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The Neapolitan Pizza: processing, distribution, innovation and environmental aspects

Supervisor

Ch.mo Prof. Paolo Masi

Co-supervisors

Ch.mo Prof. Mauro Moresi

Prof.ssa Annalisa Romano

PhD student

Dott. Falciano Aniello

Coordinator

Prof.ssa Amalia Barone

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Thesis committee

Supervisor

Prof. Paolo Masi

Professor of food science and technology

University of Naples Federico II

Co-supervisor

Prof. Mauro Moresi

Professor of food science and technology

University of Tuscia

Co-supervisor

Prof.ssa Annalisa Romano

Professor of food science and technology

University of Naples Federico II

Summary

Abstract

Not only is the Neapolitan pizza one of the most popular and well-known products of the Italian gastronomy, but also is one of the pillars of the food service and catering industry.

Recently, its Disciplinary of Production which defines the standards for raw materials and technology parameters was encoded by the Official Journal of the Italian Republic n. 56/2010. In addition, the importance of the ‘art’ of Neapolitan pizza making has been inscribed in the List of Intangible Cultural Heritage of Humanity (Jeju, South Corea, 7 December 2017).

The typicality of Neapolitan pizza essentially lies in the technology used in the preparation of leavened dough, raw materials used to garnish and its rapid cooking in a wood-fired oven.

Despite its worldwide popularity and economic relevance, Neapolitan pizza is a topic that has attracted little interest from the scientific community.

While from a scientific point of view Neapolitan pizza is a neglected topic, from the media point of view there is growing attention towards the potential impact of the consumption of pizzas made according to the traditional technology on human health. The information generally disclosed, even if unsupported by scientific evidence, has negative economic effects.

The introduction of some innovations in the Neapolitan pizza production process, such as the use of sourdough, alternative flours, medium-long shelf-life ready-to-use dough balls, new pizza service systems, as well as a scientific analysis of the phenomena occurring during the Neapolitan pizza baking in traditional wood-burning ovens, might improve the qualitative aspects of the Neapolitan pizza, develop alternative baking systems, and achieve a circular economy to slash food waste formation.

Therefore, the purpose of this doctoral thesis was to investigate the different aspects of the Neapolitan pizza production process, as reported below.

In order to develop and characterize a liquid sourdough to be used in the Neapolitan pizza production process, it was investigated the effect of refreshment on the growth of endogenous microorganisms during the preparation of liquid mother yeast (DY 200) incubated for 6 days using wheat flours from two different geographical locations (i.e., Italian and Mexican flours), and their effects on physicochemical properties. The results showed that there is no need for refreshment during the first 6 days of incubation.

The use of jujube powder as alternative flour was evaluated. The idea was to exploit the beneficial properties of jujube powder by using it to make composite flours in the development of a functional pizza base, produced in the Neapolitan style. The total phenolic and antioxidant properties of the pizza base, texture and color analysis of the samples were assessed. The results demonstrated that jujube powder could be considered as a potential healthy functional ingredient, without promoting adverse effects on the physical and sensory characteristics of pizza.

The possibility of developing ready-to-use dough balls with a medium-high shelf life using low refrigeration temperatures was investigated. The samples were evaluated as a function of the leavening time, and after 28 days of storage. The chemical-physical and microbiological parameters did not show any significant differences, and the dough balls with a longer leavening time (16 h) showed characteristics similar to the fresh one and good rolling properties.

The operation of a pilot-scale wood-fired pizza oven from its start-up phase to firing was characterized to evaluate its thermal efficiency. To manage the firing of the bricks, the oven was lit at a wood flow rate (Q_{fw}) of 3 kg/h for just 1 hour on the 1st day, for 2 hours on the 2nd day, for 4 hours on the 3rd day and for about 8 hours on 4. Regardless of how often it was fired, after 4-6 hours the temperature of the vault or the floor of the furnace approached an equilibrium value of 546 ± 53 °C or 453 ± 32 °C, respectively. The initial temperature gradient of the kiln floor was found to be linearly related to Q_{fw}, while the maximum floor temperature tended to an asymptotic value of 629 ± 43 °C at Q_{fw}=9 kg/h. The known water boiling test has been adapted to evaluate the heat absorbed by a predetermined quantity of water when the pizza oven was operating in pseudo-stationary conditions at Q_{fw}=3 kg/h. The thermal efficiency of this oven was 13 ± 4%, a value further confirmed by other baking tests with four different white and tomato pizza products.

The combustion reaction of the oak logs of a wood-burning oven on a pilot scale and maintained in quasi-stationary conditions was modelled, and the composition of the fumes was measured. The external temperatures of the wall and floor of the oven were thermographically scanned, so that it was possible to verify the material and energy balances and therefore evaluate that the heat loss rates through the fumes and insulated kiln chamber were respectively equal to 46 % and 26% of the energy supplied by the combustion of wood. The enthalpy accumulation rate in the internal chamber of the oven was approximately 3.4 kW, sufficient to keep the vault and floor temperatures of the oven almost constant, but also to cook one or two pizzas at the same time. This speed was predicted by contemplating the simultaneous heat transfer mechanisms of radiation and convection between the furnace vault and floor surfaces. The effectiveness of the semi-empirical modeling developed here was further verified by reconstructing quite accurately the time course of water heating in aluminum pans with a diameter close to that of a typical Neapolitan pizza. The heat flow from the furnace roof to the water tank was approximately 73% to 15% radiative and convective, while the remaining 12% was conductive from the furnace floor.

The phenomena that occur during the cooking of the Neapolitan pizza in a wood-burning oven on a pilot scale operating in almost stationary conditions such as: the rise of the rim, the heat and mass transfer, and the degree of browning and the apparence of burning spots of pizza samples garnished in different ways were studied since the heat transfer during the cooking of the pizza is not at all uniform and is particularly complex. Regardless of the garnish ingredients used, the rim height increased from 0.8 ± 0.1 cm to 2.3 ± 0.3 cm in just 80 s of cooking. During the cooking of the pizza, the temperature of the oven floor remained practically constant (439 ± 3 °C), while that under each pizza decreased the faster the greater the mass of the pizza placed on it. The maximum temperature of the bottom of the pizza was 100 ± 9 °C, while that of the top side of the pizza varied according to the type of topping and the different humidity content and emissivity of the ingredients. The overall weight loss was about 10 g in all types of pizza examined. Thanks to the use of the IRIS electronic eye, it was possible to quantify the brown or black areas. The upper area had higher degrees of browning and blackening than the lower one, whose maximum values of about 26 and 8% are observed respectively in the white pizza as it is. These results are needed to develop an accurate modeling and control strategy to reduce variability and maximize quality attributes of Neapolitan pizza.

The cradle-to-grave carbon footprint of the different versions of the True Neapolitan Pizza was estimated in accordance with the PAS 2050 standard method. By assuming the same specific greenhouse gas emissions associated to some life cycle phases in the case of a typical Neapolitan *pizzeria* (i.e., energy consumption, refrigerant gas leakage, detergent production and wastewater treatment), the Marinara and Margherita pizza carbon footprint was about 4 and 5.1 kg CO_{2e}/kg, respectively. By garnishing the latter with buffalo mozzarella cheese, its footprint would increase up to ~8.4 kg CO_{2e}/kg. Such difference in their environmental impacts mainly derives from the use of condiments of only vegetable or even animal origin, these varying the protein and lipid contents and consequently the energy value of each pizza type.

Finally, it was evaluated how the material and sensory properties change over time from the moment the pizza is taken out of the oven and placed in a cardboard box and when it is eaten at home. Furthermore, to avoid having to dispose of the unused balls of leavened dough at the end of the daily work activity in the pizzeria, the feasibility of a new take-away pizza service was evaluated with the final aim of improving the sensorial quality of the pizza perceived at home. These balls of dough were transformed into pizzas, cooked in a wood-burning oven, quickly frozen, packaged, stored in a freezer until sold, transported or delivered to your home, and finally heated in a domestic oven. The sensory acceptability of frozen pizza samples was compared to that of freshly baked pizza samples, as such, after queuing on a plate for only 5 minutes or being stored in cardboard boxes for 10, 20 or 30 minutes. These boxes slowed down the cooling of the pizza but improved its gumminess as the storage time lengthened. While panelists generally preferred freshly baked pizza, the frozen pizza samples were the far favorites over all of the other samples examined here. The cradle-to-grave carbon footprint and cost of frozen pizza were also assessed to show how such a food product, which would have been wasted, could be profitably converted into a high-quality alternative take-away pizza service.

Riassunto

La Pizza Napoletana, oltre ad essere uno dei prodotti più apprezzati e conosciuti della gastronomia italiana, è uno dei pilastri della ristorazione.

Di recente, è stato codificato un Disciplinare di Produzione che definisce gli standard per le materie prime e i parametri tecnologici (G.U. Repubblica Italiana n.56/2010). Inoltre, l'importanza dell'"arte" di fare la pizza napoletana è stata riconosciuta come "Patrimonio Culturale Immateriale dell'Umanità" (Jeju, Corea del Sud, 7 dicembre 2017).

La tipicità della pizza napoletana risiede essenzialmente nella tecnologia utilizzata, nella preparazione dell'impasto lievitato, nelle materie prime utilizzate per guarnire e nella cottura rapida nel forno a legna.

Nonostante la popolarità mondiale e la sua rilevanza economica, la pizza Napoletana è un argomento che ha suscitato, sin qui, scarso interesse da parte della comunità scientifica.

Mentre da un punto di vista scientifico la pizza napoletana è un argomento trascurato, dal punto di vista mediatico si registra una crescente attenzione sul potenziale impatto che il consumo di pizze, prodotte secondo la tecnologia tradizionale, può avere sulla salute umana. Le informazioni che vengono divulgate, pur non essendo suffragate da riscontri scientifici, hanno, sovente, ricadute economiche negative.

L'introduzione di alcune innovazioni nel processo di produzione della pizza napoletana come l'utilizzo di lievito madre, farine alternative, impasti per pizza a media-lunga shelf-life pronti all'uso, nuovi sistemi di servire la pizza da asporto, e le conoscenze scientifiche sui fenomeni che si verificano durante la fase di cottura della pizza napoletana nel tradizionale forno a legna, utile anche per sviluppare sistemi di cottura alternativi, possono migliorare ulteriormente gli aspetti qualitativi della pizza napoletana e produrre benefici in termini di impatto ambientale.

Pertanto, lo scopo della presente tesi di dottorato è stato quello di indagare su diversi aspetti del processo di produzione della pizza napoletana, che verranno mostrati in seguito.

Al fine di sviluppare e caratterizzare un sourdough liquido da utilizzare nel processo di produzione della pizza napoletana, si studiato l'effetto dei rinfreschi sulla crescita di microrganismi endogeni durante la preparazione di lievito madre liquido (DY 200) incubato per 6 giorni utilizzando farine di frumento provenienti da due diverse località geografiche (farina italiana e messicana), e i loro effetti su alcune proprietà fisico-chimiche. I risultati hanno mostrato che nei primi 6 giorni di incubazione non è necessario effettuare rinfreschi.

È stato valutato l'effetto della farina di giuggiola da utilizzare come ingrediente nella preparazione d'impasti per pizza. L'idea era di sfruttare le proprietà benefiche della farina di giuggiola utilizzandola per realizzare farine composite nello sviluppo di una base per pizza funzionale, prodotta alla maniera napoletana. Sono stati valutati i composti fenolici totali e le proprietà antiossidanti della base della pizza, la consistenza e il colore dei campioni. I risultati hanno dimostrato che la farina di giuggiola potrebbe essere considerata un potenziale ingrediente funzionale, senza promuovere effetti negativi e modificare le caratteristiche fisiche e sensoriali delle pizze.

È stata studiata la possibilità di sviluppare panetti di pasta pronti all'uso con una shelf life medio-alta utilizzando basse temperature di refrigerazione. I campioni sono stati valutati in funzione del tempo di lievitazione, e dopo 28 giorni di conservazione. I parametri chimico-fisici e microbiologici non hanno mostrato differenze significative, e gli impasti con un tempo di lievitazione più lungo (16 h) hanno mostrato caratteristiche simili al prodotto fresco e buone proprietà di laminazione.

È stato caratterizzato il funzionamento di un forno per pizza a legna su scala pilota dalla sua fase di avviamento fino alla messa a regime per valutarne l'efficienza termica. Per gestire gli shock termici cui sonoo soggetti i mattoni refrattari usati per la costruzione, il forno è stato acceso ad una portata di legna (Qfw) di 3 kg/h per 1 sola ora il 1° giorno, per 2 ore il 2° giorno, per 4 ore il 3° giorno e per circa 8 ore il 4° giorno. Indipendentemente dalla sua frequenza di accensione, dopo 4-6 ore la temperatura della volta e della platea del forno si è avvicinata a un valore di equilibrio di 546 ± 53 °C o 453 ± 32 °C, rispettivamente. Il gradiente di temperatura iniziale della platea del forno è risultato essere linearmente correlato a Qfw, mentre la temperatura massima della volta tendeva ad un valore asintotico di 629 ± 43 °C a Qfw=9 kg/h. Il test di evaporazione dell'acqua è stato adattato per valutare il calore assorbito da una prefissata quantità di acqua quando il forno per pizza funzionava in condizioni pseudo-stazionarie a Qfw=3 kg/h. Il rendimento termico di questo forno è stato del 13 ± 4%, valore ulteriormente confermato da altre prove di cottura di cottura eseguite adoperando quattro diverse tipologie di pizza.

È stata modellata la reazione di combustione dei ceppi di quercia in un forno a legna su scala pilota e mantenuto in condizioni quasi stazionarie, ed è stata misurata la composizione dei fumi. Sono state scansionate termograficamente le temperature esterne della parete e del pavimento del forno, cosicché è stato possibile verificare i bilanci di materia ed energia e quindi valutare che i tassi di perdita di calore attraverso i fumi e la camera del forno coibentata erano rispettivamente pari al 46% e al 26% dell'energia fornita dalla combustione della legna. Il tasso di accumulo entalpico nella camera interna del forno è stato di circa 3,4 kW, sufficiente a mantenere pressoché costanti non solo le temperature di volta e platea del forno, ma anche di cuocere una o due pizze contemporaneamente. Tale velocità è stata prevista contemplando i meccanismi simultanei di trasferimento del calore di irraggiamento e convezione tra la volta del forno e le superfici del pavimento. L'efficacia della modellazione semi-empirica qui sviluppata è stata ulteriormente verificata ricostruendo in modo abbastanza accurato l'andamento temporale del riscaldamento dell'acqua in teglie di alluminio con un diametro vicino a quello di una tipica pizza napoletana. Il flusso di calore dalla volta del forno alla teglia contenente l'acqua era di tipo radiativo e convettivo per circa il 73% e il 15% rispettivamente, mentre il restante 12% era di tipo conduttivo dalla platea del forno

Sono stati studiati i fenomeni che si verificano durante la cottura della pizza Napoletana in un forno a legna su scala pilota operante in condizioni pressoché stazionarie come l'evoluzione del cornicione, il trasferimento di calore e massa, il grado di doratura e bruciatura dei campioni di pizza guarnite in modi diversi, in quanto la trasmissione del calore durante la cottura della pizza non è affatto uniforme ed è particolarmente complessa. Indipendentemente dagli ingredienti utilizzati per guarnire, l'altezza del cornicione è aumentata da 0,8 ± 0,1 cm a 2,3 ± 0,3 cm in soli 80 s di cottura. Durante la cottura della pizza, la temperatura del piano del forno è rimasta pressoché costante (439 ± 3 °C), mentre quella sotto ogni pizza è diminuita tanto più velocemente quanto maggiore è la massa della pizza appoggiata su di essa. La temperatura massima del lato inferiore della pizza è stata di 100 ± 9 °C, mentre quella della parte superiore della pizza variava a seconda del tipo di farcitura e del diverso contenuto di umidità ed emissività degli ingredienti del topping. La perdita di peso complessiva è stata di circa 10 g in tutti i tipi di pizza esaminati. Grazie all'utilizzo dell'occhio elettronico IRIS è stato possibile quantificare il grado di imbrunimento e bruciatura. La zona superiore presentava gradi di imbrunimento e bruciatura maggiori rispetto a quella inferiore, i cui valori massimi di circa 26 e 8% si osservano rispettivamente nella pizza bianca tal quale. Questi risultati sono necessari per sviluppare un'accurata strategia di modellazione e controllo per ridurre la variabilità e massimizzare gli attributi di qualità della pizza napoletana

Si è stimata l’impronta di carbonio dalla culla alla tomba delle diverse versioni della Pizza Napoletana Verace conformemente al metodo standard PAS 2050. Assumendo gli stessi contributi emissivi riscontrati nel caso di una pizzeria tipica napoletana per alcune fasi del ciclo di vita (consumi energetici, perdite di gas refrigeranti, produzione di detersivi e trattamento delle acque reflue). Il carbon footprint della pizza Marinara è risultato dell’ordine di 1,7 kg CO2e/kg, pari a circa la metà di quello della pizza Margherita guarnita con fiordi-latte. Per quest’ultima, il condimento con mozzarella di bufala ne aumenterebbe l’impronta a ~8,4 kg CO2e/kg. Il diverso impatto ambientale deriva soprattutto dall’impiego di condimenti di origine solo vegetale od anche animale, che ne modificano i tenori proteico e lipidico e di conseguenza il valore energetico.

Infine, è stato valutato come cambiano le proprietà chimico-fisiche e sensoriali al trascorrere del tempo dal momento in cui la pizza viene sfornata e messa in una scatola di cartone e il momento del suo consumo a casa. Inoltre, per evitare di smaltire i panetti di pasta lievitata inutilizzate al termine della quotidiana attività lavorativa in pizzeria, è stata valutata la fattibilità di un nuovo servizio di pizza da asporto con l'obiettivo finale di migliorare la qualità sensoriale della pizza percepita a casa. Tali palline di pasta venivano trasformate in pizze, cotte nel forno a legna, rapidamente congelate, confezionate, conservate in congelatore fino alla vendita, al trasporto o alla consegna a domicilio e infine riscaldate in un forno domestico. L'accettabilità sensoriale dei campioni di pizza congelata è stata confrontata con quella dei campioni di pizza appena sfornata, in quanto tali, dopo la sosta in un piatto per 5 minuti o essere stati conservati in scatole di cartone per 10, 20 o 30 minuti. La permanenza nelle scatole rallenta il raffreddamento della pizza ma ne aumentala gommosità con il prolungarsi del tempo di conservazione. Anche se i consumatori generalmente preferivano la pizza appena sfornata, i campioni di pizza surgelata erano di gran lunga i preferiti rispetto a tutti gli altri campioni qui esaminati. Sono stati valutati anche l'impronta di carbonio dalla culla alla tomba e il costo della pizza surgelata per mostrare come un tale prodotto alimentare, che sarebbe stato sprecato, potrebbe essere proficuamente convertito in un servizio di pizza da asporto alternativo di alta qualità.

Chapter 1

General Introduction

Neapolitan pizza is one of the most popular products of the Italian gastronomy.

Its spread around the world has led to the development of numerous variants of the original technology, adapting the process to different consumer tastes and processing techniques compatible with regulations in force in various regions and countries. Although different, the ways to make the pizza is based on a few steps: the preparation of the dough and its leavening, the potioning of the dough in balls, a second leavening stage, the lamination of the dough ball obtained, the garnishing step and the final cooking in wood-fired oven. The way in which these operations are made distinguish the Neapolitan pizza from the others version.

To protect the art of making pizza at "Neapolitan way", the European Commission Regulation no. 97/2010 (EC, 2010) entered the name Pizza Napoletana in the register of traditional specialities guaranteed (TSG) of Class 2.3 (Confectionery, bread, pastry, cakes, biscuits, and other baker’s wares) to define and thus preserve its original characteristics, and 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 (UNESCO, 2017).

However, the disciplinary of production of the Neapolitan pizza TSG leaves wide margins of discretion on both materials used in making dough and the ways dough is made and it is leavened. On the other hand, it sets limits on the use of specific ingredients for the garnishing of the pizza, which appears dictated only by a protectionist spirit of some typical local productions and in some cases, they have no historic evidence. Indeed, they are anachronistic if we consider what make pizza a product of universal popularity is the variability of raw materials that can be used for garnish it. Furthermore, some types of pizza, although not foreseen by the disciplinary, they are fully part of the tradition.

The typicality of the Neapolitan pizza with respect to the different versions that have spread over time in Italy and abroad is not in the ingredients used to garnish the base but in the preparation of the leavened dough and in the cooking technique.

Pizza is one of the pillars of the catering industry which, only in Italy, counts 61000 pizzerias, 150000 employees and sales near 20 Giga euro per year. Despite the worldwide popularity and its economic relevance, Neapolitan pizza is a topic that has attracted little interest from the scientific community. At the beginning of the project, only a few works were registered by the reference databases SCOPUS and WOS, (Ciarmiello and Marrone 2016; Caporaso et al 2015; Coppola et al 1997) and only recently has a systematic examination of the relationships between the preparation technology, the characteristics of the ingredients and the quality perceived by consumers have appeared in the literature (Masi et al 2016).

While from a scientific point of view, Neapolitan pizza is a topic neglected, from the media point of view there is growing attention on potential impact that the consumption of pizzas, produced according to the traditional technology, may have on human health. The information even if they are not supported by scientific evidence, they often have negative economic effects, as well as generating confusion among consumers. For example, some news released through the media has produced some alarmism, in particular on the formation of associated harmful compounds due to cooking in wood-burning ovens (RAI broadcast, Reportage of 10/5/2014), with resulting in a sharp contraction in consumption corresponding to its own knock down. After all, the link between nutrition and health is one of the themes of greater relevance to which the specialized scientific community draws attention e in particular, as regards baked goods for large consumption.

As previously pointed out, the typicality of Neapolitan pizza lies essentially in the technology used in the preparation of leavened loaves and in rapid firing in refractory brick reverberatory ovens. Such ovens generally consist of a base of tuff and fire brick covered by a circular cooking floor over which is built a dome made of refractory materials to minimize heat dispersion. Their geometric dimensions allow the temperature of the cooking floor and vault to be kept at about 430 °C and 485 °C, guaranteeing the Neapolitan pizza cooking speed and typical actibutes characterized by a raised rim with very thin crust and irregular cooking, soft to the cut, with the typical flavor of well-cooked bread, and a central part finely alveolar soft, elastic, easily foldable with possible sporadic bubbles, more or less scorched, in the parts not covered by the topping ingredients.

The heat transfer during the cooking process of a wood-burning oven involves several mechanisms of heat energy transport at the same time. During the start-up phase, the combustion of the wood in the rear part of the oven allows the transfer of heat to the refractory bricks which are brought to the operating temperature. Heat is transmitted from the flame to the bricks essentially through two mechanisms: radiation and conduction.

During operation, combustion is slowed down and regulated to balance the heat dispersed in the environment and that absorbed by the pizza during cooking in order to maintain the temperature profile inside the oven constant over time. As regards the heat supplied by the oven to the pizza being cooked, it is transferred by conduction through the contact surface between the oven floor and the pizza, while by radiation and natural convection to the parts of the pizza not in direct contact with the oven floor.

The thermal power transmitted by conduction from the floor to the pizza, depends on the temperature difference between the floor and the base of the pizza, as well as on the thermal properties of the dough.

The power transmitted by radiation from the top of the oven to the top surface of the pizza will depend on the geometric characteristics of the oven, the properties (emissivity) of the construction materials, the geometry and thermal properties (emissivity) of the surface of the pizza, as well as the temperatures of the top surface of the oven and the surface of the pizza. Finally, the heat transmitted by convection will depend on the temperatures of the surface of the pizza and the surrounding air and on the convective transmission coefficient which depends on the properties of the air that touches the exposed surface of the pizza.

