production sites or regional distribution centers to the restaurant, assuming an average distance of 100 km via LCV, while light trucks were used for transporting firewood. Postconsumer waste (organic, unsorted, and packaging waste) was disposed of at the collection center (average distance of 50 km) using waste collection trucks, according to the aforementioned scenario of Italian urban solid waste management (Ronchi and Nepi, 2020).

Table 5 shows the estimated values of GHG emissions associated with various stages of the life cycle of the True Neapolitan Pizza. Overall, GHG emissions associated with the preparation and consumption of a Marinara pizza amounted to approximately 1.7 kg CO_{2e}/kg, while for 1 kg of Margherita pizza, they ranged from 3.3 to 3.4 kg CO_{2e} or from 4.0 to 4.2 kg CO_{2e} if topped with mozzarella cheese or PDO buffalo mozzarella, respectively. As expected, the carbon footprint of the Marinara pizza was significantly lower, especially when compared to that of the Margherita pizza topped with buffalo mozzarella. This diversity in GHG emissions stemmed from the use of condiments of either vegetable or animal origin (mainly mozzarella cheese or buffalo mozzarella).

Table 4. Main sales unit mass (SUM), and type and mass (PM) of the primary packaging for each raw material used in the preparation of the True Neapolitan Pizza, as well as the mass packaging-to-product ratio (PM/SUM).

Raw Material	Mass Sale Unit (SUM) [kg]	Packaging		PM/SUM [g/kg]
		type	mass (PM) [g]	
Oak logs	800	EPAL wood pallet	25,000	31.25
Soft wheat flour	25	Paper bag	115	4.60
Compressed yeast	0.025	Multilayer	1	0.04
Peeled tomatoes	0.4	Metal can	70	0.18
PDO buffalo mozzarella	3	PS tray	161	53.67
TSG mozzarella cheese	1	PE bag	1	1.0
Grana Padano cheese	2	PE bag	3	1.5
Kitchen salt	1	Cardboard box	33	33.0
Extra virgin olive oil	~5	Metal can	232	46.4
Oregano	1	PET jar	186	186.0
Garlic	0.1	PE net	1	10.0
Basil	0.3	PE tray	597	1990.0
Pizza box	–	Multilayer box	168	-

EPAL, European Pallet Association; PE, polyethylene; PET, polyethylene terephthalate; PS, polystyrene.

Table 5. Contribution of GHG emissions from various life cycle stages of the True Neapolitan Pizza (TSG) in Marinara and Margherita variants (topped with mozzarella cheese, MC, or buffalo mozzarella, BM).

Life Cycle Phase	Carbon Footprint [g CO_{2e}/pizza]					
	Marinara		Margherita + MC		Margherita + BM	
	min	max	min	max	min	max
Ingredient production	208	266	945	1190	1227	1543
Beverage production	33	47	40	55	58	77
Transportation	66	77	80	94	81	95
Detergent production	5					
Electricity use	198					
Firewood use	15					
Refrigerant leakage	24					
Wastewater treatment	16					
Waste disposal	9	10	15	19	20	25
Overall carbon footprint (CF)	574	659	1339	1617	1664	1998
Specific carbon footprint [kg CO_{2e}/kg]	*1.72*	*1.70*	*3.28*	*3.42*	*4.03*	*4.22*

It is important to note that the carbon footprints calculated for the different variants of the True Neapolitan Pizza cannot be directly compared, not only due to the different unit mass but also due to the different composition that affects their relative energy value. By extracting the composition of various ingredients from the food composition tables of the Italian food and nutrition center (https://www.alimentinutrizione.it/sezioni/tabelle-nutrizionali), Table 6 shows the protein, fat, and carbohydrate composition, as well as the energy value of the different types of pizza under examination, from which the specific carbon footprint values are obtained.

For 1 g of raw protein intake, GHG emissions are minimal (32 g) in the case of Marinara pizza and maximum (50 g) in the case of Margherita pizza topped with buffalo mozzarella. Conversely, the intake of 1 g of fats results in emissions of 65–73 g CO_{2e} in the case of Marinara pizza and 56–58 g CO_{2e} in the case of Margherita pizza topped with buffalo mozzarella. At an equal energy intake of 1 kcal, CO_{2e} emissions are minimal (1 g) in the case of Marinara pizza and maximum (2 g) in the case of Margherita pizza topped with buffalo mozzarella.

Conclusions

In this study, the cradle-to-grave carbon footprint of pizza meals served in a typical Neapolitan pizzeria was estimated using the PAS 2050 method. Pizzas cooked in a traditional wood-fired oven had a carbon footprint of approximately 3.15 kg CO_{2e}/kg, while those cooked in an electric oven certified by the *Associazione Verace Pizza Napoletana* showed a slightly higher footprint of 3.19 kg CO_{2e}/kg.

To mitigate the environmental impact of pizzerias, several sustainable practices (i.e., adopting more sustainable

Table 6. Protein, fat, and carbohydrate composition, and energy value (EV) of True Neapolitan Pizza (TSG) in Marinara and Margherita variants (topped with mozzarella cheese, MC, or with buffalo mozzarella, BM), and specific carbon footprint values.

Parameter	Unit	Marinara Pizza		Margherita Pizza+MC		Margherita Pizza+BM	
		min	max	min	max	min	max
Raw protein	[g/pizza]	18	21	34.7	41.7	33.1	39.7
Fat	[g/pizza]	8	10	24.8	31.6	28.8	36.5
Carbohydrates	[g/pizza]	107	121	107	122	107	121
EV	[kcal/pizza]	570	661	790	938	818	973
CF	[g CO_{2e}/pizza]	574	659	1339	1617	1664	1998
CF_P	[g CO_{2e}/g prot]	32	32	39	39	50	50
CF_F	[g CO_{2e}/g fat]	73	65	54	51	58	55
CF_{EV}	[g CO_{2e}/kcal]	1.0	1.0	1.7	1.7	2.0	2.1

production methods for cheeses, using lighter and reusable containers for beverages and fresh vegetables, employing commercial vans compliant with EC emission standards, utilizing electric ovens to reduce particle emissions, and transitioning to renewable energy sources) were identified.

Moreover, distinct disparities in the environmental impact among the variants of True Neapolitan Pizza were revealed. For example, the Marinara pizza had a carbon footprint of approximately 1.7 kg CO_{2e}/kg, roughly half that of the Margherita pizza topped with mozzarella cheese. Adding buffalo mozzarella to the Margherita increased its carbon footprint to 4.2 kg CO_{2e}/kg. These differences are primarily attributed to ingredient choices, which not only affect protein and lipid levels and, consequently, the overall energy value, but also shape the sustainability profile of pizza offerings. These findings can pave the way for informed decisions toward a greener culinary landscape. However, further research utilizing a multi-environmental life cycle analysis is warranted to comprehensively assess the environmental impact of pizza production and consumption.

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