All these mechanisms evolve in transitory conditions since the temperatures of the pizza, the floor and the air touching the surface change significantly during cooking.

From this brief analysis the cooking process is not linked to the way in which the heat energy is administered to the oven but rather to the temperature profile that is established in the oven during the cooking of the pizza.

The use of wood-fired ovens is, on one side, a prerequisite for assuring the main sensory characteristics of the Neapolitan pizza, on other side, it is the Achilles' heel of this food product because the wood burning is a significant source of air pollutants (carbon monoxide, polycyclic aromatic hydrocarbons, sulfur dioxide, nitrogen oxide, black carbon, and particulate matter, PM).

In fact, the use of the wood-fired oven has been banned in many cities and countries, and 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/), since this oven succeeded in a series of physical and sensory tests. Nevertheless, many traditionalists and especially the members of another opposing Association (Associazione Pizzaioli Napoletani) were skeptical about this type of oven and disapprove its use because it did not meet the general requirements.

An adequate modeling of the heat transmission phenomena that govern the rapid cooking of pizzas could generate the design of types of ovens capable of providing the same thermal power transmitted by traditional wood-fired ovens with a lower environmental impact, with less production of combustion fumes and more in compliance with the safety standards which in some territories prohibit the use of this type of oven.

While the specification fixes certain limitations, it does not explicitly prohibit the use of semi-finished products for the production of Neapolitan pizzas, for example, loaves produced outside the premises where the lamination, garnishing and cooking of the pizza takes place.

Even if the restaurant sector proves to be a driving factor for the economy, it has a negative effect on the environmental impact. The carbon footprint of restaurants appears to be high for several reasons related to the high proportion of food and energy wasted, the latter through excess heat and noise from inefficient heating equipment, fans, air conditioning systems, lights and refrigerators.

Italian people define pizza as a comfort food. According to the various players in the Food Delivery market, pizza was the first ready-to-eat food among the most ordered dishes. The home delivery or take-away pizza, as soon as it has been baked, is set into a cardboard box and delivered in no more than 30 minutes. The time elapsed between the pizza preparation and its consumption affects its sensory characteristics, which decrease as the transportation time increases. According to the disciplinary it is forbidden to freeze or store vacuum-packed pizza for which the only permitted method is the use of boxes, commonly in cardboard which, in addition to compromising the sensory quality of the pizza, present a high risk of releasing heavy metals and related disposition of the problems.

Aim and Thesis outline

The aim of this research was to introduce some innovations in the production process of Neapolitan pizza such us such as the use of liquid sourdoughs, alternative flours, medium-long shelf-life pizza doughs, and filling a gap in the scientific knowledge of the phenomena that occur during the cooking phase of the Neapolitan pizza in the traditional wood oven. This research aim was explored in a sequence of separate studies published or submitted to scientific journals.

The first chapter is a general introduction followed by 8 works reported as scientific papers that are published or submitted to scientific journals.

In order to develop and characterize a liquid sourdough to be used in the pizza production process, in the **Chapter 2** was investigated the effect of refreshments on the growth of endogenous microorganisms during the preparation of liquid sourdough (DY 200) using wheat flours from two different geographical locations (Italian and Mexican flour), and their effects on physicochemical properties.

In **Chapter 3** the effect of jujube powder to be used as an alternative flour was evaluated. In the study it was proposed to exploit the beneficial properties of jujube powder by using it to make composite flours in the development of a functional pizza base, produced in the Neapolitan way. The total phenolic and antioxidant properties of the pizza base, the texture, and color analysis of the samples were evaluated.

The Disciplinary of Production of Neapolitan Pizza TSG (n°56/2010), that defines the standards for raw materials and technological parameters, does not prohibit the possibility of using semi-finished products for the production of Neapolitan pizzas, or dough balls produced outside the premises where the rolling, garnishing and cooking of the pizza takes place, therefore in **Chapert 4** was to investigate on the possibility to develop an innovative technology to obtain a dough balls ready-to-use, with a medium-high shelf life useful for pizzas making compatible with the disciplinary of Pizza Napoletana production.

In **Chapter 5** was characterize the operation of a pilot-scale wood-fired pizza oven from its start-up phase (according to the procedure suggested by the manufacturer) to its baking operation to provide a basis for future modelling of novel pizza oven design. The well-known water boiling test, generally used to measure the thermal efficiency of cookstoves was adapted to measure the energy efficiency of the pizza oven in pseudo-steady state conditions when heating a prefixed amount of water or different pizza types, while in **Chapter 6** was to develop a semi-empirical model of a wood-fired pizza oven operating in quasi steady-state conditions. To this end, the first goal was to check for the material and energy balances upon modelling of the combustion reaction of oak logs, measuring the composition of flue gas, and scanning the temperatures of the external oven walls and floor via a thermal imaging camera. The second goal was to estimate the heat losses through flue gas and insulated oven chamber so as to derive the enthalpy accumulation rate in the internal oven chamber and attempt its mathematical prediction. By analogy with the water boiling tests used to evaluate the energy efficiency of domestic cooking appliances, the third goal was to perform several water heating tests to simulate the water heating profile via the heat transfer mechanisms of radiation, convection, and conduction, and thus evaluate the net energy transferable to pizza during baking.

In **Chapter 7** the phenomena that occur during the cooking of the Neapolitan pizza in a wood-burning oven on a pilot scale operating in almost stationary conditions were studied since the heat transfer during the cooking of the pizza is not at all uniform and is particularly complex. Therefore, the first aim of this work was to measure the different area sections of pizza covered or not by the main topping ingredients (i.e., tomato puree, sunflower oil, or mozzarella cheese), as well the growth of the raised rim, by image analysis. The second and third aims were to monitor the time course of the temperature of the aforementioned areas and pizza weight loss during the baking of pizza samples differently garnished. The final one was to monitor the evolution of the degree of browning or burning of the pizza samples undergoing baking by means of an electronic eye and develop a kinetic model able to describe the extent of browning and blackening areas as a function of time and temperature.

The **Chapter 8** reports the study carried out 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].

Whereas in Italy its consumption of pizza in restaurants or pizzerias is predominant, a growing percentage of consumers makes use of take-away pizza or home delivery service. In such cases uncontrolled heat and mass transfer processes occurring as the pizza is put in a cardboard box and delivered at home significantly affect the pizza sensory quality, therefore in **Chapter 9** a new takeaway layout was proposed. Specifically, the aim of the work was to compare the sensory acceptability of quick-frozen and reheated pizza in a domestic oven with that of freshly baked pizza samples, as served at the table immediately or after 5 minutes of queuing at the pizza counter, or packed in cardboard boxes for 10, 20 or 30 minutes. In addition, such comparison was extended to a few relevant chemico-physical parameters, namely the pizza thermal mapping, weight loss due to water vaporization and instrumental texture profile. Finally, the extra energy consumption associated to such a procedure was determined and used to perform a streamlined Life Cycle Assessment (LCA) to identify the related cradle-to-grave greenhouse gas (GHG) emissions in compliance with the Publicly Available Specification (PAS) 2050 standard method (BSI, 2011) and operating costs.

Finally, in **Chapter 10** the conclusions and future prospects are reported and summarized.

References

Albu, A., & Buculei, A. (2011). The study of the influence of the cardboard package on the quality of the food product. Case study-pizza packed in cardboard box. The USV Annals of Economics and Public Administration, 11(1), 40-48.

Ciarmiello, M., & Morrone, B. (2016). Analisi termica numerica di un forno elettrico per pizze napoletane. Giornale internazionale di calore e tecnologia, 34 (2), S351-S358.

Cimini, A., Moresi, M. (2022). Environmental impact of the main household cooking systems - A survey. Italian Journal of Food Science, 34 (1), 86–113.

Conchione, C., Picon, C., Bortolomeazzi, R., & Moret, S. (2020). Hydrocarbon contaminants in pizza boxes from the Italian market. Food Packaging and Shelf Life, 25, 100535.

EC (2010). Commission Regulation (EU) No. 97/2010. Entering a Name in the Register of Traditional SPECIALITIES guaranteed [Pizza Napoletana (TSG)]. Off. J. Eur. Union 2010. 34. 5. Available online: https://eur-lex.europa.eu/legalcontent/ EN/TXT/HTML/?uri=OJ:L:2010:034:FULL (accessed on 26 January 2022).

Grim RE, Johns WD (1951) Reactions accompanying the firing of brick. Journal American Ceramic Society, 34(3), 71-76.

Manhiça FA (2014) Efficiency of a Wood-Fired Bakery Oven–Improvement by Theoretical and Practical. Chalmers Tekniska Hogskola (Sweden).

Manhiça F. A., Lucas C., Richards T. (2012). Wood consumption and analysis of the bread baking process in wood-fired bakery ovens. Applied Thermal Engineering, 47, 63-72.

Masi, P., Romano, A., Coccia, E. (2015). The Neapolitan pizza. A Scientific Guide about the Artisanal Process; Doppiavoce: Napoli, Italy

UNESCO (United Nations Education. Scientific and Cultural Organization) (2017). Decision of the Intergovernmental Committee: 12.COM 11.B.17. 2017. Available online: https://ich.unesco.org/en/decisions/12.COM/11.B.17 (accessed on 26 January 2022).

Wong SY, Zhou W, Hua J (2007) CFD modelling of an industrial continuous bread-baking process involving U-movement. Journal of Food Engineering, 78(3), 888-896

Chapter 2

Effect of the refreshment on the liquid sourdough preparation

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Abstract

The aim of this work was to investigate the effect of refreshments on the growth of endogenous microorganisms during liquid sourdough preparation by using an Italian and Mexican wheat flours and its effects on the physico-chemical properties (pH, total titratable acidity, water activity, moisture content and reducing sugars). The liquid sourdoughs were prepared (DY 200) and incubated for 6 days at 20°C. The sourdoughs were refreshed every day and compared with the not-refreshed ones. Preliminary results showed that in the early stages of the microbial growth process, their population was greater in the sourdough made from the Mexican wheat flour than that of the Italian one. However, after 6 days, the microbial population was not significantly different in refreshed or not-refreshed samples for both sourdoughs (Italian and Mexican). Similarly, physicochemical properties did not show significant differences.

Keywords: backslopping; leavening agent; sourdough; spontaneous fermentation

Introduction

The art of baking is a very ancient technology. The beer foam was initially used for leavening of bread by ancient Egyptians, which was then replaced by sourdough (Carnevali et al., 2007); in fact the sourdough fermentation is one of the oldest cereal fermentations known by mankind. Sourdough is a mixture of wheat and/or rye flour and water, possibly with added salt, fermented by spontaneous lactic acid bacteria (LAB) and yeasts from the flour and environment. The microbial ecosystem var-ies from one sourdough to another depending on the geo-graphical position, which determines its acidifying and leavening capability. The microbial community makes the dough metabolically active and can be reactivated and optimised in time through consecutive refreshments (or re-buildings, replenishments, backslopping) (Corsetti and Settanni, 2007). The term 'refreshment' deals with the technique by which a dough made of flour, water, and sometimes other ingredients ferments spontaneously, and it is subsequently added as an inoculum to start the fermentation of a new mixture of flour and water or other ingredients.

The sourdough fermentation is a process with very com-plex mechanisms (Hammes and Gänzle, 1998; Thiele et al., 2002), and during fermentation carbohydrates and flour proteins undergo biochemical changes due to the action of microbial and indigenous enzymes (Spicher, 1983). The rate and magnitude of these changes greatly affect the sourdough properties and ultimately the qual-ity of the final baked product (Arendt et al., 2007). Many intrinsic properties of sourdough depend on the meta-bolic activities of its resident LAB: lactic fermentation, proteolysis and synthesis of volatile compounds, produc-tion of anti-mold, and antiropiness are among the most important activities during the fermentation of sour-dough (Gobbetti et al., 1999; Hammes and Gänzle, 1998). The fermentation of natural yeast consequently improves the dough properties, such as improving the volume, tex-ture, flavour and nutritional value of bread, delaying the staling process of bread, and protecting bread from mold and bacterial spoilage (De Vuyst and Vancanneyt, 2007). In fact, nowadays, its application is on the rise, and sour-dough is used in the production of a variety of products such as bread, pizza, cakes and crackers, as the improved quality of sourdough bakery products became an import-ant marketing tool (De Vuyst and Gänzle, 2005). Because fermentation can be performed as firm dough or as a liq-uid suspension of flour in water, sourdoughs can vary in its consistency. The ratio of flour and water is called the dough yield (DY) and is defined as: DY = (flour weight + water weight) × 100/flour weight. Following this approach, wheat sourdough with DY 160 is firm dough, while DY 200 is liquid sourdough (Decock and Cappelle, 2005). The liquid fermentation system is preferred by industries due to the following technological and analyt-ical advantages: (1) ease of management and reproduc-ibility under operating conditions; (2) easier control of fermentation parameters (e.g. temperature, pH, dough yield), and addition of nutrients (e.g. vitamins, peptides, carbohydrates) to condition microbial performance; (3) greater suitability to deal with microbial metabolism to obtain an optimal organoleptic profile; (4) greater suit-ability of application as natural starter without changes to the current bread formulations; and (5) increased suitability for use with different technologies to produce various baked goods (Carnevali et al., 2007). This work was carried out to investigate the effect of refreshments on the growth of endogenous microorganisms during the preparation of liquid sourdough (DY 200) incubated for 6 days using wheat flours from two different geographical locations (Italian and Mexican flour), and their effects on physicochemical properties, such as pH, total titratable acidity (TTA), water activity (aw), moisture content and reducing sugars.

Materials and Methods

Materials

For liquid sourdough preparation, two types of commercial wheat soft flour ‘00’ were used. The first flour type, Mexican flour, had a protein content of 11.1%, fat 2.2%, carbohydrates 71.6% and fibres 2.1% (San Antonio, Tres Estrellas, Toluca, México). The second one was the Italian flour, with a protein content of 11%, fat 2%, carbohydrates 72% and fibres 2% (La Molisana, Campobasso, Italy). The average moisture content of both flour types was 13%.

Chemicals

The following were used for the study: Plate count agar (PCA), potato dextrose agar (PDA) (BD, Franklin Lakes, NJ, USA), NaCl, NaOH, 3,5-dinitrosalicylic acid, sodium potassium tartrate, D-glucose. All chemicals used were of analytical grade, purchased from Sigma–Aldrich (St. Louis MO, USA).

Preparation of sourdoughs

Four types of liquid sourdough were prepared, two for each type of flour (Mexican and Italian flour). The liquid sourdough was prepared by mixing 500 g of flour with 500 mL of distilled water. The ingredients were mixed in a spiral mixer (Grilletta IM5, Famag s.r.l, Milano, Italy) for 10 min at speed 1, and the sourdoughs were fermented at 25°C ± 1 for 6 days. The samples were remixed every day for 5 min, and one sample for each type of flour was refreshed by removing 200 g of dough that was replaced with 100 g of flour plus 100 mL of distilled water. The ali-quots of samples, taken each day before remixing, were used for the following experiments. Table 1 shows the different samples prepared.

Table 1. Different samples of liquid sourdough.

DMNR	Sourdough not refreshed, prepared with Mexican flour
DMR	Sourdough refreshed, prepared with Mexican flour
DINR	Sourdough not refreshed, prepared with Italian flour
DIR	Sourdough refreshed prepared, with Italian flour

Determination of microbial populations

Serial dilutions of liquid sourdough samples in 0.85 % NaCl solution were used for determining the microbial count using the following media: PCA for estimation of total aerobic mesophilic bacteria and PDA containing 14 mg/L of tartaric acid, 50 mg/L of chloramphenicol, and 50 mg/L of Rose Bengal for yeasts and other fungi. Exactly, 1 mL of appropriate dilutions was pour plated in triplicate. Counts of total aerobic mesophilic bacteria were obtained after 48 h of incubation at 37°C, while the count of yeast and other fungi were obtained after 5 days of incubation at 30°C (Ben Omar and Ampe, 2000). All values were performed by counting on a colony counter. Results were calculated as the means of three determinations ± standard deviation.

Determination of pH, titratable acidity, moisture content, water activity and reducing sugars

The values of pH were determined using a pH meter equipped with an immersion probe, calibrated using standard solutions at pH 7.00, 4.01 and 10.00. After calibration, the electrode was rinsed with distilled water, dried and immersed in the sample.

Total titratable acidity was measured in 10 g sample, which was homogenised with 90 mL of distilled water for 3 min in a Stomacher apparatus (Seward, London, UK) and expressed as the amount (mL) of 0.1 M NaOH needed to achieve a pH of 8.3 (Ercolini *et al.*, 2013).

The moisture content using the thermobalance (XM 50 Precisa, Biltek, Esenler, Istanbul, Turkey) was calculated using the following Equation 1:

$$\text{Moisture content } (\%) = \frac{(\text{Mi} - \text{Mf})}{(\text{Mi})} \text{ X } 100 \qquad (1)$$

Mi – fresh weight, g

Mf – dry weight, g

The values of water activity (aw) were determined by Aqua-Lab instrument (CX-2, Decagon Devices, Pullman, WA, USA), calibrated with saturated KCl (aw = 0.984) standard. The determination was carried out by preparing a homogeneous sample of the product. The value was detected in balanced conditions and read directly on the screen.

Reducing sugars were determined using DNS assay (Wood *et al.*, 2012). DNS reagent contain 3,5-dinitrosalicylicacid (10 g/L), sodium potassium tartrate (30 g/L) and NaOH (16 g/L) and is stored in darkness at room temperature. D-glucose calibration curves were created covering appropriate ranges as described in the relevant sections. Each reaction contained 50 µL of sample and 1 mL of DNS reagent (1:20, sample:DNS reagent). The resulting solutions were heated in a thermocycler (Biometra T-Gradient, Germany) at 100°C for 1 min, and held for 2 min at 20°C to cool, and analysed using a spectrophotometer (Genesys 10UV, Thermo Scientific, Waltham, MA, USA) at 540 nm.

Results and Discussion

The microbial population of the sourdoughs was enumerated using two different culture media: PCA for estimation of total aerobic mesophilic bacteria and PDA for yeasts and other fungi. Figure 1 shows the growth of aerobic mesophilic bacteria during the 6 days of incubation. The initial concentration of bacteria was higher in sourdoughs made with Mexican flour (4 Log UFC/g) than in sourdoughs made with Italian flour (3.2 Log UFC/g). In Mexican sourdoughs, refreshed or not, growth was intense and reached almost stationary phase in the first 3 days of fermentation; on the other hand, the Italian sourdoughs reached stationary phase after 5 days, probably due to lower initial population than Mexican sourdoughs.

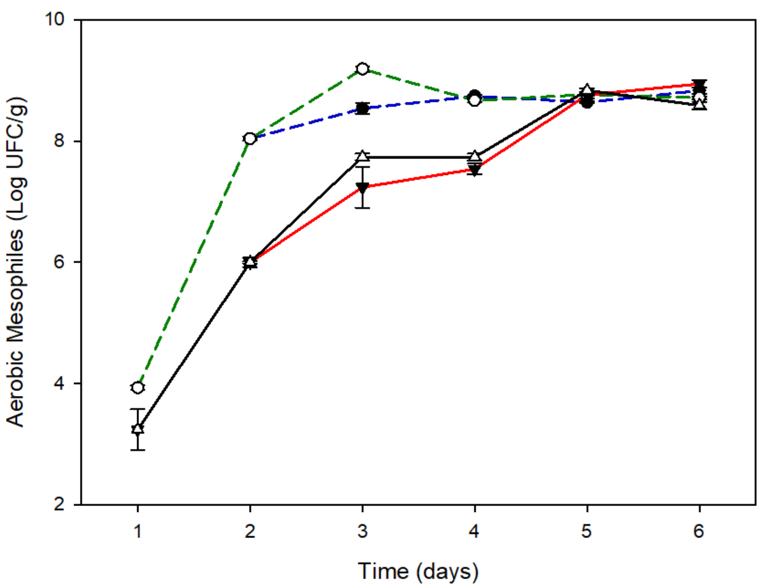

Figure 1. Growth of total aerobic mesophilic bacteria (Log UFC/g) of the different sourdoughs, with PCA method. (○): DMR, (●): DMNR, (△): DIR, (▼): DINR. Each value is represented as mean ± SD (n = 3).

The growth of yeasts during the 6 days of incubation (Figure 2) showed a growing trend similar to bacteria; in this case, the initial concentration of yeasts was higher in sourdoughs made with Mexican flour (4.2 Log UFC/g) than in sourdoughs made with Italian flour (3.8 Log UFC/g).

Initially, the microbial population of the sourdough represents that of the flour. Each microbial group did not generally exceed 5 Log UFC/g. During the time, LAB and yeasts become more adapted to the environmental conditions of the sourdough, to the point of dominating the mature sourdough. Similar studies state that the population ranged from 6 to 9 Log UFC /g and 5 to 8 Log UFC /g, respectively (Minervini *et al.*, 2012).

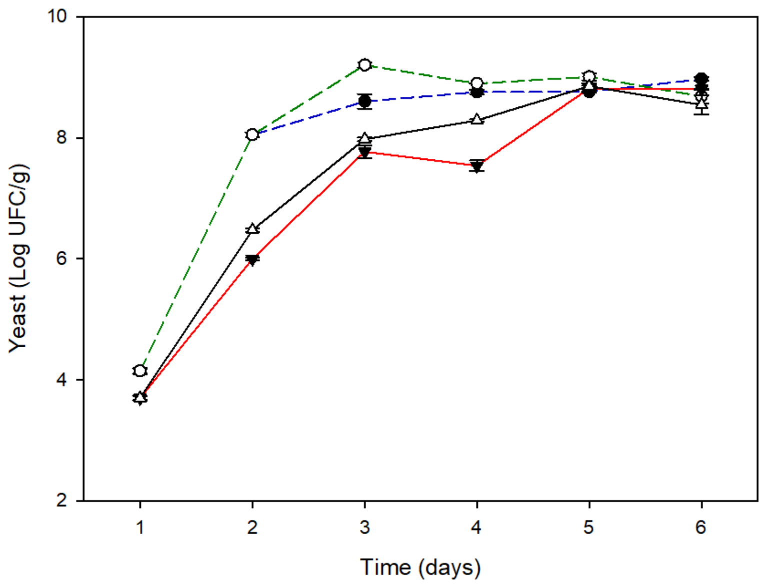

Figure 2. Growth of yeast and other fungi (Log UFC/g) of the different sourdoughs, with PDA method. (○): DMR, (●): DMNR, (△): DIR, (▼): DINR. Each value is represented as mean ± SD (n = 3).

Figures 3 and 4 show the results for pH and TTA. The initial pH values in Mexican and Italian sourdoughs were 5.9 and 5.6, respectively, while the TTA was 0.8 mL and 0.1M NaOH in each. During fermentation, the physicochemical parameters change, mainly due to the microbial metabolism (Paramithiotis *et al.*, 2014). The pH values decreased after 6 days of incubation to 3.7 both for Mexican and Italian sourdoughs. Similar pH values were also found by Vrancken *et al.*, (2011). Generally, the pH values between 3.5 and 4.3 are considered as an index of well-developed sourdough fermentation (Gobbetti and Gänzle, 2012). However, in the Mexican sourdoughs, the pH decreased quickly after 3 days of incubation with respect to the Italian sourdoughs that showed a gradual trend. No differences were observed between the pH values of refreshed or not-refreshed sourdoughs. These results are in accordance with the bacterial growth, and their produced metabolites such as lactic acid (Maifreni *et al.*, 2004). In fact, TTA values increased in both Mexican and Italian sourdoughs, with higher values in the Mexican one due to the higher bacterial population at the beginning. After 6 days of incubation the not-refreshed sourdoughs showed higher values of TTA than those refreshed for both flours. This behaviour can be related to the refreshment procedure that can act as a dilution factor on the sourdough.

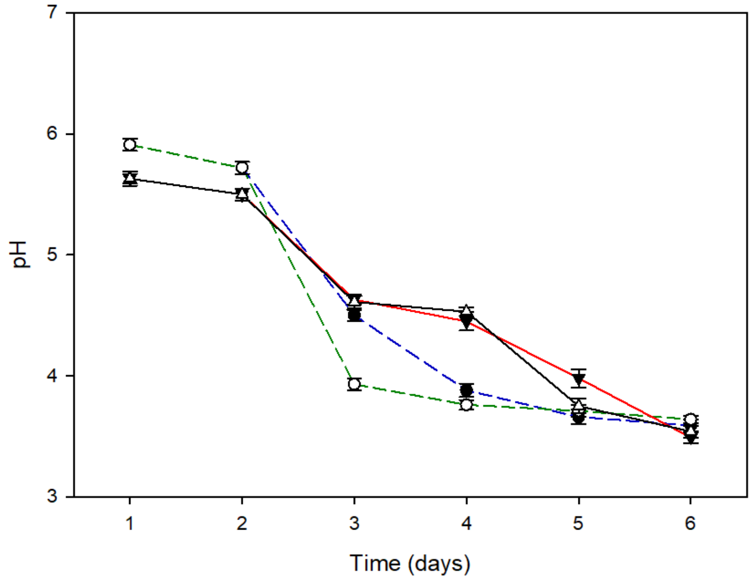

Figure 3. Evolution of pH of the different sourdoughs during 6 days of incubation. (○): DMR, (●): DMNR, (△): DIR, (▼): DINR. Each value is represented as mean ± SD (n = 3).

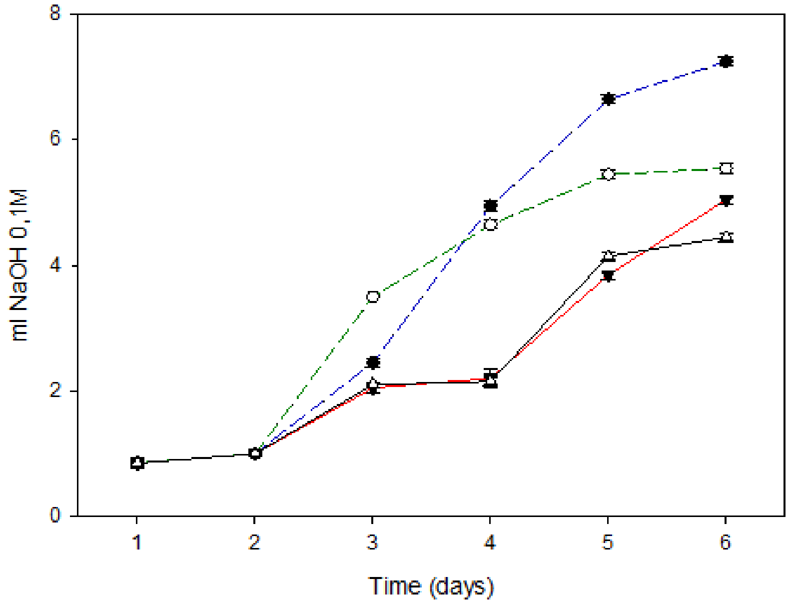

Figure 4. Evolution of TTA of the different sourdoughs during 6 days of incubation. (○): DMR, (●): DMNR, (△): DIR, (▼): DINR. Each value is represented as mean ± SD (n = 3).

Figures 5 and 6 show the moisture content (%) and aw values. In each sourdough, there are no significant differences in moisture content and aw values during the 6 days of incubation both in the refreshed and not-refreshed sourdoughs. These results confirm that both the incubation and refreshment did not affect the aqueous environment in the sourdoughs, preserving the favourable condition for microbial growth (Tecante, 2019). Minervini *et al.* (2014) stated that aw values between 0.96 and 0.98 do not limit the growth of most microorganisms.

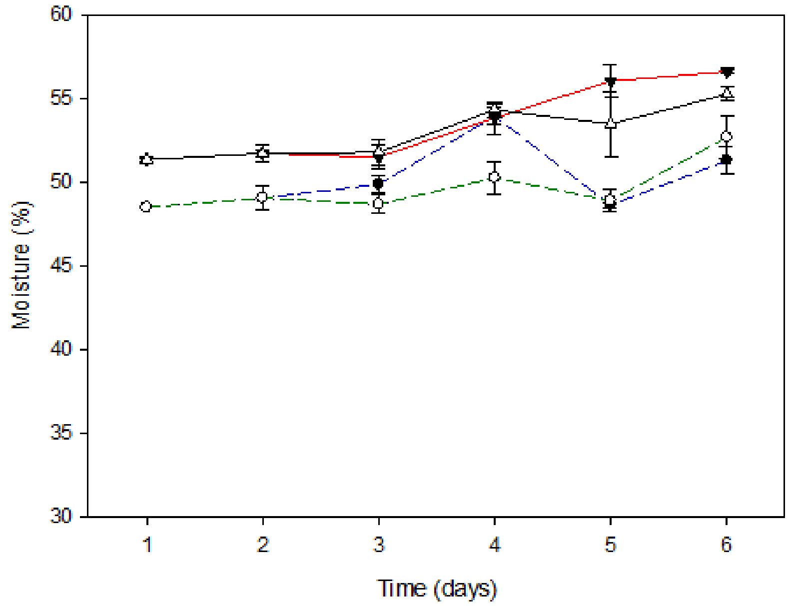

Figure 5. Evolution of Moisture content (%) of the different sourdoughs during 6 days of incubation (○): DMR, (●): DMNR, (△): DIR, (▼): DINR. Each value is represented as mean ± SD (n = 3).

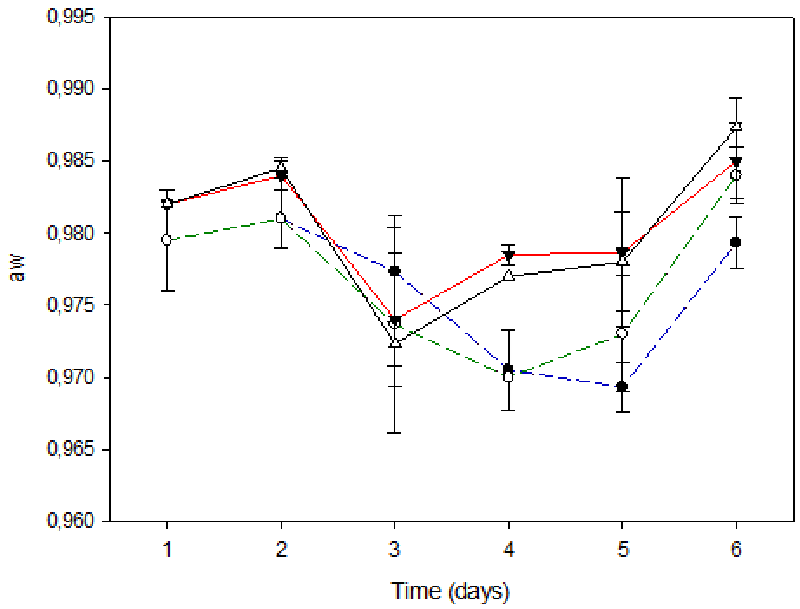

Figure 6. Evolution of water activity of the different sourdoughs during 6 days of incubation (○): DMR, (●): DMNR, (△): DIR, (▼): DINR. Each value is represented as mean ± SD (n = 3).

Figure 7 shows the results of reducing sugar content during the fermentation. As shown during incubation, the reducing sugars increased linearly reaching its maximum concentration in each sourdough after 4 days, which can be related to the amylolytic activity of bacteria (Tecante, 2019). Also in this case, the values show greater reducing sugars in Mexican than in Italian sourdoughs, probably due to higher initial microbial population. Moreover, the differences in reducing sugar content observed in the refreshed and not-refreshed sourdoughs could be related to the sourdough refreshment, where there is increased polysaccharides concentration, due to fresh flour addition.

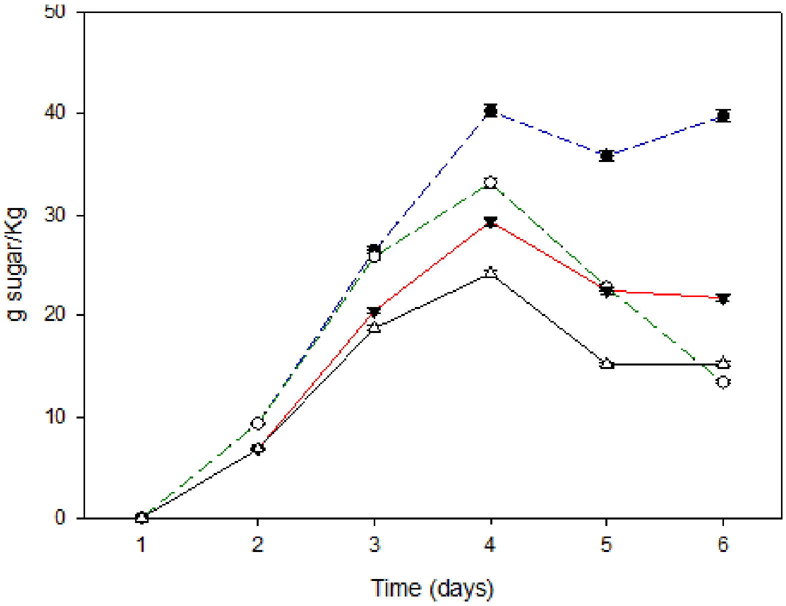

Figure 7. Evolution of reducing sugars (g/kg). (○): DMR, (●): DMNR, (△): DIR, (▼): DINR. Each value is represented as mean ± SD (n = 3).

Conclusions

These results showed that in the early stages of microbial growth, the microbial population was greater in the sourdough made from the Mexican wheat flour than the Italian one, due to different geographic environments. However, after 6 days of incubation, the microbial populations were not significantly different in both types of sourdoughs, either refreshed or not refreshed. In addition, there were no significant differences in the physicochemical properties of refreshed or not-refreshed sourdoughs. In summary, daily refreshment is not necessary during the first 6 days of liquid sourdough preparation.

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References

Arendt, E.K., Ryan, L.A. and Dal Bello, F. 2007. Impact of sourdough on the texture of bread. Food Microbiology. 24(2): 165–174. https://doi.org/10.1016/j.fm.2006.07.011

Ben Omar, N. and Ampe, F. 2000. Microbial community dynamics during production of the Mexican fermented maize dough pozol. Applied and Environmental Microbiology. 66(9): 3664–3673. https://doi.org/10.1128/AEM.66.9.3664-3673.2000

Carnevali, P., Ciati, R., Leporati, A. and Paese, M. 2007. Liquid sourdough fermentation: Industrial application perspectives. Food Microbiology. 24(2): 150–154. https://doi.org/10.1016/j.fm.2006.07.009

Corsetti, A. and Settanni, L. 2007. Lactobacilli in sourdough fermentation. Food Research International. 40(5): 539–558. https://doi.org/10.1016/j.foodres.2006.11.001

De Vuyst, L. and Gänzle, M. 2005. Second international symposium on sourdough: from fundamentals to applications. Trends in Food Science & Technology. 1(16): 2–3. https://doi.org/10.1016/2Fj.tifs.2004.08.003

De Vuyst, L. and Vancanneyt, M. 2007. Biodiversity and identification of sourdough lactic acid bacteria. Food Microbiology. 24(2): 120–127. https://doi.org/10.1016/j.fm.2006.07.005

Decock, P. and Cappelle, S. 2005. Bread technology and sourdough technology. Trends in Food Science & Technology. 16(1–3): 113–120. https://doi.org/10.1016/j.tifs.2004.04.012

Ercolini, D., Pontonio, E., De Filippis, F., Minervini, F., La Storia, A., Gobbetti, M. and Di Cagno, R. 2013. Microbial ecology dynamics during rye and wheat sourdough preparation. Applied and Environmental Microbiology. 79(24): 7827–7836. https://doi.org/10.1128/AEM.02955-13

Gobbetti, M., De Angelis, M., Arnaut, P., Tossut, P., Corsetti, A. and Lavermicocca, P. 1999. Pentosani aggiunti nella panificazione: fermentazioni di pentosi derivate da batteri lattici a lievitazione naturale. Microbiologia degli Alimenti. 16(4): 409–418.

Gobbetti, M. and Gänzle, M. (eds.). Handbook on sourdough biotechnology. Springer Science & Business Media, New York, NY, USA, pp 97-99

Hammes, W.P. and Gänzle, M.G. 1998. Sourdough breads and related products. In: Wood, B.J.B. (ed.) Microbiology of fermented foods. Blackie Academic and Profesional, London, 199 pp.

Maifreni, M., Marino, M. and Conte, L. 2004. Lactic acid fermentation of *Brassica rapa*: chemical and microbial evaluation of a typical Italian product (brovada). European Food Research and Technology. 218(5): 469–473. https://doi.org/10.1007/s00217-004-0877-6

Minervini, F., De Angelis, M., Di Cagno, R. and Gobbetti, M. 2014. Ecological parameters influencing microbial diversity and stability of traditional sourdough. International Journal of Food Microbiology. 171: 136–146. https://doi.org/10.1016/j.ijfoodmicro.2013.11.021

Minervini, F., Lattanzi, A., De Angelis, M., Di Cagno, R. and Gobbetti, M. 2012. Influence of artisan bakery-or laboratory-propagated sourdoughs on the diversity of lactic acid bacterium and yeast microbiotas. Applied and Environmental Microbiology. 78(15): 5328–5340. https://doi.org/10.1128/AEM.00572-12

Paramithiotis, S., Doulgeraki, A.I., Karahasani, A. and Drosinos, E.H. 2014. Microbial population dynamics during spontaneous fermentation of *Asparagus officinalis* L. young sprouts. European Food Research and Technology. 239(2): 297–304. https://doi.org/10.1007/s00217-014-2222-z

Spicher, G. 1983. Baked goods. In: Rehm J.H., Reed G. (eds.) Biotechnology. Verlag Chemie, Weinheim, Germany, pp. 1– 80.

Tecante, A. 2019. Chemical and rheological description of pozol dough fermentation inoculated with *Streptococcus infantarius* subsp. infantarius 25124 and *Lactobacillus plantarum* A6. International Journal of Biotechnology & Bioengineering. 5: 1–9.

Thiele, C., Gänzle, M.G. and Vogel, R.F. 2002. Contribution of sourdough lactobacilli, yeast, and cereal enzymes to the generation of amino acids in dough relevant for bread flavor. Cereal Chemistry. 79(1): 45–51. https://doi.org/10.1094/CCHEM.2002.79.1.45

Vrancken, G., Rimaux, T., Weckx, S., Leroy, F. and De Vuyst, L. 2011. Influence of temperature and backslopping time on the microbiota of a type I propagated laboratory wheat sourdough fermentation. Applied and Environmental Microbiology. 77(8): 2716–2726. https://doi.org/10.1128/AEM.02470-10

Wood, I.P., Elliston, A., Ryden, P., Bancroft, I., Roberts, I.N. and Waldron, K.W. 2012. Rapid quantification of reducing sugars in biomass hydrolysates: improving the speed and precision of the dinitrosalicylic acid assay. Biomass and Bioenergy. 44: 117–121. https://doi.org/10.1016/j.biombioe.2012.05.003

Chapter 3

Developing of functional pizza base enriched with jujube (*Ziziphus jujuba*) powder

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Abstract

In recent years, foods are chosen not only for their nutritional value but also for their functional benefits on human health and prevention of several pathologies. Those foods, known as functional foods, are classified as fortified, enriched, or enhanced foods. Phytochemicals and phenolic antioxidants in plants, including fruits, vegetables, herbs, and spices are recognized as active ingredient used in functional food. The jujube fruit is rich in phenolic compounds with a high antioxidant activity and represents a good candidate in functional food development. The aim of this work was to develop a functional pizza base, produced in the Neapolitan style, exploiting the beneficial properties of jujube. The doughs were prepared by replacing the wheat flour with 2.5%, 5.0% and 7.5% (w/w) of Ziziphus jujube powder (ZJP) and cooked. Chemical analyses showed that both total phenolic compounds and antioxidant activity increased with the growing amount of ZJP. The addition of ZJP darkened the pizza base and raised its hardness, gumminess and chewiness. However, no difference was found in springiness and cohesiveness of the samples with or without ZJP. These results suggest that jujube powder can be successfully introduced into pizza dough as a functional ingredient.

Keywords: pizza base; jujube fruit; functional food; antioxidant activity; polyphenolic compounds

Introduction

In recent years, a growing demand of food products with functional properties is registered. Among food products, baked goods are consumer products, so the current trend of the baked goods industry is to create health-beneficial baked goods. The use of composite flour (a blend of wheat and non-wheat flours) may provide additional nutrients contained in the non-wheat material, thus improving the nutritional value of the bakery products [1]. Hence, in relation to good health demands, the nutritional value of wheat-based food products can be enhanced by supplementation with other nutrients from different sources [2].

There are many studies available on the development of functional bakery goods like bread [3-5], cookies [6], biscuits [7] and cakes [8].

Among bakery products, pizza is consumed and liked worldwide. Due to the simplicity of its preparation and good taste, pizza is also a popular snack that could be a promising vehicle for functional compounds and thus satisfy health-conscious customers [9,10]. Vitamins, minerals, dietary fibers, and phytochemicals present in plants contribute to the functionality of foods enriched by them. However, to satisfy consumers, it should not be overlooked that the addition of functional compounds must preserve or improve the sensory characteristics of the final products.

The jujube plant (*Ziziphus jujuba*, Mill) belongs to the *Rhamnaceae* family, and it is largely diffused in China. Nowadays, its cultivation is also found in other regions of the world, including Russia, South Asia, Southwestern United States, Australia and Southern Europe. The fresh jujube fruit and its derivatives (paste, puree, syrup, etc.) have been largely used in traditional Chinese medicine and as a dietary supplement with high contents of bioactive compounds such as dietary fibers, mineral, and natural antioxidant compounds like phenols and flavonoids. It is well known that the presence of phenolic compounds in food can be particularly important for consumers both for their antioxidant properties and other biochemical properties which prevent the development of diseases, such as neurodegenerative diseases [11]. Nevertheless, due to the short shelf-life of the fresh product, jujube powder was recently proposed as the best product to be used in many food formulations to develop functional foods [12].

In this context, the present study aims to exploit the beneficial properties of jujube powder by using it to make composite flours in the development of a functional pizza base, produced in the Neapolitan style. Total phenol and antioxidant properties of pizza base containing ZJP were analyzed after baking and compared with the control. In addition, the texture attributes and the chromatic analysis of the samples were also evaluated.

Materials and Methods

Chemicals

Methanol, Folin-Ciocalteu's (FC) reagent, gallic acid, aluminum chloride, potassium acetate, DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS (2,2′-azinobis-3-ethylbenzothiazoline-6-sulfonic acid), and other chemicals were purchased by Carlo Erba (Italy). The *Ziziphus jujuba* fruits were provided by the arboriculture section of the Department of Agricultural Sciences, University of Naples Federico II, Portici, Napoli, Italy.

Ziziphus jujuba powder (ZJP) preparation

The intact ripened jujube fruits were washed with distilled water to remove impurities and pitted. The pitted fruits were stratified on perforated trays and dried under a stream of hot air (2 m / s) at 40 °C for 72 h. The dried samples were ground using a laboratory mill (Model 3100, Perten Instruments Italia Srl, Rome, Italy) with a 0.5 mm sieve. The obtained powder was further sieved at 0.2 mm to obtain homogeneous particle size. The ZJP obtained was packaged in a hermetically sealed dark glass jar and stored at room temperature until use.

Chemical analysis of ZJP

The soluble dietary fibers (SDF) and insoluble dietary fibers (IDF) contents were determined according to the gravimetric enzymatic method as previously described by [13]. Protein content (N×6.25) and total fat were measured by Kjeldahl's method and Soxhlet apparatus, respectively. Total carbohydrates were evaluated by the phenol sulphuric acid method [14]. Moisture content was assessed according to AOAC method [15]. Ash content was detected by keeping sample (3 g) for 5 h at 550 °C in a muffle furnace.

Preparation of the pizza base

The dough was prepared in the Neapolitan way. The recipe included 60% soft wheat flour type "00" (Caputo Rossa Pizzeria; 74 % total carbohydrates, 13 % protein, 1.5 % fat, and 0.02 % ash) (Antimo Caputo S.r.l., Napoli, Italy), 38 % deionized water, 1.9 % sodium chloride of Sicily (Italkaly, Palermo, Italy) and 0.1 % fresh yeast (Lievital, Lesaffre Italia S.p.a, Parma, Italy). For the preparation of the functional pizza base, the wheat flour was replaced with 2.5% (ZJP-2.5), 5% (ZJP-5) and 7.5% (ZJP-7.5) (w/w) ZJP, respectively. The ingredients were mixed using the spiral mixer (Grilletta IM5, Famag S.r.l., Milano, Italy) for 18 minutes, then 250g loaves were formed and leavened in a climatic cell (Binder, type KBF-S, Tuttlingen, Germany) at 22 °C and 80% relative humidity for 16 hours. Finally, the loaves were rolled and baked for 90 s (floor: 400 °C; vault: 450 °C) in an electric oven (iDeck, iD60/60D, Moretti Forni S.p.A., Pesaro and Urbino, Italy) with refractory stone on the floor. The cooked samples were allowed to cool at room temperature before use. For chemical analyses, whole pizzas were cut in small pieces, freeze-dried, ground, sieved though a 0.2 mm sieve and stored at -20°C.

Preparation of methanolic extracts for analysis

ZJP or pizza base powder (1 g) were mixed with 25 mL of aqueous methanol (70% v/v) and swirled at room temperature for 2h. Samples were then centrifuged at 12000 x g for 15 min in a centrifuge at 20°C. The supernatants were recovered and stored on ice in the dark and the pellets were subjected to another extraction. At the end the supernatants were collected and stored at -23°C until the analysis.

Total phenol and flavonoid content

The total phenolic content (TPC) was determined according to Sun et al. [16], with slight modifications. The extracts (50 μL) were mixed with 70 μL of FC reagent and 880 μL of distilled water. The mixture was thoroughly mixed by vortex for 1 minute and incubated for 5 minutes at room temperature. Subsequently 530 μL of distilled water and 70 μL of 7.5% (w/v) sodium carbonate were added to each tube and incubated for 15 minutes at 45 °C in the dark; then the absorbance was measured at 760 nm using the UV-VIS spectrophotometer (V-730, JASCO International Co Ltd, Sennincho Hachioji, Japan). Gallic acid was used as standard and the results were expressed as mg of Gallic Acid Equivalent (GAE)/g dry weight (DW). Total flavonoid content (TFC) was measured according to Sagar & Pareek [17] without modifications. The extracts (0.5 mL) were poured into the tubes containing 1.5 mL of methanol (80%) and mixed. Then, 1M potassium acetate (0.1 mL), 10% aluminum chloride (0.1 mL) and distilled water (2.8 mL) were added, mixed and incubated at room temperature for 30 minutes. After incubation the absorbance was measured at 410 nm. The standard used was quercetin and the results were expressed as mg quercetin equivalent (QE)/g DW.

Antioxidant activity

The antioxidant activity was detected by using both $ABTS^{\bullet+}$ and $DPPH^{\bullet}$ assays according to the method of Duan et al. [18]. Briefly, ABTS was dissolved in deionized water at 7 mM concentration. The ABTS cationic radical ($ABTS^{\bullet+}$) was produced by reacting the ABTS solution with 2.45 mM potassium persulfate (final concentration) and allowing the mixture to stand in the dark at room temperature for 12−16 h before use. For the analyses, the $ABTS^{\bullet+}$ solution was diluted in 96% ethanol to an absorbance of 0.7 (±0.02) at 732 nm, then 1 mL of this solution was mixed with 25 μL of 70% methanol (blank) or sample extracts. The samples were incubated for 10 min at room temperature and then the absorbance at 732 nm was measured.

The methanolic solution of $DPPH^{\bullet}$ (0.1 mM) was freshly prepared, and then 950 μL were mixed with 50 μL of sample extract or 50 μL of methanol (blank). The samples were incubated for 1h in the dark at room temperature, and then the absorbance at 517 nm was measured.

Radical scavenging activity was calculated using the following formula (A):

$$ABTS^{\bullet+} \text{ or } DPPH^{\bullet} \text{ scavenging activity (\%)} = (A_b - A_s)/A_b \times 100, \qquad \text{(A)}$$

where A_b = absorbance of the blank sample, and A_s = absorbance of the extract.

Texture profile analysis (TPA) of cooked pizza base

Textural properties including hardness, chewiness, cohesiveness, springiness, adhesiveness and gumminess were investigated by using a texture profile analyzer (TMS-Pro Texture Analyzer, Food Technology Corporation, Virginia, USA). Six slices of 30 x 30 mm were cut from the pizza raised rim, then thirty-six measurement (6 slice x 6 sample) were performed for each typology of pizza base. The TPA test consists of compressing the slice, twice, to 50% of its initial height with a cross-head speed of 1 mm/s and a time of 10s between compressions using an aluminum probe plate (25 mm diameter) and a 50 N load cell.

Color analysis of cooked pizza base

The color analysis was performed by using an electronic eye IRIS Alpha-Mos (Visual Analyzer, IRIS VA 400, Alpha M.O.S., Toulose, France). The results were shown according to the CIE L*, a*, b* scale. The parameters L* (brightness: 0 = black, 100 = white), a* (green (-), redness (+)) and b* (light blue (-), yellow (+)) were measured on the whole sample surface. Color differences (ΔE) were determined by using the equation (B) [19,20]:

$$\Delta E = \sqrt{(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2} \qquad \text{(B)}$$

where L_0, a_0, and b_0 correspond to the CIE colour parameters of the pizza control.

Statistical Analysis

The experimental data in triplicate were subjected to analysis of variance (ANOVA) and expressed as mean ± SD (n = 6). ANOVA was performed by using the one-way analysis of variance procedures. Duncan's multiple range test was used to analyze the significant difference of means, and $p<0.05$ was considered to be statistically significant. JMP software 10.0 (SAS Institute, Cary, NC, USA) was used for data analysis.

Results and Discussion

The ZJP is a good source of the functional compounds largely proposed as food fortification [21]. The fortification of the Neapolitan pizza, the most consumed Italian traditional food in the world, represents an interesting strategy to promote the functional benefits of ZJP to prevent diseases and improve human wellbeing.

The chemical composition and antioxidant properties of ZJP are shown in Table 1.

Table 1. Proximate composition and antioxidant properties of ZJP.

Components	
Total carbohydrates (g/100 g DW)	81.46 ± 0.34
Soluble dietary fibres (g/100 g DW)	1.64 ± 0.08
Insolube dietary fibres (g/100 g DW)	5.91 ± 0.12
Fat (g/100 g DW)	3.44 ± 0.09
Proteins (g/100 g DW)	6.83 ± 0.13
Moisture (g/100 g DW)	4.58 ± 0.18
Ash (g/100 g DW)	3.29 ± 0.09
Phenols (mg GAE/g DW)	17.62 ± 0.02
Flavonoids (mg QE/g DW)	3.51 ± 0.12
ABTS (radical scavenging activity %)	61.07 ± 1.42
DPPH (radical scavenging activity %)	50.05 ± 2.31

Each value is expressed as mean ± SD (n = 6).

In agreement with the literature [12], the total sugars represent the most abundant constituents of ZJP. Among the total sugars, the insoluble dietary fibers (5.91 ± 0.12 g/100g) were found to be much higher than soluble dietary fibers (1.64 ± 0.08 g/100g). Insoluble fibers (cellulose, lignin and hemicellulose) are known to have potential health benefits due to their ability to absorb water; this increases fecal mass and viscosity by promoting the movement of material through the digestive system [22]. The recommended quantity of dietary fibers intake per adult is 25–38 g, and recent studies report that for every 10 g of additional fiber added to a diet, the mortality risk of coronary heart disease decreases by 17–35% [23,24]. Dietary fibers also possess technological characteristics that can be involved in food formulation, showing in texture change and improvement of the stability of the food during production and storage.

In addition, the regular intake of natural antioxidants such as phenols and flavonoids promotes the risk reduction of various diseases by counteracting oxidative stress. Phenols (17.62 ± 0.2 mg GAE/g) and flavonoids (3.51 ± 0.12 mg QE/g) contents of ZJP result higher compared to that detected in other products used for the food fortification [4,5]. Moreover, ZJP showed a significant DPPH$^{•}$ and ABTS$^{•+}$ radical scavenging capacity (Table 1). Thus, ZJP can be considered a good fortifying agent suitable for improving beneficial effects on health through its antioxidant and radical scavenging properties.

For this purpose, enriched pizza bases were prepared by adding ZJP at 2.5%, 5% and 7.5% (w/w) respectively, and the results of phenols and flavonoids contents as well as the antioxidant ability detected by two free radical antioxidant methods (DPPH and ABTS) are reported in Table 2.

Table 2. Total phenolic content (TPC), total flavonoid content (TFC) and radical scavenging activity tested by ABTS$^{•+}$ and DPPH$^{•}$ assays of pizza base enriched with ZJP.

Samples	**TPC** (mg GAE/g DW)	**TFC** (mg QE/g DW)	**ABTS (%)**	**DPPH (%)**
Control	0.82 ± 0.04^{a}	0.01 ± 0.01^{a}	33.18 ±1 .33^{a}	18.46 ± 0.70^{a}
ZJP 2.5 %	1.02 ± 0.07^{b}	0.06 ± 0.01^{b}	50.69 ± 3.08^{b}	23.57 ± 0.37^{b}
ZJP 5.0 %	1.28 ± 0.09^{c}	0.09 ± 0.01^{c}	65.86 ± 2.77^{c}	45.46 ± 0.26^{c}
ZJP 7.5 %	1.51 ± 0.05^{d}	0.11 ± 0.03^{c}	78.52 ± 3.74^{d}	55.29 ± 0.51^{d}

Each value is expressed as mean ± SD (n = 6).
Means with same letters in the same column are not significantly different (P < 0.05) by Duncan's multiple range test.

Phenols and Flavonoids contents showed a positive association with the replacement of wheat flour with ZJP in the pizza base formulations (Control < ZJP 2,5% < ZJP 5,0% < ZJP 7,5%). As expected, a similar trend was observed for the antioxidant ability detected by DPPH and ABTS assays.

These results are attributed to the important content in the jujube fruit of phytochemicals, in particular phenols (Table 1) which represent the main components with high antioxidant activity [11]. However, flavonoids and phenols can participate individually or synergistically in the antioxidant capacity [8]. Similar results were observed in the fortification of baked goods with natural raw materials, such as eggplant flour [6], jujube (var Lotus) powder [8], onion skin powder [17], mallow powder [25] and black cherry pomace extract [26], where the fortification provided better antioxidant abilities with a linear relationship between TPC and antioxidant properties. Therefore, pizza bases fortified with ZJP improved their nutritional quality with better stability against oxidation.

The effects of the ZJP addition to the textural attributes of fortified pizza bases were analyzed by using a texture profile analysis. The crust of baked samples was compressed twice between the plates of the texture analyzer which imitates the jaw action. The results show that the replacement of flour with ZJP significantly increases the hardness, gumminess and chewiness (Table 3) with the following trend: Control < ZJP 2,5% < ZJP 5,0% < ZJP 7,5%. This behavior can be associated with the increase of insoluble dietary fiber due to the addition of ZJP (Table 1) and is in agreement with other studies in which the addition of fibers to dough is able to increase the hardness and the derived parameters, like chewiness and gumminess [8,17,27-30]. However, although these parameters showed a significant increase, the variation, in absolute value, was not high enough to modify the acceptability of the fortified products. In fact, the other direct attributes, such as adhesiveness, springiness and cohesiveness, detected by the TPA showed very low differences between the fortified pizzas and the control.

Table 3. Effect of ZJP enrichment on the textural profile of pizza base variants.

Samples	Hardness (N)	Adhesiveness (Nmm)	Cohesiveness	Springiness (mm)	Gumminess (N)	Chewiness (mJ)
Control	3.75 ± 0.06^{a}	0.27 ± 0.02^{a}	0.72 ± 0.01^{a}	9.58 ± 0.20^{a}	2.69 ± 0.01^{a}	25.81 ± 0.71^{a}
ZJP 2.5 %	4.31 ± 0.28^{b}	0.25 ± 0.03^{a}	0.71 ± 0.01^{a}	9.72 ± 0.27^{a}	3.08 ± 0.16^{b}	30.12 ± 0.99^{b}
ZJP 5.0 %	5.00 ± 0.28^{c}	0.24 ± 0.02^{a}	0.70 ± 0.02^{a}	9.81 ± 0.03^{a}	3.46 ± 0.10^{c}	33.81 ± 0.68^{c}
ZJP 7.5 %	5.82 ± 0.17^{d}	0.20 ± 0.02^{b}	0.70 ± 0.03^{a}	9.96 ± 1.27^{a}	4.08 ± 0.21^{d}	40.75 ± 2.31^{d}

Each value is expressed as mean ± SD (n = 36).
Means with same letters in the same column are not significantly different ($P < 0.05$) by Duncan's multiple range test.

The color is one of the main characteristics that defines the acceptability of food by consumers. To compare the effect of the ZJP addition on the Neapolitan pizza color, the total surface of samples was analyzed with an electronic eye and the CIELab results obtained for all samples are presented in Table 4. The total color differences (ΔE) is an important parameter since it considers all differences encountered between L*, a* and b* values of the samples in respect to the control, giving a valid tool to evaluate the relationship between the visual perception and the numerical analyses [31].

Table 4. Colour values of pizza base variant.

Samples	L*	a*	b*	ΔE
Control	62.77 ± 0.37^{a}	1.14 ± 0.24^{a}	27.90 ± 0.21^{a}	-
ZJP 2.5 %	62.50 ± 0.67^{a}	1.39 ± 0.03^{a}	27.70 ± 0.50^{a}	0.41
ZJP 5.0 %	60.18 ± 0.58^{bc}	1.69 ± 0.03^{ab}	27.61 ± 0.07^{a}	2.66
ZJP 7.5 %	58.51 ± 0.64^{c}	2.19 ± 0.15^{b}	28.23 ± 0.55^{a}	4.40

Each value is expressed as mean ± SD (n = 6).
Means with same letters in the same column are not significantly different (P < 0.05) by Duncan's multiple range test.

It is well known that a ΔE value higher than 1 can be associated with a significant chromatic difference between the sample and the control. However, a ΔE < 2 can be noticeable only by an experienced observer; for ΔE < 3.5 the difference is appreciated also by an unexperienced observer; while ΔE > 3.5 can be considered a clear color difference between the samples [32]. Results reported in Table 4 indicate that a chromatic difference can be observed only in the samples containing 5% and 7.5% of ZJP whit a strong difference in the higher amount of ZJP. These results are associated principally with the reduction of L* and the increase of a* values (Table 4). The decrease of lightness is due to the higher fiber's content of ZJP which, as reported by [8], is able to decrease the sponge cakes lightness. Moreover, it is well known that when a powder is added to the flour, its type and color may affect the chromatic perception of the final product, which can be also influenced by the baking process [33]. Thus, the significant increase (p<0.05) of a* value observed in the samples containing 5% and 7.5% of ZJP can be associated with the intrinsic color of ZJP, or to the colored compounds generated from caramelization and Maillard reaction occurring during baking [34].

4. Conclusions

In conclusion, when ZJP is used as fortifier in Neapolitan Pizza, the textural characteristics (hardness, gumminess and chewiness) and the chromatic properties are affected as the amount of ZJP added increases. However, the differences are not enough to change the overall acceptability of the products.

The incorporation of ZJP in Neapolitan pizza base formulation markedly increased the fibre, total phenolic and flavonoid contents and the radical scavenging activity. Therefore, ZJP could be considered a potential health-promoting functional ingredient, without promoting negative effects and without changing the desirable physical and sensorial characteristics of the Neapolitan pizza. Further studies are needed to verify its health giving properties in vivo, after ingestion and full digestion

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References

1. De Ruiter, D. Composite flours. In *Advances in cereal science and technology*; De Ruiter, D., Ed.; St. Paul, MN: American Association of Cereal Chemist, 1978; pp. 349–381.
2. Field, K.M., Duncan, A.M., Keller, H.H., Stark, K.D., & Duizer, L.M. Effect of micronutrient powder addition on sensory properties of foods for older adults. *Journal of food science* **2017**, 82(10), 2448-2455. DOI:10.1111/1750-3841.13849.
3. Gawlik-Dziki, U., Kaszuba, K., Piwowarczyk, K., Świeca, M., Dziki, D., & Czyż, J. Onion skin—Raw material for the production of supplement that enhances the health-beneficial properties of wheat bread. *Food Research International* **2015**, 73, 97-106. DOI:10.1016/j.foodres.2015.02.008.
4. Dhen, N., Rejeb, I.B., Boukhris, H., Damergi, C., & Gargouri, M. Physicochemical and sensory properties of wheat-Apricot kernels composite bread. *LWT* **2018**, 95, 262-267. DOI:10.1016/j.lwt.2018.04.068.
5. Bedrníček, J., Jirotková, D., Kadlec, J., Laknerová, I., Vrchotová, N., Tříska, J., Samková, E. & Smetana, P. Thermal stability and bioavailability of bioactive compounds after baking of bread enriched with different onion by-products. *Food chemistry* **2020**, 319, 126562. DOI:10.1016/j.foodchem.2020.126562.
6. Uthumporn, U., Woo, W.L., Tajul, A.Y., & Fazilah, A. Physico-chemical and nutritional evaluation of cookies with different levels of eggplant flour substitution. *CyTA-Journal of Food* **2015**, 13(2), 220-226. DOI:10.1080/19476337.2014.942700.

7. Mridula, D., Gupta, R.K., & Manikantan, M.R. Effect of incorporation of sorghum flour to wheat flour on quality of biscuits fortified with defatted soy flour. *American Journal of Food Technology* **2007**, 2(5), 428-434. DOI:10.3923/ajft.2007.428.434.

8. Najjaa, H., Ben Arfa, A., Elfalleh, W., Zouari, N., & Neffati, M. Jujube (*Zizyphus lotus* L.): Benefits and its effects on functional and sensory properties of sponge cake. *PloS one* **2020**, 15(2), e0227996. DOI:10.1371/journal.pone.0227996.

9. Kanaujiya, G., & Neetu, S. To Nutritional Profile of Dietary Fibre Pizza Base and Sensory Evaluation of Develop Product. *International Journal of Advance Research, Ideas and Innovations in Technology*, **2017**, 3(6), 932-936.

10. Biljwan, M., Naik, B., Sharma, D., Singh, A., & Kumar, V. Recent Development in Dough Based Bakery Products: A Mini Review. *The Pharma Innovation Journal* **2019**, 8(5), 654-658.

11. Gao, Q.H., Wu, C.S., Wang, M., Xu, B.N., & Du, L.J. Effect of drying of jujubes (*Ziziphus jujuba* Mill.) on the contents of sugars, organic acids, α-tocopherol, β-carotene, and phenolic compounds. *Journal of Agricultural and Food Chemistry* **2012**, 60(38), 9642-9648. DOI:10.1021/jf3026524.

12. Rashwan, A.K., Karim, N., Shishir, M.R. I., Bao, T., Lu, Y., & Chen, W. Jujube fruit: A potential nutritious fruit for the development of functional food products. *Journal of Functional Foods* **2020**, 75, 104205. DOI:10.1016/j.jff.2020.104205.

13. Prosky, L., Asp, N.G., Schweizer, T.F., Devries, J.W., & Furda, I. Determination of insoluble, soluble, and total dietary fiber in foods and food products: interlaboratory study. *Journal of the Association of Official Analytical Chemists* **1988**, 71(5), 1017-1023.

14. Dubois, M., Gilles, K.A., Hamilton, J.K., Rebers, P.T., & Smith, F. Colorimetric method for determination of sugars and related substances. *Analytical Chemistry* **1956**, 28(3), 350-356. DOI:10.1021/ac60111a017.

15. AOAC. Official Methods of Analysis of *The Association of Official Analytical Chemists International*, Gaithersburg, MD, USA, **2000**, 17th Edition.

16. Sun, T., Powers, J.R., & Tang, J. Evaluation of the antioxidant activity of asparagus, broccoli and their juices. *Food Chemistry* **2007**, 105(1), 101-106. DOI:10.1016/j.foodchem.2007.03.048.

17. Sagar, N.A., & Pareek, S. Dough rheology, antioxidants, textural, physicochemical characteristics, and sensory quality of pizza base enriched with onion (*Allium cepa* L.) skin powder. *Nature Scientific Reports* **2020**, 10, 18669. DOI:10.1038/s41598-020-75793-0.

18. Duan, Y., Jin, D.H., Kim, H.S., Seong, J.H., Lee, Y.G., Kim, D.S., Chung, H.S., & Jang, S.H. Analysis of total phenol, flavonoid content and antioxidant activity of various extraction solvents extracts from onion (*Allium cepa* L.) peels. *Journal of the Korean Applied Science and Technology* **2015**, 32(3), 418-426. DOI:10.12925/jkocs.2015.32.3.418.

19. Ibarz, A. El color como parámetro de caracterización de alimentos. *Theknos* **1989**, 112, 48-52.

20. Vásquez-Parra, J.E., Ochoa-Martínez, C.I., & Bustos-Parra, M. Effect of chemical and physical pretreatments on the convective drying of cape gooseberry fruits (*Physalis peruviana*). *Journal of Food Engineering* **2013**, 119(3), 648-654. DOI:10.1016/j.jfoodeng.2013.06.037.

21. Gao, Q.H., Wu, C.S., & Wang, M. The jujube (*Ziziphus jujuba* Mill.) fruit: a review of current knowledge of fruit composition and health benefits. *Journal of Agricultural and Food Chemistry* **2013**, 61(14), 3351-3363. DOI:10.1021/jf4007032.

22. Lattimer, J.M., & Haub, M.D. Effects of dietary fiber and its components on metabolic health. *Nutrients* **2010**, 2(12), 1266-1289. DOI:10.3390/nu2121266.

23. Streppel, M.T., Ocké, M.C., Boshuizen, H.C., Kok, F.J., & Kromhout, D. Dietary fiber intake in relation to coronary heart disease and all-cause mortality over 40 y: the Zutphen Study. *The American Journal of Clinical Nutrition* **2008**, 88(4), 1119-1125. DOI:10.1093/ajcn/88.4.1119.

24. Pereira M.A., O'Reilly E., Augustsson K., Fraser G.E., Goldbourt U., Heitmann B.L., Hallmans G., Knekt P., Liu S.M., Pietinen P., Spiegelman D., Stevens J., Virtamo J., Willett W.C., Ascherio A. Dietary fiber and risk of coronary heart disease—A pooled analysis of cohort studies. *Archives of Internal Medicine*, **2004**, 164, 370–376. DOI:10.1001/archinte.164.4.370.

25. Fakhfakh, N., Jdir, H., Jridi, M., Rateb, M., Belbahri, L., Ayadi, M. A., Nasri, M. & Zouari, N. The mallow, *Malva aegyptiaca* L. (*Malvaceae*): phytochemistry analysis

and effects on wheat dough performance and bread quality. *LWT* **2017**, 75, 656-662. DOI:10.1016/j.lwt.2016.10.015.

26. Šaponjac, V.T., Ćetković, G., Čanadanović-Brunet, J., Pajin, B., Djilas, S., Petrović, J., Lončarević, I., Stajčić, S. & Vulić, J. Sour cherry pomace extract encapsulated in whey and soy proteins: Incorporation in cookies. *Food Chemistry* **2016**, 207, 27-33. DOI:10.1016/j.foodchem.2016.03.082.

27. Michalak-Majewska, M., Sołowiej, B., & SłAwińska, A. Antioxidant activity, technological and rheological properties of baked rolls containing dried onions (*Allium cepa* L.). *Journal of Food Processing and Preservation* **2017**, 41(1), e12914. DOI:10.1111/jfpp.12914.

28. Piazza, L., & Masi, P. Development of crispness in cookies during baking in an industrial oven. *Cereal Chemistry* **1997**, 74(2), 135-140. DOI:10.1094/CCHEM.1997.74.2.135.

29. Grigelmo-Miguel, N., Carreras-Boladeras, E., & Martin-Belloso, O. Influence of the addition of peach dietary fiber in composition, physical properties and acceptability of reduced-fat muffins. *Food Science and Technology International* **2001**, 7(5), 425-431. DOI:10.1106/FLLH-K91M-1G34-Y0EL.

30. Javanmardi, F., Nayebzadeh, K., Saidpour, A., Barati, M., & Mortazavian, A.M. Optimization of a functional food product based on fibers and proteins: rheological, textural, sensory properties, and in vitro gastric digestion related to enhanced satiating capacity. *LWT* **2021**, 147, 111586. DOI:10.1016/j.lwt.2021.111586.

31. Sant'Anna, V., Gurak, P.D., Marczak, L.D.F., & Tessaro, I.C. Tracking bioactive compounds with colour changes in foods–A review. *Dyes and Pigments* **2013**, 98(3), 601-608. DOI:10.1016/j.dyepig.2013.04.011.

32. Mokrzycki, W.S., & Tatol, M. Colour difference ΔE-A survey. *Machine Graphic Vision* **2011**, 20(4), 383-411.

33. Sudha, M.L., Baskaran, V., & Leelavathi, K. Apple pomace as a source of dietary fiber and polyphenols and its effect on the rheological characteristics and cake making. *Food Chemistry* **2007**, 104(2), 686-692. DOI:10.1016/j.foodchem.2006.12.016.

34. Purlis, E., & Salvadori, V.O. Bread browning kinetics during baking. *Journal of Food Engineering* **2007**, 80(4), 1107-1115. DOI:10.1016/j.jfoodeng.2006.09.007.

Chapter 4

Study of a medium-high shelf life ready-to-use dough balls for making “Pizza Napoletana’’

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Chapter 5

Performance characterization of a traditional wood-fired pizza oven

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Abstract

Neapolitan pizza, a renowned Italian food recognized as one of the traditional specialties guaranteed (TSG) by European Commission Regulation no. 97/2010, should be exclusively baked in wood-fired ovens for about 90 s. Despite its extensive use in restaurants and rotisserie shops all around the world, such equipment has been very poorly studied so far. The main aims of this work were to characterize the operation of a pilot-scale wood-fired pizza oven from its start-up phase to its baking operation and assess its thermal efficiency. To manage brick firing, the oven was lighted at firewood feed rate (Q_{fw}) of 3 kg/h for just 1 hour on the 1st day, for 2 hours on the 2nd day, for 4 hours on the 3rd day and for about 8 hours on the 4th one. Independently of its lighting frequency, after 4-6 h the oven vault or floor temperature approached an equilibrium value of 546 ± 53 °C or 453 ± 32 °C, respectively. The initial oven floor temperature gradient resulted to be linearly related to Q_{fw}, while the maximum floor temperature tended to an asymptotic value of 629 ± 43 °C at Q_{fw}=9 kg/h. The well-known *water boiling test* was adapted to assess the heat absorbed by a prefixed amount of water when the pizza oven was operating in pseudo-steady state conditions at Q_{fw}=3 kg/h. The thermal efficiency of such oven was 13 ± 4 %, this value being further confirmed by other baking tests with four different white and tomato pizza products.

Key words: baking test; energy consumption; thermal efficiency; transitory and pseudo-steady-state regime performance; water heating test; wood-fired pizza oven.

Practical Application

Despite wood-fired pizza ovens are largely used all over the world, little is known about their transitory and pseudo-steady-state regime performance. This study shows how perform the start-up procedure of a pilot-scale equipment and, independently of the operator’s ability, how achieve pseudo-steady- state conditions using different firewood feed rates. Finally, its thermal efficiency was assessed by water heating and pizza baking tests, this allowing a rough estimation of firewood consumption.

INTRODUCTION

Neapolitan pizza is an Italian food well known in the global market. It was recognized as one of the traditional specialties guaranteed (TSG) by the European Commission Regulation no. 97/2010 (EC, 2010). Even the art of the Neapolitan pizza maker (*Pizzaiuolo*) was inscribed on the Representative List of the Intangible Cultural Heritage of Humanity by the United Nations Education, Scientific and Cultural Organization (UNESCO, 2017). All its production steps (namely, preparation of dough, its rising process, ball shaping, garnishing, and baking) were fully described by Masi et al. (2015). It is worth noting that the Neapolitan Pizza TSG should be exclusively baked in wood-fired ovens for about 90 s (EC, 2010).

Wood-fired ovens are widely used in restaurants, rotisserie shops and bakeries all around the world. Today, in the United States there are about 77,000 pizzerias employing more than 1 million people (Kuscer, 2022), while in Italy approximately 127,000 companies with pizzeria activities are currently operating with the help of circa 100,000 employees (Anon, 2020). In Italy, the overall turnover of pizza is near to € 15 billion per year (Anon, 2020). 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 (Anon, 2020).

As a result of the widespread use of wood-fired ovens, there is a growing attention towards their stack emissions since these are regarded as responsible for indoor and outdoor air pollution. The burning of wood logs or briquettes in pizzerias was in fact found to be a major source of black carbon and particulate matter with size smaller than 2.5 μm ($PM_{2.5}$) within the Metropolitan Area of São Paulo (Brazil), where it is located one of the largest megacities in the world with more than 20 million inhabitants, 8 million vehicles, and 8,000 pizzerias, about 6,400 of which being equipped with pizza ovens fueled with approximately 48 metric tons/year of firewood (Kumar et al., 2016). The average concentration of $PM_{2.5}$ at the exit of the oven chimney was found to be as high as 6171 $\mu g/m^3$, while that in indoor areas was near to 68 $\mu g/m^3$ (Lima et al., 2020), a level definitively greater than the indoor 24-h mean level (15 $\mu g/m^3$) recommended by WHO (2018).

In the technical literature, wood-fired ovens have been very poorly studied so far. Igo *et al*. (2020) evaluated that the thermal efficiency of a metal fired-wood oven to heat 20 liters of water from 35 to 90 °C was about 19%, while the energy lost by hot fumes or dispersed through the oven walls was about 55% or 26%, respectively. The efficiency of two indirect and semi-direct wood-fired bakery ovens was assessed by measuring an overall consumption of 0.55 and 0.90 kg of wood per kg of wheat flour baked, respectively (Manhiça, 2014; Manhiça *et al*., 2012). Practically, no information about the thermal performance of wood-fired pizza ovens is currently available, and this is a strong limitation in modelling mass and heat transfer mechanisms during pizza baking. On the contrary, the performance of alternative electric pizza ovens in steady and unsteady operating conditions was analyzed by resorting firstly to a three-dimensional numerical model (Ciarmiello and Morrone, 2016a), and secondly to a three-dimensional Computational Fluid Dynamics model to simulate radiative and convective heat transfer mechanisms (Ciarmiello and Morrone, 2016b). During pizza cooking, the decrease in the oven floor temperatures was primarily affected by wall emissivity, while the increase in pizza temperature was sensitive to pizza and wall emissivity in the ranges of 0.6-1.0 or 0.7-1.0, respectively (Ciarmiello and Morrone, 2016b).

Wood-fired ovens generally consist of a base of tuff and fire brick covered by a circular cooking floor over which is built a dome made of refractory materials to minimize heat dispersion. Their geometric dimensions (i.e., cooking floor diameter of 105-140 cm; vault height of 40-45 cm; oven mouth of 45-50 cm in width and 22-25 cm in height) allow the temperature of the cooking floor and dome to be kept at about 430 °C and 485 °C, respectively, this ensuring the baking quality of the Neapolitan Pizza TSG (EC, 2010).

The operation of a wood-fired oven accounts for four interactive processes: combustion, heat, flow, and mass transfer. As firewood burns in a specific area of the baking floor, releasing energy and forming the flame, air naturally enters through the open entry door of the oven and makes firewood burning, while the resulting flue gases are discharged through the oven chimney. Heat transfer is just one of such processes and no exact solution can be obtained unless four groups of equations, corresponding to all these processes, are solved simultaneously. In particular, the basic unsteady-state energy equation of heat transfer from the flame to the oven walls and floor must include a mathematical model of heat transfer in the oven, its solution generally being of the numerical type. Even for an approximate solution the amount of calculation is very large and semiempirical methods are those most often used for engineering design (Zhang et al., 2016).

The main aim of this work was to characterize the operation of a pilot-scale wood-fired pizza oven from its start-up phase (according to the procedure suggested by the manufacturer) to its baking operation to provide a basis for future modelling of novel pizza oven design. The well-known *water boiling test*, generally used to measure the thermal efficiency of cookstoves (Global Alliance for Clean Cookstoves, 2014), was adapted to measure the energy efficiency of the pizza oven in pseudo-steady state conditions when heating a prefixed amount of water or different pizza types.

MATERIALS AND METHODS

Raw materials

To prepare the Neapolitan pizza bases used in this work the following ingredients were used: (i) soft wheat flour type 00 with a nominal moisture content of 12% w/w was kindly supplied by Mulino Caputo (Antimo Caputo Srl, Naples, Italy), (ii) fresh brewer's yeast (Lesaffre Italia, Trecasali, Parma, Italy), (iii) Sicilian fine table salt (Italkali, Petralia, Palermo, Italy), and (iv) deionized water at 16-18 °C. Each pizza base was baked as such or garnished using sunflower oil (Mepa Srl, Terzigno, Naples, Italy) and/or tomato puree at 7.0±0.2 °Brix (Mutti SpA, Parma, Italy). The wood-fired oven was fed with dry, seasoned oak logs from the Royal Park of Portici (Department of Agricultural Sciences of the University of Naples - Federico II), their average weight, length, and diameter being equal to 600±200 g, 250±20 mm, and 40±10 mm, respectively.

Pizza preparation

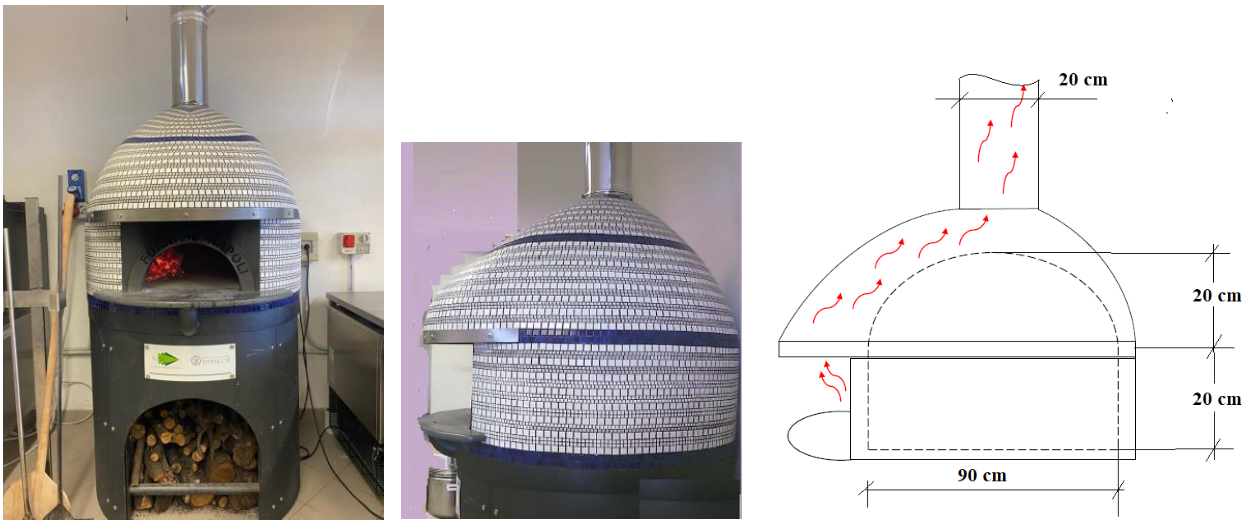
The pizza dough was prepared by mixing 1,600 g of soft wheat flour type 00 and 50 g of table salt with 1 L of deionized water at room temperature, where 1 g of fresh brewer's yeast had been previously dispersed to allow its hydration for about 3 min. Such operation was carried out in a spiral mixer (Grilletta IM5, Famag Srl, Milan, Italy) set at level 1 for 18 min (see Fig S1 in the supplement). The dough was then left resting at room temperature for 20 min. Thereafter, the dough was subdivided into dough balls weighing ~250 g each. These were placed over 60 cm x 40 cm plastic trays (Giganplast, Monza and Brianza, Italy), and stored in a climatic chamber (KBF 240, Binder, Tuttlingen, Germany) to let them rise at 22 °C and 80% relative humidity for 18 h to hydrolyze enzymatically aliquots of starches and proteins and obtain a more extensible and digestible structure (see Fig. S2). The leavened loaves were sprinkled with a pinch of flour, and then manually laminated under the pressure of both hands' fingers from the center outwards by turning the resulting disc several times. The final disc (i.e., the pizza base) had a diameter of about 28 ± 1 cm and an average mass of 250 ± 1 g. Such a base was baked as such (sample A) or garnished as shown in Table 1 (samples B-D).

Table 1: Samples of Neapolitan Pizza submitted to baking tests in the wood-fired oven used in this work.

Sample	Topping	Overall mass [g]
A	No garnishment	250±1
B	Sunflower oil (30 g)	280±2
C	Tomato puree (70 g)	320±2
D	Tomato puree (70 g) and sunflower oil (30 g)	350±3

Equipment

Fig. 1 shows the pilot-scale wood-fired pizza oven used in this work together with its chamber geometry. The oven chamber can be approximated to a cylinder, having diameter and height of 90 cm and 20 cm, respectively, surmounted by an oblate ellipsoidal vault of the same height. The pizza oven had a semicircular open mouth, its diameter and height being equal to 44 and 22 cm, respectively. The oven walls and floor were about 10-cm in thickness. Oak logs were fed through the mouth of the pizza oven. As they were burning, the hot combustion flue gases were naturally drawn up and out of the chimney, while ambient air as it (at 36.4±4.8 °C and 20.4±0.9 % Relative Humidity) was sucked inside through the entry door. About one fourth of the floor surface area was occupied by burning wood logs, while the remaining surface area being was used for pizza baking.



a) **b)** **c)**

Figure 1: Front (**a**) and lateral (**b**) pictures of the wood-fired pizza oven used in this work together with the geometry of its chamber (**c**).

Start-up procedure

The start-up procedure for this wood-fired pizza oven was carried out as recommended by the manufacturer (MV Napoli Forni, Naples, Italy). The oven was fed with 1 kg of oak logs every 20 min (i.e., 3 kg/h) and fired for just 1 h on the first day (see Fig. S3). Then, the same operation was repeated for 2 h on the second day, for 4 h on the third day, and finally for ~8 h on the fourth day. During such lighting tests the temperatures of the oven vault (T_V) and floor (T_{FL}) were monitored using a thermal imaging camera (FLIR E95 42°, FLIR System OU, Estonia) equipped with an uncooled microbolometer thermal sensor with dimension 7.888 x 5.916 mm and resolution 464 x 348 pixels. The pixel pitch of the sensor is 17 µm, the lens 10 mm and a field of view of 42° x 32°.

After such start-up procedure, the wood-fired pizza oven was retained as fully operative. In the circumstances, by feeding the oven with 3 kg of oak logs per hour (Q_{fw}) for about 6 h, it was possible stabilized the values of T_{FL} and T_V, as reported below. Then, the firewood feed rate (Q_{fw}) was varied from 3 to 9 kg/h to measure the responsiveness of the initial growth rate of T_{FL}. In the meanwhile, the mean superficial velocity (v_{FG}) and temperature (T_{FG}) of flue gases at the exit section of the oven chimney were simultaneously measured using a Hotwire Anemometer mod RS PRO RS-8880 (RS Components, Corby, United Kingdom), while the flue gas temperature at the oven mouth was determined using the temperature logger 175 T3 (Testo SE & Co. KGaA, Titisee-Neustadt, Germany). The fraction of wood logs that were effectively exploited to create heat during these trials was assessed by feeding the oven at each selected woodfire rate (Q_{fw}) for about 6 h. One hour later, the residual unburned wood logs were separated from wood ashes and weighted. The combustion efficiency (η_{comb}) was defined as the ratio between the masses of such unburned residues and overall mass of oak logs supplied during each firing test.

Baking tests

Once the oven had been pre-heated at Q_{fw}= 3 kg/h for 6 h, the following tests were carried out in triplicate:

(1) A circular aluminum tray (26 cm in diameter and 19.35 g in mass) was filled with 300 g of deionized water at an initial temperature of 25.8±0.2 °C, weighted and then introduced into the oven, where it was kept for 10 to 80 s. As soon as the tray had been withdrawn from the oven, the temperature of the oven floor was suddenly measured in several areas different from that occupied by the tray using the above thermal imaging camera. Then,

the mass of the water remaining in the tray and its temperature were measured using an analytical balance (Gibertini, Milano, Italy) and a temperature logger 175 T3 (Testo SE & Co. KGaA, Titisee-Neustadt, Germany), respectively.

(2) Each pizza sample of the 4 types shown in Table 1 was baked in the wood-fired oven for 20, 40, 60, and 80 s. As soon as each sample was removed from the oven, the temperature of the oven floor area previously occupied by the sample itself, as well as that of the annular area around the sample itself, was measured as reported above. Then, as soon as the pizza sample had been extracted from the oven, the temperatures of the pizza disc in the rim, and upper and lower central areas were measured using the thermal imaging camera. Finally, the sample mass was determined to assess its weight loss.

Energy performance assessment of the pizza oven

By neglecting the energy contribution of inlet air and firewood, the thermal performance of the pizza oven was assessed by writing the following heat balance:

$$E_{fw} = E_S + E_W + E_{FG} \qquad (1)$$

where E_{fw} is the energy supplied by firewood, E_S the energy absorbed by the sample of choice, E_W the energy lost by walls, and E_{FG} the energy dissipated by flue gases.

Oak logs used here had moisture (x_W) and ash (x_A) contents of 5.67±0.17 and 2.89±0.66 g/100 g of wet matter, respectively. According to Vassilev et al. (2010), the dry matter of oak wood would contain 50.6% carbon (x'_C), 42.9% oxygen (x'_O), 6.1% hydrogen (x'_H), 0.3% nitrogen (x'_N), and 0.1% sulfur (x'_S). Thus, its higher (HHV) and lower (LHV) heating values were estimated as follows (Mukunda, 2009):

$$HHV = 33.823\ x'_C + 144.249\ (x'_H - x'_O/8) + 9.418\ x'_S \qquad (2)$$

$$LHV = HHV - 22.604\ x'_H - 2.581\ x_M \qquad (3)$$

where x'_C, x'_H, x'_O, and x'_S are the weight fractions of carbon, hydrogen, oxygen, and sulfur on dry basis of the biomass under study, and x_M the moisture content on wet matter. Thus, since HHV and LHV were about 18.19 and 16.66 MJ/kg, the energy supplied by oak logs was estimated as

$$E_{fw} = \eta_{comb}\ Q_{fw}\ LHV\ t \qquad (4)$$

where Q_{fw} is the firewood feed rate (kg/h), t the heating time (in h), and η_{comb} the combustion efficiency.

The energy stored by each sample, as such or including its vessel, upon its heating from the initial temperature (T_{S0}) to a generic temperature (T_S), and the vaporization energy of the water lost were calculated as

$$E_S = (m_S\, c_{ps} + m_V\, c_{pV})\,(T_S - T_{S0}) + m_{ev}\, \lambda_{ev} \quad (5)$$

with

$$m_{ev} = m_{S0} - m_S \quad (6)$$

where m_{S0} and m_S are the initial and current masses of the sample, m_{ev} is the water evaporated, m_V the mass of vessel, λ_{ev} the latent heat of water vaporization at T_S (in °C), c_{pS} and c_{pV} are the specific heat values of sample and vessel (in kJ kg^{-1} K^{-1}).

The efficiency of the pizza oven (η_{PO}) was estimated as the ratio between the energy absorbed by the load and that supplied by firewood (direct method):

$$\eta_{PO} = E_S/E_{fw} \quad (7)$$

Table 2 shows all the parameters used to calculate □$_{PO.}$

Table 2: Parameters used to estimate the thermal efficiency of the wood-fired pizza oven during the water heating and baking tests performed in this work.

Parameter	Value	Unit	References
Mass of water (m_{S0})	300.0±0.1	g	
Mass of aluminum tray (m_V)	19.35±0.05	g	
Mass of pizza samples (m_{S0})	250-350	g	
Specific heat of water (c_{PW})	4.186	kJ kg^{-1} K^{-1}	Singh et al. (2009)
Specific heat of aluminum tray (c_{PV})	0.890	kJ kg^{-1} K^{-1}	Singh et al. (2009)
Specific heat of dough (c_{PD}) or tomato puree (c_{PT}) at x_W	$0.837 + 3.349\, x_W$	kJ kg^{-1} K^{-1}	Heldman and Lund (2007)
Specific heat of sunflower oil (c_{PSO})	$(1.86±0.03) + (2.25±0.22)\, x10^{-3}\, T_S$	kJ kg^{-1} K^{-1}	Santos et al. (2005)
Latent heat of water evaporation (λ_{ev})	$1.919x10^3 \left(\frac{T_S + 273.15}{T_S + 239.24}\right)^2$	kJ kg^{-1}	Henderson-Sellers (1984)

Statistical analysis of data

Each baking test was carried out in triplicate. All parameters were shown as average ± standard deviation (sd) and were analyzed by Tukey test at a probability level (p) of 0.05. One-way analysis of variance was carried out using SYSTAT version 8.0 (SPSS Inc., 1998).

RESULTS AND DISCUSSION

Start-up procedure of the wood-fired pizza oven

The start-up procedure is aimed at controlling the intensity of the thermal reactions taking place during firing of the refractory bricks installed inside the wood-fired pizza oven under study. In clay materials, such reactions may be either endothermic (as due to dehydration process, change in crystal phase or destruction of lattice structure) or exothermic (as due to oxidation or new crystalline phase formation) (Grim and Johns, jr., 1951). The loss of lattice water from the clay mineral components may be abrupt, thus the heating rate is to be controlled to limit structural change and cause little or no disruption of the brick.

In this case, as suggested by the oven manufacturer, the oven was fired at a rate of 1 kg of firewood every 20 min for just 1 hour on the first day, for 2 hours on the second day, for 4 hours on the third day and for about 8 hours on the fourth one.

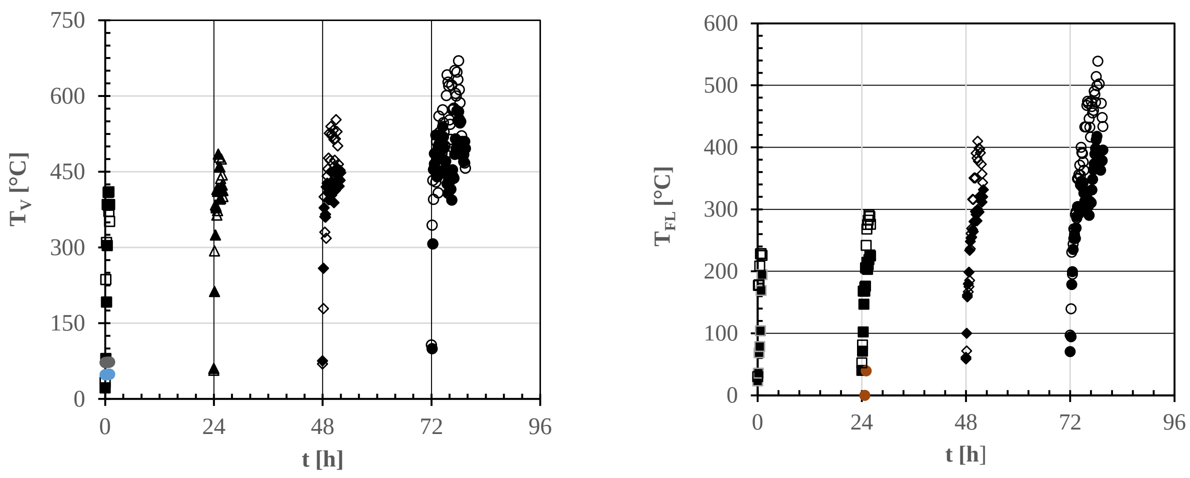


Figure 2: Time (t) course of the oven vault (T_V: **left**) and floor (T_{FL}: **right**) temperatures as measured using a thermal imaging camera during the first start-up procedure (closed symbols) and the repeated one a week later (open symbols): ■, □, day 1; ▲,△, day 2; ◆, ◇, day 3; ●, ○, day 4.

Fig. 2 shows the time course of the temperatures of the oven vault (T_V) and floor (T_{FL}) during the start-up procedure. It can be noted a steep increase in both temperatures in consequence of the heat released by burning logs. Moreover, as the heating time during each step was prolonged from 1 h to about 8 h, the initial values of T_V and T_{FL} tended to progressively increase thanks to the low thermal dispersivity of the insulated oven walls. As shown in Table S1 in the supplement, the initial mean values of the vault temperature gradient reduced from about 450 °C/h to 340 °C/h as the start-up procedure progressed. By contrast, the initial derivate of the oven floor temperature with respect to time was approximately constant (148±42 °C/h).

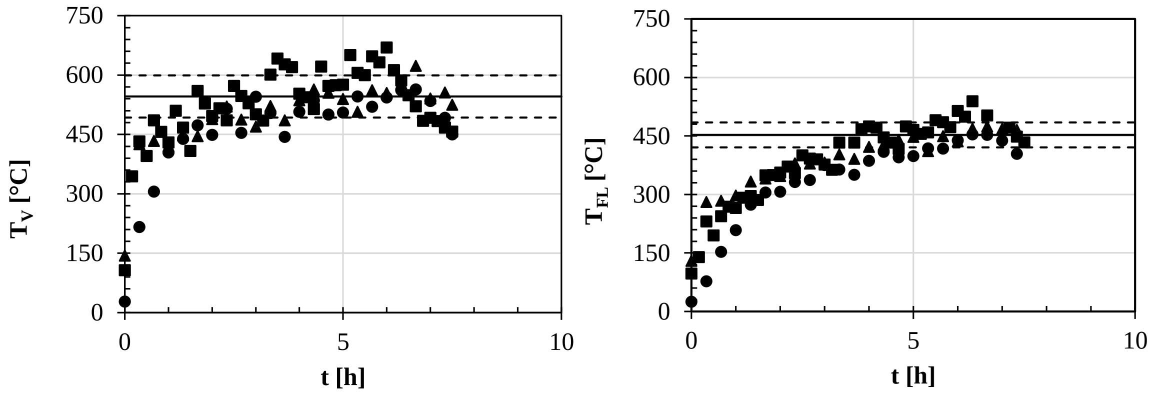


Figure 3: Time (t) course of the oven vault (T_V: **left**) and floor (T_{FL}: **right**) temperatures as measured using a thermal imaging camera during the lighting on the 11th (■), 22nd (●) and 23rd (▲) day: ——, mean steady-state temperature; -----, (mean ± sd) steady-state temperature.

Fig. 3 shows the repeatability degree of the heating process of the pilot-scale pizza oven when fed with 3 kg of oak logs per hour. Independently of the lighting frequency of the wood-fired oven, after 4- to 6-h firing T_V or T_{FL} tended to a pseudo-steady state value of 546 ± 53 °C or 453 ± 32 °C, respectively. Thus, all the following baking tests were performed on condition that the pizza oven had been fired for not shorter than 6 h. Finally, it was studied how the initial growth rate of T_{FL} was affected by firewood feed rate (Q_{fw}) in the range of 3 to 9 kg/h. Fig. S4 in the supplement shows the time course of T_{FL} at different Q_{fw} values. Whatever Q_{fw}, the oven floor temperature increased almost linearly with time, reached a maximum value, and then started to decline 30-40 min after firewood feeding had been stopped. For working times t≤70 min, the increase in the oven floor temperature with respect to its initial value (T_{FL}-T_{FLo}) was linearly related to the heating time (t), as pointed out by the coefficients of determination (r^2) listed in Table 3.

Table 3: Mean and standard deviation (sd) values of the gradient of the oven floor temperature [(dT_{FL}/dt)] and relative coefficient of determination (r^2) as a function of firewood feed rate (Q_{fw}) used during a few lighting tests.

Q_{fw}	dT_{FL}/dt [°C/h]	r^2
[kg/h]	mean ± sd	
3.0	185 ± 3 [a]	1.00
3.0	178 ± 29 [a]	0.91
3.0	113 ± 4 [b]	0.99
4.5	252 ± 20 [c]	0.96
6.0	304 ± 25 [d]	0.96
6.0	349 ± 13 [d]	0.99
9.0	402 ± 35 [e]	0.95
9.0	450 ± 50 [e]	0.92
9.0	394 ± 41 [e]	0.93
9.0	437 ± 42 [e]	0.94

Mean values of the oven floor temperature gradient followed by different superscript letters significantly differ by the Tukey test ($p<0.05$).

Fig. *4 left* shows that the initial gradient of the oven floor temperature ($dT_{FL}/dt|_0$) was linearly related to Q_{fw} as

$$\frac{dT_{FL}}{dt}\Big|_0 = (49 \pm 2)\, Q_{fw} \qquad (r^2=0.99) \qquad (8)$$

By contrast, the maximum value of the floor temperature ($T_{FL,max}$) increased linearly for $Q_{fw}<4$ kg/h, but tended to an asymptotic value of 629 ± 43 °C for $Q_{fw}=9$ kg/h (Fig. 4 at left). Thus, a quadratic least squares regression was estimated to related $T_{FL,max}$ to Q_{fw}:

$$T_{FL,max} = (165 \pm 11)\, Q_{fw} - (10.6 \pm 1.3)\, (Q_{fw})^2 \qquad (r^2=0.99) \qquad (9)$$

Both Eq.s (8) and (9) might be used to control the thermal performance of the wood-fired pizza oven.

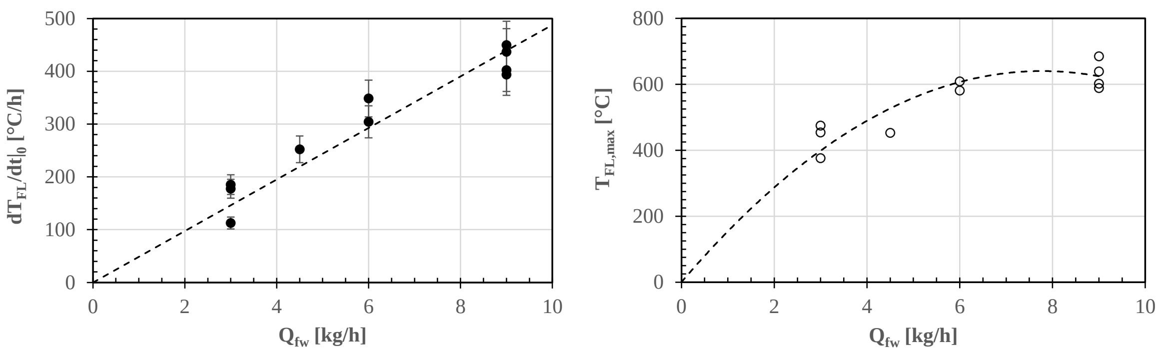


Figure 4: Effect of firewood feed rate (Q_{fw}) on (**left**) the derivate of the oven floor temperature with respect to time ($dT_{FL}/dt|_0$) at t=0, and (**right**) maximum oven floor temperature ($T_{FL,\,max}$) in the wood-fired pizza oven used here. Each broken line was plotted using Eq. (8) or (9).

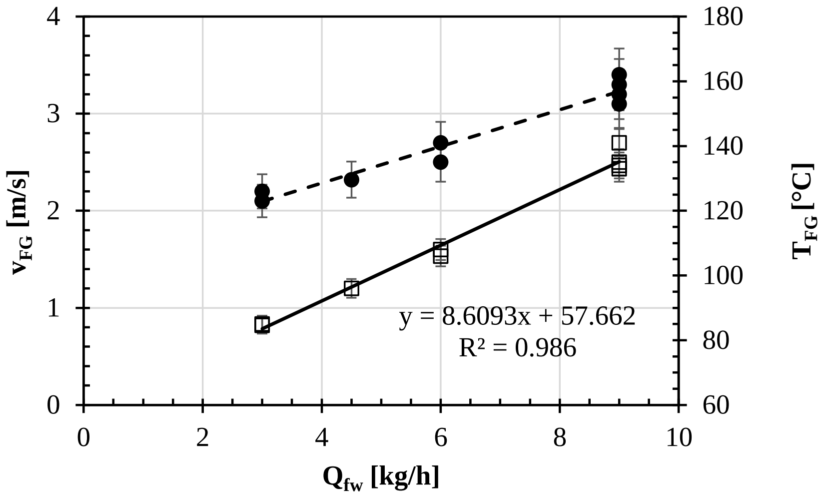


Figure 5: Effect of firewood feed rate (Q_{fw}) on the mean superficial velocity (v_{FG}: ●) and temperature (T_{FG}: □) of flue gases at the exit section of the oven chimney. The broken or continuous line was plotted using Eq. (10) or (11).

As the oak logs had been fed through the mouth of the pizza oven and had started to burn, the resulting hot combustion flue gases having a lower density than the outside air density were naturally forced to flow out of the oven chimney. Their effective volumetric flow rate is directly proportional to chimney height, temperature difference between the ascending flue gases and the outside air, and pressure drops along the chimney path (Rahman et al., 2021). Thus, as the woodfire feeding rate (Q_{fw}) was increased from 3 to 9 kg/h, the increase in the temperature of flue gases lowered their density and this enhanced their volumetric flow rate. As shown in Fig. 5, the mean superficial velocity (v_{FG}) and temperature (T_{FG}) of flue gases at the exit section of the oven chimney as measured using a Hotwire Anemometer were found to be almost linearly related for Q_{fw}:

$$v_{FG} = (0.19 \pm 0.02) \times Q_{fw} + (1.5 \pm 0.1) \qquad (r^2 = 0.954) \qquad (10)$$

$$T_{FG} = (8.6 \pm 0.4) \times Q_{fw} + (57.7 \pm 2.7) \qquad (r^2 = 0.986) \qquad (11)$$

Finally, in a few burning tests carried out at Q_{fw} equal to 3 or 9 kg/h, the residual unburned wood logs amounted to about (13±3) or (21±4) % of the overall mass of oak logs supplied, respectively. Thus, the combustion efficiency (η_{comb}) tended to reduce from 87±3 % to 79±4 % as Q_{fw} was increased from 3 to 9 kg/h, respectively. Owing to the linear relationship between the other parameters characterizing the operation of the natural draft chimney of the wood-fired pizza oven and firewood feed rate, η_{comb} is expected to decrease linearly from the above maximum and minimum values.

Such results might help unskilled operators to operate the wood-fired pizza oven in quasi-steady-state regime when woodfire feeding rate was varied from 3 to 9 kg/h.

Performance of the wood-fired pizza oven

Water heating test

Once the pilot-scale wood-fired pizza oven had been pre-lighted at Q_{fw}=3 kg/h for 6 h, prefixed amounts of deionized water (300 g), as contained in aluminum circular trays having approximately the same diameter of a Neapolitan pizza, were heated for different times. Throughout such tests, the oven floor temperature was practically constant (448 ± 5 °C). On the contrary, the sample temperature (T_S) increased from T_{S0} (25.8 ± 0.2 °C) to 77.3 ± 1.2 °C, while its mass (m_S) decreased from 300 ± 0 g to 264 ± 4 g in just 80 s. Such data allowed the energy stored by the sample (E_S) to be calculated using Eq. (5) in conjunction with the thermal properties listed in Table 2. E_S was then referred to the energy generated by oak combustion, as calculated via Eq. (4), to estimate the thermal efficiency of the pizza oven (η_{PO}) using Eq. (7).

Table 4 shows all the parameters either directly measured (T_{FL}, T_{S0}, T_S, m_W) or estimated (E_S, E_{fw}, η_{PO}) as reported above.

The average energy efficiency for the pizza oven examined here was equal to (14.7 ± 0.5) %. It was in line with that of traditional domestic ovens, but smaller than that estimated by Igo *et al*. (2020) for a metal fired-wood oven. The thermal efficiency of well-insulated conventional electric ovens usually ranges from 10% to 15%, while that of gaseous ovens varies from 6% to 7% because of the higher air flows and electric glow-bar that run continuously to reignite the gas flame should it blow out (Barratt, 2021; Hager and Morawicki, 2013). Thus, the great majority of heat was lost by hot fumes or dispersed through the oven walls by convention or open oven mouth by radiation

Table 4: Main results (mean ± sd) of three repeated water heating tests performed in a wood-fired pizza oven fed with 3 kg/h of oak logs: effect of time (t) on the oven floor temperature (T_{FL}), initial (T_{S0}) and current (T_S) temperatures of water samples, instantaneous mass of water (m_W), energy stored by the sample (E_S), combustion heat (E_{fw}), and oven efficiency (η_{PO}).

t	T_{FL}	T_{S0}	T_S	m_W	E_S	E_{fw}	η_{PO}
[s]	[°C]	[°C]	[°C]	[g]	[kJ]	[kJ]	[%]
0	-	25.8±0.2 ^{a}	25.8±0.2 ^{a}	300.0±0.1 ^{a}	0.0	0	-
10	447.0±6.6 ^{a}	25.8±0.2 ^{a}	44.3±1.5 ^{b}	298.0±1.0 ^{b}	28±4	120.8	23.4±3.5 ^{a}
20	449.0±1.7 ^{a}	25.8±0.3 ^{a}	52.0±1.0 ^{c}	296.0±1.7 ^{c}	43±5	241.6	17.6±2.0 ^{a,b}
30	449.3±4.7 ^{a}	25.8±0.1 ^{a}	58.7±1.2 ^{d}	293.0±1.0 ^{c}	58±3	362.4	15.9±1.0 ^{b}
40	448.7±6.0 ^{a}	25.8±0.1 ^{a}	64.0±1.0 ^{e}	288.3±2.3 ^{c}	74±6	483.2	15.4±1.3 ^{b}
50	446.0±3.0 ^{a}	25.8±0.2 ^{a}	70.7±0.6 ^{f}	285.0±1.0 ^{c}	90±1	604.0	14.9±0.2 ^{b}
60	445.0±3.0 ^{a}	25.7±0.2 ^{a}	72.7±0.6 ^{g}	280.7±1.5 ^{d}	102±4	724.8	14.0±0.5 ^{b,c}
70	449.7±8.5 ^{a}	25.7±0.3 ^{a}	75.7±1.5 ^{h}	269.3±5.9 ^{e}	129±14	845.6	15.3±1.6 ^{b}
80	449.0±7.0 ^{a}	25.6±0.4 ^{a}	77.3±1.2 ^{h}	264.0±3.6 ^{e}	143±8	966.4	14.8±0.9 ^{b}

Mean values within the same parameter followed by different superscript letters significantly differ by the Tukey test ($p<0.05$).

Pizza baking tests

During such tests, white and tomato pizzas, as such or topped with sunflower oil, were baked for no more than 80 s in a pre-heated wood-fired oven at Q_{fw}=3 kg/h for 6 h.

Table 5 shows all the parameters directly measured, such as the temperature of the oven floor exposed to fire (T_{FL}) or shielded by the pizza sample undergoing baking (T_{FLbp}), temperatures of different pizza sectors, such as its rim (T_{SR}) and upper (T_{SU}) and lower (T_{SL}) central areas, as well as the mass of sample (m_S). Moreover, Table 5 lists the instantaneous values of other calculated parameters, such as the moisture mass fraction on an oil-free basis (x_W), energy stored by the sample (E_S), combustion heat (E_{fw}), and oven efficiency (η_{PO}). Since the temperature of the pizza samples was generally not uniform throughout any test, its average temperature ($T_{S,ave}$) was estimated by weighing the temperatures of the pizza sectors mentioned above on a mass basis, by assuming that the rim, upper and lower areas represented about 15%, 78% and 7% of the overall sample mass, respectively. Moreover, the temperature of the areas topped with sunflower oil was used to calculate the sensible heat stored in the oil ingredient.

Table 5: Main results (mean ± sd) of three repeated baking tests performed in a wood-fired pizza oven fed with 3 kg/h of oak logs using four different pizza types: effect of time (t) on the instantaneous temperature of the oven floor exposed to fire (T_{FL}) or shielded by the pizza sample (T_{FLbp}), temperatures of the pizza rim (T_{SR}), upper (T_{SU}) and lower (T_{SL}) areas, mass of sample (m_S), moisture fraction (x_W), average sample temperature ($T_{S,ave}$), energy stored by the sample (E_S), combustion heat (E_{fw}), and oven efficiency (η_{PO}).

t	T_{FL}	T_{FLbp}	T_{SR}	T_{SU}	T_{SL}	m_S	x_W	$T_{S,ave}$	E_S	E_{fw}	η_{PO}
[s]	[°C]	[°C]	[°C]	[°C]	[°C]	[g]	[g/g]	[°C]	[kJ]	[kJ]	[%]
White pizza											
0	442 ± 9 ^{a}	442 ± 9 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	250.0±1.0 ^{a}	0.450	21.0±0.1 ^{a}	0.0	0	-
20	441 ± 7 ^{a}	363 ±10 ^{b}	80.0±3.0 ^{b}	103.0±2.0 ^{b}	84.0±2.0 ^{b}	248.2±0.2 ^{b}	0.446	98.5±0.7 ^{b}	48.9±5.0 ^{a}	241.6	20.2±0.2 ^{a}
40	436 ±11 ^{a}	348 ± 5 ^{b}	116.0±3.0 ^{c}	138.0±7.0 ^{c}	97.0±2.0 ^{c}	245.9±0.6 ^{c}	0.440	131.8±2.5 ^{c}	72.4±6.0 ^{b}	483.2	15.0±0.3 ^{b}
60	435 ± 7 ^{a}	332 ± 7 ^{c}	130.0±6.0 ^{d}	157.0±6.0 ^{d}	102.0±2.0 ^{d}	243.0±1.0 ^{d}	0.434	149.2±4.0 ^{d}	87.1±4.0 ^{c}	724.8	12.0±0.3 ^{c}
80	432 ±10 ^{a}	325 ± 5 ^{c}	148.0±9.0 ^{e}	182.0±9.0 ^{e}	106.0±3.0 ^{d}	240.6±0.7 ^{e}	0.428	171.5±2.1 ^{e}	103.5±8.0 ^{d}	966.4	10.7±0.1 ^{d}
White pizza garnished with sunflower oil											
0	446 ± 5 ^{a}	448 ± 7 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	280.0±2.0 ^{a}	0.450	21.0±0.1 ^{a}	0.0	241.6	-
20	443 ± 6 ^{a}	351 ±11 ^{b}	86.0±3.0 ^{b}	100.0±3.0 ^{b}	81.0±2.0 ^{b}	278.4±0.2 ^{a}	0.446	97.0±1.0 ^{b}	52.3±0.7 ^{a}	483.2	21.6±0.3 ^{a}
40	441 ± 7 ^{a}	342 ± 9 ^{b}	116.0±7.0 ^{c}	128.0±6.0 ^{c}	93.0±5.0 ^{c}	276.7±0.6 ^{b}	0.442	124.0±3.0 ^{c}	72.8±2.0 ^{b}	724.8	15.1±0.4 ^{b}
60	439 ±11 ^{a}	327 ± 7 ^{c}	149.0±7.0 ^{d}	148.0±5.0 ^{d}	101.0±3.0 ^{d}	272.4±1.3 ^{c}	0.432	145.0±1.0 ^{d}	93.8±0.6 ^{c}	966.4	12.9±0.1 ^{c}
80	434 ± 8 ^{a}	314 ± 7 ^{b,c}	169.0±9.0 ^{e}	156.0±4.0 ^{d}	105.0±2.0 ^{d}	267.7±1.6 ^{d}	0.421	155.0±2.0 ^{e}	108.1±0.9 ^{d}	241.6	11.2±0.1 ^{d}
Tomato pizza											
0	443 ± 8 ^{a}	440 ± 7 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	320.0±2.0 ^{a}	0.555	21.0±0.1 ^{a}	0.0	241.6	-
20	442 ± 7 ^{a}	339 ±10 ^{b}	83.0±2.0 ^{b}	59.0±2.0 ^{b}	75.0±2.0 ^{b}	319.1±0.3 ^{a}	0.553	63.6±1.4 ^{b}	38.7±1.2 ^{a}	483.2	16.0±0.5 ^{a}
40	439 ± 7 ^{a}	328 ± 6 ^{b}	113.0±4.0 ^{c}	71.0±2.0 ^{c}	92.0±3.0 ^{c}	317.1±0.5 ^{b}	0.551	79.0±0.8 ^{c}	56.1±0.6 ^{b}	724.8	11.6±0.1 ^{b}
60	438 ± 8 ^{a}	320 ±10 ^{b,c}	124.0±3.0 ^{d}	76.0±2.0 ^{d}	96.0±2.0 ^{c}	314.1±0.3 ^{c}	0.546	84.8±1.1 ^{d}	67.2±0.9 ^{c}	966.4	9.3±0.1 ^{c}
80	436 ± 6 ^{a}	304 ± 5 ^{c}	136.0±3.0 ^{e}	81.0±2.0 ^{e}	101.0±2.0 ^{d}	311.2±0.8 ^{d}	0.542	90.6±0.4 ^{e}	77.9±0.3 ^{d}	241.6	8.1±0.1 ^{d}
Tomato pizza garnished with sunflower oil											
				Tomato area / Oil area							
0	440 ± 7 ^{a}	438 ±10 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a} / 21.0±0.1 ^{a}	21.0±0.1 ^{a}	350.0±3.0 ^{a}	0.555	21.0 ± 0.1 ^{a}	0.0	241.6	-
20	438 ± 5 ^{a}	332 ±12 ^{b}	88.0±3.0 ^{b}	61.0±3.0 ^{b} / 89.0±5.0 ^{b}	74.0±3.0 ^{b}	349.4±0.1 ^{a}	0.554	66.3 ±2.6 ^{b}	44.5±2.5 ^{a}	483.2	18.4±1.0 ^{a}
40	437 ± 7 ^{a}	318 ± 5 ^{b,c}	115.0±5.0 ^{c}	73.0±2.0 ^{c} / 100.0±4.0 ^{c}	87.0±2.0 ^{c}	347.2±0.5 ^{b}	0.551	80.3 ±0.1 ^{c}	62.0±0.1 b	724.8	12.8±0.1 ^{b}
60	437 ± 6 ^{a}	313 ± 7 ^{b,c}	128.0±5.0 ^{d}	79.0±2.0 ^{d} / 103.0±2.0 ^{c}	93.0±2.0 ^{d}	344.7±0.3 ^{c}	0.547	87.3 ±0.6 ^{d}	73.2±0.5 ^{c}	966.4	10.1±0.1 ^{c}
80	436 ± 6 ^{a}	309 ± 7 ^{c}	141.0±2.0 ^{e}	84.0±2.0 ^{e} / 106.0±2.0 ^{c}	102.0±2.0 ^{e}	341.0±1.9 ^{d}	0.542	94.0 ±0.5 ^{e}	86.5±0.5 ^{d}	241.6	9.0±0.1 ^{d}

Mean values within the same parameter at different baking times followed by different superscript letters significantly differ by the Tukey test ($p<0.05$).

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First, during all such tests the wood-fired oven behaved in almost quasi-steady-state conditions, its floor temperature showing no statistically significant variation around 439 ± 8 °C at the probability level of 0.05. Second, the moisture content on an oil-free basis (x_W) of white pizza samples reduced from 0.45 to 0.42 g/g, while that of tomato pizza ones from 0.56 to 0.54 g/g. The temperature of the upper central areas of white pizza samples tended to the smoke point (~211 °C) of sunflower oil at ambient pressure (http://www.centrafoods.com/blog/edible-oil-smoke-flash-points-temperature-chart; accessed on 15 March 2022), whereas that of the tomato pizza counterparts increased to a value well below the boiling of water, that is 82-84 °C (Table 5). By contrast, owing to its direct contact with the oven floor the lower side of each sample rapidly reached a temperature more (105-106 °C) or less (101-102 °C) greater than the water boiling point depending on its smaller or greater moisture content, respectively. When topped with oil, each pizza sample stored a greater amount of energy, that is 108 instead of 104 kJ in the case of white pizza, or 87 vs. 78 kJ in the case of tomato pizza (Table 5). It can be noted that the specific energy stored by pizza samples reduced almost linearly ($r^2 = 0.88$) from 430 ± 5 to 254 ± 1 kJ/kg as the mass of the garnished pizza sample increased from 0.25 to 0.35 kg. Since the pizza oven was operating in pseudo-steady-state conditions, the net heat flux transferred to each pizza sample by radiation and convention was in all probability about constant and almost insensitive to the emissivity of the different pizza topping ingredients used (Ciarmiello and Morrone, 2016b). Thus, despite the difference in the thermal properties (including emissivity) of the pizza topping ingredients, the increase in the temperature of each pizza sample was inversely proportional to its overall mass. Finally, the oven efficiency resulted to be not statistically different at the 95% confidence level when baking white pizza as such (14.5 ± 3.8 %), and white (15.2 ± 4.1 %) and tomato pizzas (12.6 ± 3.8 %) both topped with sunflower oil. The thermal efficiency reduced to (11.2 ± 3.2 %) in the case of tomato pizza as such, this being statistically different from the above values at the probability level of 0.05. Altogether, the average thermal efficiency of the wood-fired oven examined in this work was around (13 ± 4 %) when referring to both the water heating and baking tests mentioned above. Obviously, such an efficiency is to be regarded as overestimated, since it accounts for the only combustion energy freed during the baking tests and neglects the energy supplied by firewood during the preliminary 6-h pre-lighting step needed to put the oven in quasi pseudo-steady state conditions.

In the circumstances, despite the high quality of baking provided by such equipment, its use results not only in excessive consumption of biomass fuels, this leading to natural forest degradation and deforestation especially in a few areas of Africa (Okino et al., 2021), but also in high indoor levels of air pollutants (i.e., carbon monoxide, polycyclic aromatic hydrocarbons, sulfur dioxide, nitrogen oxide, black carbon, and particulate matter), as observed in several metropolitan areas (Apurva, 2016; Kumar et al., 2016) and in a study dealing with the environmental profile of a few households cooking systems, including firewood ones (Cimini and Moresi, 2022).

To surmount such problematic issues, the Associazione Verace Pizza Napoletana (AVPN, 2004) would allow the use of an alternative electric oven [i.e., the *Scugnizzo Napoletano* one developed by Izzo Forni, Naples, Italy: https://www.izzoforni.it/izzonapoletano/ (accessed on 9 March 2022)], since such an oven succeeded in a series of physical and sensory tests, as well as numerical ones using a three-dimensional Computational Fluid Dynamics numerical model under unsteady and steady conditions (Ciarmiello and Morrone, 2016b).

CONCLUSIONS

In this work, the performance of a pilot-scale wood-fired pizza oven like those commonly used in Neapolitan pizzerias in Italy was assessed. Firstly, its start-up procedure was performed. Second, it was studied how, independently of the operator's ability, the oven can be put in quasi-steady-state conditions with its dome and floor temperatures exhibiting no appreciable fluctuations by varying firewood feed rate from 3 to 9 kg/h. Third, two different baking tests were carried out using either just water or 4 pizza types as such or topped with tomato puree and/or sunflower oil. In both tests the thermal efficiency was around 13% of the energy supplied by oak log burning. In the circumstances, the use of such equipment leads to an inefficient use of wood as well as poor indoor and outdoor air quality. Further work should be aimed at modelling the time course of the heat transferred via radiation, convention, and conduction radiative to each pizza under baking.

Nomenclature

c_{pi} Specific heat of the i-th component [kJ kg^{-1} K^{-1}]

dT_{FL}/dt Gradient of the oven floor temperature [°C/h]

E_{FG} Energy dissipated by flue gases [kJ]

E_{fw} Energy supplied by firewood [kJ]

E_S Energy absorbed by the sample undergoing baking [kJ]

E_W Energy lost by oven walls [kJ]

HHV Higher heating value of oak wood [MJ/kg]

LHV Lower heating value of oak wood [MJ/kg]

m_{ev} Mass of water evaporated [kg]

m_S Instantaneous mass of sample [kg]

m_V Mass of vessel [kg]

m_{WE} Mass of water evaporated, as defined by Eq. (3) [kg]

p Probability level

$PM_{2.5}$ Particulate matter with size smaller than 2.5 μm (g/m^3)

Q_{fw} Firewood feed rate (kg/h)

r^2 Coefficient of determination

t Baking time [s or h]

T_{FG} Temperature of flue gases at the exit section of the oven chimney [°C]

T_{FL} Temperature of the oven floor [°C]

T_{FLbp} Temperature of the oven floor shielded by a pizza sample [°C]

T_S Instantaneous temperature of each sample [°C]

$T_{S,ave}$ Average temperature of a pizza sample [°C]

T_{SL} Temperature of the lower central area of a pizza sample [°C]

T_{SR} Temperature of the pizza rim [°C]

T_{SU} Temperature of the upper central area of a pizza sample [°C]

T_V Temperature of the oven vault [°C]

T_W Average oven wall temperature [°C]

v_{FG} superficial velocity of flue gases at the oven chimney exit [m/s]

x'_i Mass fraction of the generic i-th component of wood on dry mass [g/g]

x_A Ash content of wood on wet matter [g/g]

x_W Moisture content of wood on wet matter [g/g]

Greek Symbols

η_{comb}	Combustion efficiency of oak logs [dimensionless]
η_{PO}	Thermal efficiency of the pizza oven, as defined by Eq. (12) [dimensionless]
λ_{ev}	Latent heat of water vaporization at T_S [kJ/kg]

Subscripts

0	Initial
C	Referred to carbon
D	Referred to dough
H	Referred to hydrogen
N	Referred to nitrogen
O	Referred to oxygen
S	Referred to sulfur
SO	Referred to sunflower oil
T	Referred to tomato puree
V	Referred to vessel
W	Referred to water

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References

Anon. (2020) *Pizza, un business che lievita anno per anno*. Available online: https://www.cna.it/pizza-un-business-che-lievita-anno-per-anno/ (accessed on 10 May 2022).

Apurva (2016). Tandoors, Burning of Solid Waste Adding to Dirty Delhi Air: IIT Study. The Indian Express. Available online: https://indianexpress.com/article/india/india-news-india/tandoors-burning-of-solid-waste-adding-to-dirty-delhi-air-iit-study/ (accessed on 9 March 2022).

AVPN (Associazione Verace Pizza Napoletana) (2004). Disciplinare Internazionale per L'ottenimento del Marchio Collettivo "Verace Pizza Napoletana"—(Vera Pizza Napoletana). Available online: https://www.pizzanapoletana.org/public/pdf/Disciplinare_AVPN.pdf (accessed on 9 March 2022).

Barratt, N. (2021). Different oven types explained! Available at: https://www.canstarblue.co.nz/appliances/ovens/different-types-of-ovens-explained/ (last checked on 6 March 2022).

Ciarmiello, M., Morrone, B. (2016a). Numerical thermal analysis of an electric oven for Neapolitan pizzas. International Journal of Heat and Technology, 34 (Special Issue 2), S351-S358. doi:10.18280/ijht.34S223

Ciarmiello, M., Morrone, B. (2016b). Why not using electric ovens for Neapolitan pizzas? A thermal analysis of a high temperature electric pizza oven. Energy Procedia, 101, 1010-1017. doi:10.1016/j.egypro.2016.11.128

Cimini, A., Moresi, M. (2022). Environmental impact of the main household cooking systems - A survey. Italian Journal of Food Science, 34 (1), 86–113.

EC (2010). Commission Regulation (EU) No. 97/2010, Entering a Name in the Register of Traditional SPECIALITIES guaranteed [Pizza Napoletana (TSG)]. Off. J. Eur. Union 2010, 34, 5. Available online: https://eur-lex.europa.eu/legalcontent/EN/TXT/HTML/?uri=OJ:L:2010:034:FULL (accessed on 26 January 2022).

Global Alliance for Clean Cookstoves (2014). The Water Boiling Test. Version 4.2.3. Cookstove emissions and efficiency in a controlled laboratory setting.

<https://cleancookstoves.org/binary-data/DOCUMENT/file/000/000/399-1.pdf> (last checked on 4 March 2022).

Grim, R.E., Johns, W.D., jr. (1951). Reactions accompanying the firing of brick. Journal of the American Ceramic Society, 34(3), 71-76.

Hager, T.J., Morawicki, R. (2013). Energy consumption during cooking in the residential sector of developed nations: A review. Food Policy, 40, 54-63. https://doi.org/10.1016/j.foodpol.2013.02.003

Heldman D., R. Lund, D. B. (2007). Handbook of Food Engineering. 2nd Edn. CRC Press, Taylor & Francis Group, Boca Rotan, FL, USA, p. 402.

Henderson-Sellers, B. (1984). A new formula for latent heat of vaporization of water as a function of temperature. Quart. J. R. Met. Soc., 110, 1186-1190.

Igo S. W., Kokou N., Compaoré A., Kalifa P., Sawadogo G. L., and Namoano D. (2020). Experimental analysis of the thermal performance of a metal fired-wood oven. Iranian (Iranica) Journal of Energy and Environment, 11(3), 225-230.

Jones J.M., Mason P.E., Williams A. (2019). A compilation of data on the radiant emissivity of some materials at high temperatures. Journal of the Energy Institute, 92, 523-534.

Kumar, P., Andrade, M.D.F., Ynoue, R., Fornaro, A., de Freitas, E.D., Martins, J., Martins, L.D., Albuquerque, T., Zhang, Y., Morawska, L. (2016). New directions: From biofuels to wood stoves: The modern and ancient air quality challenges in the megacity of São Paulo. Atmos. Environ., 140, 364–369.

Kuscer, L. (2022). *Slice of the pie: pizza consumption trends & industry statistics*. Available online: https://muchneeded.com/pizza-consumption-statistics/ (accessed on 10 May 2022).

Lima, F.D.M.; Pérez-Martínez, P.J.; Andrade, M.D.F.; Kumar, P.; de Miranda, R.M. (2020). Characterization of particles emitted by pizzerias burning wood and briquettes: A case study at Sao Paulo, Brazil. Environ. Sci. Pollut. Res., 27, 35875–35888. https://doi.org/10.1007/s11356-019-07508-6.

Manhiça F. A. (2014). Efficiency of a wood-fired bakery oven – Improvement by theoretical and practical. PhD Thesis, Chalmers University of Technology, Gothenburg, Sweden.

Available online at: https://research.chalmers.se/en/ publication/203999 (accessed 9 March 2022).

Manhiça F. A., Lucas C., Richards T. (2012). Wood consumption and analysis of the bread baking process in wood-fired bakery ovens. Applied Thermal Engineering, 47, 63-72.

Masi, P., Romano, A., Coccia, E. (2015). The Neapolitan pizza. A Scientific Guide about the Artisanal Process; Doppiavoce: Napoli, Italy.

Mukunda, H. S. (2009). Understanding Combustion. 2nd Edn. Orient Blackswan, New Delhi, India.

Okino, J., Komakech, A.J., Wanyama, J., Ssegane, H., Olomo, E., Omara, T. (2021). Performance characteristics of a cooking stove improved with sawdust as an insulation material. J Renew Energy, vol. 2021, Art ID 9969806: 1–12. https://doi. org/10.1155/2021/9969806.

Rahman, M.M., Chu, CM., Kumaresen, S. (2021). Theory of natural draft chimney and cold inflow. In: Rahman, M.M., Chu, CM. (eds) Cold inflow-free solar chimney. Springer, Singapore, pp 13–37. https://doi.org/10.1007/978-981-33-6831-6_2

Santos, J. C. O., Santos, M. G. O., Dantas, J. P., Conceição, M. M., Athaide-Filho, P. F., Souza, A. G. (2005). Comparative study of specific heat capacities of some vegetable oils obtained by DSC and microwave oven. Journal of Thermal Analysis and Calorimetry, 79, 283–287.

Singh, R. P., Erdoğdu, F., Rahman, M. S. (2009). Specific heat and enthalpy of foods. Chp. 16. In Rahman, M. S. (Ed.) Food Properties Handbook. 2nd Edn. CRC Press, Boca Raton, FL, USA, pp. 517-543.

UNESCO (United Nations Education, Scientific and Cultural Organization) (2017). Decision of the Intergovernmental Committee: 12.COM 11.B.17, 2017. Available online: https://ich.unesco.org/en/decisions/12.COM/11.B.17 (accessed on 26 January 2022).

Vassilev, S. V., Baxter, D., Andersen, L. K., Vassileva, C. G. (2010). An overview of the chemical composition of biomass. Fuel, 89, 913–933.

WHO (World Health Organization) (2018). Ambient (Outdoor) Air Pollution. Available online: https://www.who.int/en/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health (accessed on 9 March 2022).

Zhang Y., Li Q., Zhou H. (2016). Theory and Calculation of Heat Transfer in Furnaces. Chp. 5. Elsevier, Amsterdam, pp. 131-172; https://doi.org/10.1016/B978-0-12-800966-6.00011-9

Chapter 6

Semi-empirical modelling of a traditional wood-fired pizza oven in quasi steady-state operating conditions

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Abstract

Wood-fired ovens are mandatorily used to bake the Neapolitan pizza. Unfortunately, they are still empirically operated. In this work, a pilot-scale wood-fired oven was kept operating in quasi steady-state conditions. Once the combustion reaction of oak logs had been modeled, the composition of flue gas measured and the external oven wall and floor temperatures thermo-graphically scanned, it was possible to check for the material and energy balances and thus assess that the heat loss rates through flue gas and insulated oven chamber were respectively equal to 46% and 26% of the energy supplied by burning firewood. The enthalpy accumulation rate in the internal oven chamber amounted to about 3.4 kW, this being adequate to keep not only the temperatures of the oven vault and floor practically constant, but also to bake one or two pizzas at the same time. Such a rate was predicted by contemplating the simultaneous heat transfer mechanisms of radiation and convection between the oven vault and floor surface areas. The efficacy of the semi-empirical modelling developed here was further tested by reconstructing quite accurately the time course of water heating in aluminum trays with a diameter near to that of a typical Neapolitan pizza. The heat flow from the oven vault to the water-containing tray was of the radiative and convective types for about 73% and 15%, while the residual 12% was of the conductive type from the oven floor.

Keywords: energy losses through flue gas and insulated oven chamber; energy supplied by wood combustion; material and energy balances; pseudo-steady-state regime performance; thermal efficiency; water heating test; wood-fired pizza oven.

Practical Application

Despite wood-fired pizza ovens are largely used in the restaurant and food service industry, their operation is highly dependent on the operator's ability. This study shows how a pilot-scale equipment can be kept operating in pseudo-steady-state conditions, how the heat loss rates through flue gas and insulated oven chamber can be assessed, and how the enthalpy accumulation rate in the internal oven chamber can be predicted by accounting for the simultaneous heat transfer mechanisms of radiation and convection between the oven vault and floor surface areas. Some water heating tests were performed to check further for the efficacy of the semi-empirical modelling developed here.

INTRODUCTION

Neapolitan Pizza is a traditional specialty guaranteed (TSG) by the European Commission Regulation no. 97/2010 (EC, 2010), that is to be baked in wood-fired ovens only. Such equipment is widely used in the restaurant and food service industry all over the world. Nevertheless, it has been very poorly studied so far (Igo et al., 2020; Manhiça et al., 2012; Manhiça, 2014). In contrast, the radiative and convective heat transfer mechanisms in electric pizza ovens were used to describe their performance in steady and unsteady operating conditions by means of three-dimensional numerical models (Ciarmiello & Morrone, 2016ab).

In previous work (Falciano et al., 2022), the operation of a pilot-scale wood-fired pizza oven was characterized from its start-up phase to its baking operation to provide a basis for future modelling of novel pizza oven design. When baking different white and tomato pizza products, the average thermal efficiency was equal to (13 ± 4) % (Falciano et al., 2022).

The operation of a wood-fired oven accounts for four interactive processes: combustion, heat, flow, and mass transfer. As firewood burns in a specific area of the baking floor, releasing energy and forming the flame, air naturally enters through the open entry door of the oven and makes firewood burning, while the resulting flue gas is discharged through the oven chimney. Heat transfer is just one of such processes and no exact solution can be obtained unless four groups of equations, corresponding to all these processes, are solved simultaneously. In particular, the basic unsteady-state energy equation of heat transfer from the flame to the oven walls and floor must include a mathematical model of heat transfer in the oven, its solution generally being of the numerical type. Strictly speaking, calculations for heat transfer involve semi-theoretical approaches based on experience, especially because certain parameters (i.e., thermal conductivity, thermal diffusivity, diffusion coefficient, viscosity coefficient, and emissivity) are all determined by measurement, during which an accurate relationship between these coefficients and temperature or pressure is mostly unavailable. Empirical methods also attribute uncertainty to one or several factors, including the heat transfer coefficient, thermal effective coefficient, etc. There are zero-, one-, two-, and three-dimensional models available for application to oven heating calculation. In a zero-dimensional model, all physical quantities within the furnace are uniform and the results are averaged. This method is the one most often used for engineering design (Zhang et al., 2016). One-dimensional models are used to study changes in the physical quantities along the axis (height) of the furnace, where the physical quantity in the perpendicular plane is uniform. This model has practical value for engineering projects such as large-capacity boilers. The two-dimensional model is mainly used for axisymmetric cylindrical furnaces, such as vertical cyclone furnaces (Manhiça et al., 2012). The three-dimensional model describes the furnace process (flow, temperature, chemical species fields, and so on), using three-dimensional coordinates (x, y, z). In principle, only a three-dimensional model can correctly describe the furnace process. In reality, all the equations used so far for describing the furnace process fail to obtain analytical solutions, and only the numerical methods can reach approximate solutions. Even for an approximate solution the amount of calculation is very large, slow or small-capacity computers are not up to the task. The experience method was previously most applied to zero-dimensional models due to a lack of adequate understanding of the furnace process and related mechanisms. Currently, the semiempirical method is growing in popularity. This method is based on fundamental equations, such as the thermal balance equation and radiative heat transfer equation, as well as certain coefficients or factors obtained through experimentation.

The main aim of this work was to develop a semi-empirical model of a wood-fired pizza oven operating in quasi steady-state conditions. To this end, the first goal was to check for the material and energy balances upon modelling of the combustion reaction of oak logs, measuring the composition of flue gas, and scanning the temperatures of the external oven walls and floor via a thermal imaging camera. The second goal was to estimate the heat losses through flue gas and insulated oven chamber so as to derive the enthalpy accumulation rate in the internal oven chamber and attempt its mathematical prediction. By analogy with the water boiling tests used to evaluate the energy efficiency of domestic cooking appliances (EC, 2010; Hager & Morawicki, 2013), the third goal was to perform several water heating tests to simulate the water heating profile via the heat transfer mechanisms of radiation, convection, and conduction, and thus evaluate the net energy transferable to pizza during baking.

MATERIALS AND METHODS

Equipment

Fig. 1 shows a picture of the pilot-scale wood-fired pizza oven used in this work, which was described previously (Falciano et al., 2022). The oven chamber was approximated to a cylinder, having internal diameter (D_i) and height (H_i) of 90 cm and 20 cm, respectively, surmounted by an oblate semi-ellipsoidal vault with a height equal to H_i. Thus, the overall volume of the oven chamber was estimated as

$$V_O = \frac{\pi}{4} D_i^2\, H_i + \frac{1}{6}\pi\, D_i^2\, H_i = \frac{5}{12}\pi\, D_i^2\, H_i = 0.212 \text{ m}^3 \qquad (1)$$

Figure 1. Picture of the wood-fired pizza oven used in this work.

The pizza oven had a semicircular open mouth, its radius being equal to 22 cm. Through its area (S_{OM}), one kg of seasoned oak logs every 20 min was fed. Such logs had an average weight, length, diameter, and moisture and ash contents equal to 600±200 g, 250±20 mm, 40±10 mm, and 5.67±0.17 and 2.9±0.7 % (w/w), respectively.

As woodfire was burning, the hot combustion flue gas was naturally drawn up and out of the chimney having an internal diameter of 20 cm, while ambient air as it was sucked inside through the open mouth. Its temperature and relative humidity (RH) were measured using a temperature and humidity Mini TH datalogger (XS Instruments, Carpi, Italy Italy). The overall lateral surface area of the internal oven chamber is equal to the lateral surface area of the cylinder mentioned above minus the oven mouth surface area (S_{OM}) plus the lateral surface area of the oblate semi-ellipsoidal vault, the latter being approximated using the Knud Thomsen's formula:

$$S_{SE} = 2\,\pi\,[\frac{(a\,b)^p+(a\,c)^p+(b\,c)^p}{3}]^{1/p} \qquad (2)$$

where a, b and c are the semi-axes of the ellipsoid and p (≈1.6075) is an empirical exponent yielding a relative error of at most 1.06%. Since in this specific case a=b=D_i/2 and c=H_i, the overall lateral surface of the oven chamber was

$$S_{OC} = \pi\,D_i\,H_i - S_{OM} + 2\,\pi\,[\frac{(D_i/2)^{2p}+2\,(D_i\,H_i/2)^p}{3}]^{1/p} = 1.331\ m^2 \qquad (3)$$

Finally, the surface area of the baking floor was

$$S_{FL} = \frac{\pi}{4}\,D_i^2 = 0.636\ m^2 \qquad (4)$$

The oven walls and floor were about 10 cm in thickness.

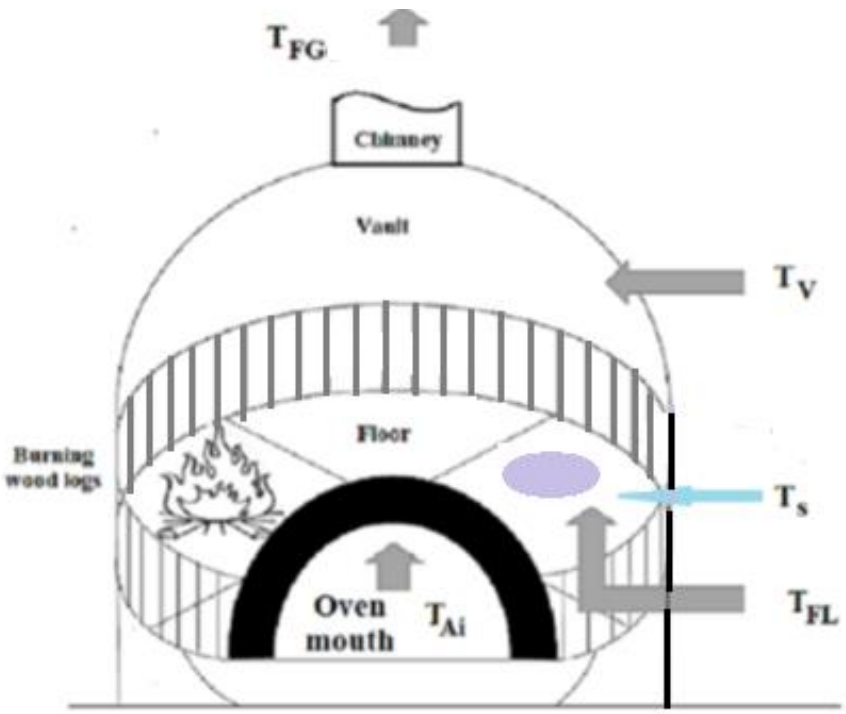

Figure 2. Schematic of the wood-fired oven showing the positions of the burning wood logs and sample to be baked, as well the temperatures of input air (T_{Ai}), exit flue gas (T_{FG}), oven floor (T_{FL}) and vault (T_V), and baking sample (T_S).

Fig. 2 shows a schematic of the wood-fired pizza oven showing the positions of the burning wood logs and sample undergoing baking. About one fourth of the floor surface area was occupied by burning wood logs, while the remaining surface area was used for pizza baking.

Wood-fired pizza oven operation

The start-up procedure for this wood-fired pizza oven, manufactured by MV Napoli Forni (Naples, Italy), was carried out as previously described (Falciano et al., 2022). In this work, the operation of the oven was stabilized by feeding 3 kg of oak logs per hour (Q_{fw}) for about 6 h. The temperatures of the oven vault (T_V) and floor (T_{FL}) were monitored using an infra-red (IR) thermal imaging camera (FLIR E95 42°, FLIR System OU, Estonia) equipped with an uncooled microbolometer thermal sensor with dimension 7.888 x 5.916 mm and resolution 464 x 348 pixels, its pixel pitch being 17 µm, focal length of lens 10 mm, and field of view of 42° x 32°. Such temperatures approached the pseudo-steady state values of (546 ± 53) °C and (453 ± 32) °C, respectively (Falciano et al., 2022). In such conditions, the mean superficial velocity (v_{FG}) and temperature (T_{FG}) of flue gas at the exit section of the oven chimney were simultaneously measured using a Hotwire Anemometer mod RS PRO RS-8880 (RS-Components, Corby, United Kingdom), while the flue gas temperature at the oven mouth was determined using the temperature logger 175 T3 (Testo SE & Co. KGaA, Titisee-Neustadt, Germany). Moreover, the dry-bulb temperature (T_A) and relative humidity (RH) of ambient air were measured at distances ranging from 0 to 150 cm from the oven entry port using a temperature and humidity Mini TH datalogger (XS Instruments, Carpi, Italy Italy). To check for the aliquot of wood logs combusted during these conditions, as another hour had elapsed from the last log feed, unburned wood logs were separated from wood ashes, weighted, and referred to the overall mass of oak logs supplied, this yielding the average woodfire combustion efficiency (η_{comb}). The composition of the flue gas exiting from the oven chimney was assessed on 21 April 2022 under meteorological conditions presenting no rain, predominantly calm winds, ambient temperature of (24.0 ± 0.6) °C and pressure of (93.3 ± 0.2) kPa, and good air quality, in accordance with the local air quality standards, as shown in Table 1.

Table 1. Chemical composition and flow condition of the flue gas exiting from the chimney of the wood-fired oven operating in quasi steady-state conditions.

Parameter	Value	Unit
Chimney diameter	200	mm
Chimney cross section	0.0314	m^2
Sampling point below chimney exit	0.7	m

Date	21 April 2022	
Exit temperature	91.1 ± 1.3	°C
Ambient pressure	93.33 ± 0.16	kPa
Ambient temperature	24.0 ± 0.6	°C
Oxygen volumetric fraction	19.8 ± 0.5	% v/v
Moisture volumetric fraction	2.0 ± 0.2	% v/v
CO_2 volumetric fraction	1.4 ± 0.2	% v/v
Average gas velocity	2.9 ± 0.3	$m\ s^{-1}$
Average gas flow rate	328 ± 43	$m^3\ h^{-1}$
Average wet gas flow rate	226 ± 30	$m^3(STP)\ h^{-1}$
Flue gas molecular mass	28.82 ± 0.03	g/mol
Flue gas density	888 ± 1	$g\ m^{-3}$

Water heating tests

Such tests were carried out in triplicate after the oven had been pre-heated at Q_{fw}= 3 kg/h for 6 h using circular aluminum trays, each one having a diameter of 26 cm and a mass of 19.35 g. Each tray was filled with about 300 g of deionized water at an initial temperature of (25.8 ± 0.2) °C, weighted and then introduced into the oven, where it was kept for 10 to 80 s. As soon as the tray had been withdrawn from the oven, the temperature of the oven floor was suddenly measured in several areas different from that occupied by the tray using the above thermal imaging camera. Then, the residual mass of the water contained in the tray was measured using an analytical balance (Gibertini, Milan, Italy), while its temperature via a temperature logger 175 T3 (Testo SE & Co. KGaA, Titisee-Neustadt, Germany).

Statistical analysis of data

Each water heating test was carried out three times. All parameters were shown as average ± standard deviation and were analyzed by Tukey test at a probability level (p) of 0.05. One-way analysis of variance was carried out using SYSTAT version 8.0 (SPSS Inc., 1998).

RESULTS AND DISCUSSION

Elemental composition and heating value of oak firewoodtion

Wood is composed of water and dry matter. According to Vassilev et al. (2010), the dry matter of oak wood contains 50.6% carbon (x'_C), 42.9% oxygen (x'_O), 6.1% hydrogen (x'_H), and several other substances, such as 0.3% nitrogen (x'_N), 0.1% sulfur (x'_S), as well as moisture and ash. In this work, the moisture (x_M) and ash (x_A) contents of oak logs amounted to 5.67±0.17 and 2.89±0.66 g per 100 g of wet matter, respectively. Thus, oak wood was characterized by the following raw molecular formula:

$CH_{1.447}O_{0.636}N_{0.005}S_{0.0007}$,

this corresponding to a molecular mass (MM_{fw}) of 23.715 g/mol. Moreover, the higher (HHV) and lower (LHV) heating values were equal to about 18.19 and 16.66 MJ/kg, respectively, as estimated via the following relationships (Mukunda, 2009):

$$HHV = 33.823\, x'_C + 144.249\, (x'_H - x'_O/8) + 9.418\, x'_S \qquad (5)$$

$$LHV = HHV - 22.604\, x'_H - 2.581\, x_M \qquad (6)$$

where *HHV* and *LHV* are expressed in MJ/kg, while x'_i is the weight fraction of the i-th element on dry basis of the biomass under study, and x_M the moisture content on wet matter.

Combustion reaction of oak firewood

It was described as follows:

$$CH_{1.447}O_{0.636}N_{0.005}S_{0.0007} + \alpha\, O_2 \rightarrow CO_2 + \beta\, H_2O + \gamma\, NO_2 + \delta\, SO_2 \qquad (7)$$

where the stoichiometric coefficients α, β, γ, and δ were estimated by writing a material balance for each element of concern, thus obtaining:

$\alpha = 1.050$; $\beta = 0.723$; $\gamma = 0.005$; $\delta = 0.0007$.

If Q_{fw} is the wet firewood feed rate (expressed in kg/h), its effective molar dry matter combustion rate (R_{fw}) (in kmol/h) would be:

$$R_{fw} = \eta_{comb} \frac{(1 - x_M - x_A)}{MM_{fw}} Q_{fw} \qquad (8)$$

where the combustion efficiency (η_{comb}) was equal to (87 ± 3) %, as determined previously under the aforementioned quasi steady-state conditions (Falciano et al., 2022). Thus, by referring to Eq. (7), the weight O_2 consumption and CO_2, NO_2, and SO_2 generation rates were expressed (in kg/h) as follows:

$$r_O = -32\,\alpha\,R_{fw} \qquad (9)$$

$$r_{CO2} = 44\,R_{fw} \qquad (10)$$

$$r_{H2O} = 18\,\beta\,R_{fw} \qquad (11)$$

$$r_{NO2} = 46\,\gamma\,R_{fw} \qquad (12)$$

$$r_{SO2} = 64\,\delta\,R_{fw} \qquad (13)$$

As due to woodfire combustion, there is ash and water vapor formation too, their corresponding weight formation rates being expressed as

$$r_A = \eta_{comb}\,x_A\,Q_{fw} \qquad (14)$$

$$r_M = \eta_{comb}\,x_M\,Q_{fw}. \qquad (15)$$

Black-box modelling of the wood-fired oven

The operation of the wood-fired pizza oven in quasi steady-state conditions was described by resorting to the black box model shown in Fig. 3 to point out simply the functional relationships between system inputs (air, and firewood) and system outputs (flue gas, heat dispersion by convention and radiation through the outer surfaces of the oven chamber and floor).

Material balances of the wood-fired oven

In the circumstances, the overall mass balance yields the following:

$$(1+U_{W,A})\,Q_A + Q_{fw} = Q_{FG} + Q_R \qquad (16)$$

with

$$Q_R = (1-\eta_{comb})\,Q_{fw} + r_A \qquad (17)$$

where Q_R accounts for residues (i.e., unburned logs and wood ash) that cumulate over the oven floor, while $U_{W,A}$ is the humidity ratio (in kg of moisture/kg of dry air) of ambient air sucked in through the oven mouth by natural draft.

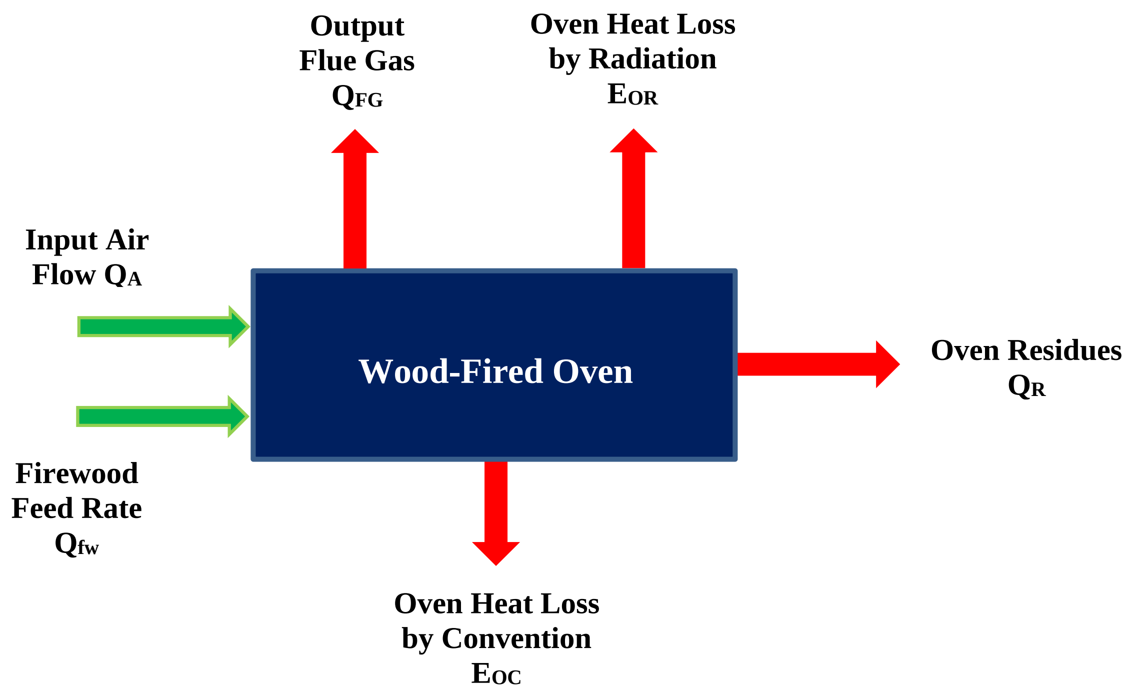

Figure 3. Black box model of the wood-fired pizza oven in quasi steady-state conditions.

Provided that dry air (Q_A) consisted of N (76.8% w/w) and O (23.2% w/w), it is possible to write the following partial elemental balances as

N: $$0.768\ Q_A = y_{N,FG}\ Q_{FG} \quad (18)$$

O_2: $$0.232\ Q_A + r_O = y_{O,FG}\ Q_{FG} \quad (19)$$

CO_2: $$r_{CO2} = y_{CO2,FG}\ Q_{FG} \quad (20)$$

H_2O: $$U_{W,A}\ Q_A + r_{H2O} + r_M = y_{H2O,FG}\ Q_{FG} \quad (21)$$

NO_2: $$r_{NO2} = y_{NO2,FG}\ Q_{FG} \quad (22)$$

SO_2: $$r_{SO2} = y_{SO2,FG}\ Q_{FG} \quad (23)$$

where $y_{i,FG}$ is the weight fraction of the i-th component of flue gas.

By summing up all the terms at the left- and right-sides of Eq.s (18-23), introducing Eq.s (8)-(15), and accounting for the average values for the moisture (x_M) and ash (x_A) contents and combustion efficiency of oak logs mentioned above, it was possible to relate the input dry air flow rate to the output flue gas rate as:

$$Q_{FG}=Q_A(1+U_{w,A})+r_O+r_{CO2}+r_{H2O}+r_M+r_{NO2}+r_{SO2} \square\ Q_A\ (1+U_{w,A})\ +0.971\ \eta_{comb}\ Q_{fw} \quad (24)$$

To estimate Q_A, the hygrometric properties of ambient air at different distances (d) from the open mouth of the pilot-scale wood-fired pizza oven operating in quasi steady-state conditions were assessed as shown in Table 2. By resorting to the humidity calculator (available online at https://www.aqua-calc.com/calculate/humidity: accessed on 20 October 2022), it was possible to calculate the corresponding humidity ratio ($U_{W,A}$), as listed in Table 2. Thus, by estimating the flue gas mass flow rate (Q_{FG}=291 ± 38 kg/h) from the data listed in Table 1 and assuming the humidity ratio of entering air as coincident with that measured at 50 cm from the oven mouth (Table 2), it was possible to calculate, via Eq. (24), the entering dry air mass flow rate (Q_A=286 ± 38 kg dry air/h). In this way, the estimated molar fractions of O_2 (19.4%), CO_2 (1.0%), and H_2O (2.2%) in the fumes were in good agreement with those experimentally determined (Table 1). Thus, the humidity ratio of flue gas ($U_{W,FG}$) resulted to be about 13.7 g of water vapor/kg of dry flue gas.

Table 2. Chemical composition and flow condition of the flue gas exiting from the chimney of the wood-fired oven operating in quasi steady-state conditions.

d [cm]	**T_A** [°C]	**RH** [%]	**$U_{W,A}$** [g of water vapor/kg of dry air]
0	68.3± 3.5	17.2 ± 0.3	35.5 ± 6.4
50	36.4 ± 4.8	20.4 ± 0.9	8.6 ± 2.6
100	24.6 ± 0.8	28.8 ± 1.1	6.0 ± 0.5
150	20.9 ± 0.2	33.1 ± 2.5	5.5 ± 0.5

By referring to Eq. (7), the theoretical oxygen required to burn 1 kg of oak logs was 2.82 g per g of firewood, while the theoretical dry air would be about 12.2 kg/kg of firewood. The effective dry air sucked in through the oven mouth by natural draft was about 95.4 kg/kg of firewood, this resulting in 682% excess air.

Heat balance of the wood-fired oven

By referring to the system boundary shown in Fig. 3, the heat balance yields the following:

$$e_A\, Q_A + \eta_{comb}\, Q_{fw}\, LHV = e_{FG}\, Q_{FG,d} + E_{OC} + E_{OR} + E_O \qquad (25)$$

where η_{comb} and LHV are the firewood combustion efficiency and lower heating value, respectively; E_{OC} and E_{OR} are the energy rate lost by convention and radiation through the external surfaces of the wood-fired oven, while E_O is the enthalpy accumulation rate inside the internal oven chamber.

The specific enthalpy of input air (e_A) and output flue gas (e_{FG}) on dry mass basis were referred to a standard reference state (e_R = 0 for water in the liquid state at 0 °C and ambient pressure) and were calculated as:

$$e_A = (c_A + U_{w,A}\, c_{Wv})\, T_A + U_{W,A}\, \lambda_{e0} \qquad (26)$$

$$e_{FG} = (c_{FG} + U_{w,FG}\, c_{Wv})\, T_{FG} + U_{W,FG}\, \lambda_{e0} \qquad (27)$$

where c_A and c_{FG} are the specific heat values of ambient air and flue gas on dry mass basis, while c_{Wv} is the specific heat of water vapor and λ_{e0} the latent heat of water evaporation at 0 °C, respectively.

When the wood-fired oven is operating in quasi steady-state conditions, its external insulated chamber and floor are generally at higher temperatures than that of ambient air. The resultant air density gradients drive natural or free convection, which is responsible for the energy lost E_{OC}, and can be estimated using the following formula:

$$E_{OC} = \sum_{i=1}^{n_O} h_{Oi}\, S_{Oi}(T_{Oi} - T_A) \qquad (28)$$

where n_O is the overall number of zones (as identified via IR thermal mapping) of the external oven chamber and floor surface areas, T_{Oi} the average temperature of the i-th zone, S_{Oi} its surface area, h_{Oi} the i-th convective heat transfer coefficient of ambient air at low-speed flow, and T_A the ambient temperature. In free convection, the dimensionless Nusselt number (*Nu*):

$$Nu = h_{Oi}\, z_i / k_A \qquad (29)$$

is a function of the dimensionless Rayleigh number (Ra) and solid shape too:

$$Ra = Gr\, Pr \qquad (30)$$

with

$$Gr = (z_i)^3\, r^2\, g\, \beta_V\, \Delta T / (\mu_A)^2 \qquad (31)$$

and

$$Pr = c_A\, \mu_A / k_A \qquad (32)$$

where *Gr* and *Pr* are the Grashof and Prandtl numbers, β_V is the volumetric coefficient of expansion of air (in K^{-1}), ΔT the difference between the temperatures (in °C) of the oven surface (T_{Oi}) and free stream (T_A); g (=9.81 m^2/s) the acceleration of gravity; c_A, μ_A, and k_A are the specific heat, dynamic viscosity and thermal conductivity of air at the i-th film temperature (T_{fi}); and z_i is a characteristic dimension of the solid surface (in m).

Table 3. Parameters used to assess the thermal performance of the wood-fired pizza oven during its quasi steady-state operation at no-load or during the water heating tests performed in this work.

Parameter	**Value**	**Unit**	**Ref.s**
Mass of water (m_{W0})	300.0±0.1	g	This work
Mass of aluminum tray (m_V)	19.35±0.05	g	This work
Specific heat of aluminum tray (c_V)	0.890	kJ kg^{-1} K^{-1}	Singh et al. (2009)
Density of air (ρ_A)	358.517 $T_K^{-1.00212}$	kg m^{-3}	Neutrium (2012)
Specific heat of air (c_A)	$7.875\times10^{-6}\,T_K^2+0.1712\,T_K + 949.72$	J kg^{-1} K^{-1}	Neutrium (2012)
Thermal conductivity of air (k_A)	$-1.3707\times10^{-8}\,T_K^2+7.616\times10^{-5}T_K + 4.5968\times10^{-3}$	W m^{-1} K^{-1}	Neutrium (2012)
Dynamic viscosity of air (μ_A)	$-8.3123\times10^{-12}\,T_K^2 +4.4156\times10^{-8}\,T_K+6.2299\times10^{-6}$	kg m^{-1} s^{-1}	Neutrium (2012)
Coefficient of expansion of air (β_{VA})	$1/T_K$	K^{-1}	Neutrium (2012)
Density of water (ρ_W)	$997.18+3.144x10^{-3}\,T-3.7574x10\text{-}3\,T^2$	kg m^{-3}	Choi & Okos (1986)
Specific heat of water (c_W)	$4176.2-9.0864x10^{-2}\,T+5.4731x10^{-3}\,T^2$	J kg^{-1} K^{-1}	Choi & Okos (1986)
Thermal conductivity of water (k_W)	$0.57109+1.7625x10^{-3}\,T-6.7036x10^{-6}\,T^2$	W m^{-1} K^{-1}	Choi & Okos (1986)
Dynamic viscosity of water (μ_W)	$10/(2.148*\{T-8.435+\sqrt{[8078.4+(T-8.435)^2]}\}-120)$	kg m^{-1} s^{-1}	Choi & Okos (1986)
Coefficient of expansion of water (β_{VW})	$81.4x10^{-4}-4.5/T_K+647.1142/T_K^2$	K^{-1}	The Engineering ToolBox (n.d.)
Latent heat of water evaporation (λ_e)	$1.919x10^3\left(\frac{T_S+273.15}{T_s+239.24}\right)^2$	kJ kg^{-1}	Henderson-Sellers (1984)
Density of water vapor (ρ_v)	$(218.1\pm0.4)/T_K$	kg m^{-3}	Green & Perry (2008, p. 2-414)
Specific heat of water vapor (c_{Wv})	2.08	kJ kg^{-1} K^{-1}	Green & Perry (2008, p. 2-414)
Thermal conductivity of water vapor (k_v)	$0.01842x(T_K)^{0.5}/(1+5485/T_K/10^{(12/TK)})$	W m^{-1} K^{-1}	Keyest & Vines (1964)
Dynamic viscosity of water vapor (μ_v)	$\exp[(-4.19\pm0.05) + (1.132\pm0.007)\,x\,\ln(T_K)]x10^{-6}$	kg m^{-1} s^{-1}	Green & Perry (2008, p. 2-414)
Density of brick, fireclay (ρ_{FB})	2640	kg m^{-3}	Green & Perry (2008, p. 2-463)

Specific heat of brick, fireclay (c_{PFB})	0.96	J kg^{-1} K^{-1}	Green & Perry (2008, p. 2-463)
Thermal conductivity of brick, fireclay (k_{FB})	1.00	W m^{-1} K^{-1}	Green & Perry (2008, p. 2-463)
Emissivity of brick, fireclay (ε_{FB})	0.9 -1x10^{-4} T_K	-	Jones et al. (2019)
Emissivity of flame (ε_F)	0.15	-	Àgueda et al. (2010)
Emissivity of ceramic refractory tiles (ε_i)	0.90	-	Anon. (n.d.)
Emissivity of polished stainless-steel type 18-8 (ε_i)	0.15	-	Anon. (n.d.)
Emissivity of flue gas (ε_G) at T=573 °C	0.074	-	Alberti et al. (2018)

Table 3 shows all the parameters used to check for the heat balance (Eq. 25) of the wood-fired oven examined here, as extracted from Àgueda et al. (2010), Alberti et al. (2018), Anon. (n.d.), Choi & Okos (1986), Green & Perry (2008), Henderson-Sellers (1984), Jones et al. (2019), Keyest & Vines (1964), Neutrium (2012), Singh et al. (2009), The Engineering ToolBox (n.d.).

As extracted from Alberti et al. (2018), Earle & Earle (2004), and Green & Perry (2008), the functional relationships relating *Nu* and *Ra* for a few solid shapes are listed in Table 4. In this way, the functional relationships related to a cylinder with characteristic dimension z_i >1 m were used to estimate the convective heat transfer coefficients of ambient air contacting each external zone of the oven chamber, while those related to a horizontal heated plate facing up or down were used to predict the convective heat transfer coefficient of ambient air contacting the slab supporting pizza or the external floor of the oven.

Table 4. Functional relationships relating the dimensionless Nusselt number (*Nu*) to the Rayleigh (*Ra*) number used to estimate the free convective heat transfer coefficient (h_O) between a free stream and different solid shapes characterized by a linear dimension z_i or between horizontal plates at different temperatures in different flow conditions, as extracted from Earle & Earle (2004) or Green & Perry (2008), respectively.

Solid shape	Fluid flow	Nu relationship	Ra range
Vertical plates and cylinder with z_i>1 m	Fully Laminar	Nu = 1.36 $Ra^{1/5}$	Ra < 10^4
	Laminar	Nu = 0.55 $Ra^{1/4}$	10^4<Ra< 10^9
	Turbulent	Nu = 0.13 $Ra^{1/3}$	Ra > 10^9
Horizontal heated plates facing up	Laminar	Nu = 0.54 $Ra^{1/4}$	1x10^5 <Ra< 2x10^7
	Turbulent	Nu = 0.14 $Ra^{1/3}$	2x10^7 <Ra< 3x10^{10}
Horizontal heated plates facing down	Laminar	Nu = 0.27 $Ra^{1/4}$	3x10^5 <Ra< 3x10^{10}
Horizontal rectangular cavity	Laminar	Nu = 0.069 $Ra^{1/3}$ $Pr^{0.074}$	3x10^5<Ra<7x10^9

By using an IR thermal imaging camera, it was possible to scan all the external lateral and frontal surface areas of the oven chamber, as well as that of its external floor and wood embers from the oven entry port, as for instance shown in Figs. 4a-4d, respectively. In this way, the heat dispersion through the external insulated wall and floor of the pizza oven might be estimated, as well as abnormal temperature mapping might reveal some faults, such as damaged insulation or gaps in the shell, giving rise to heat escape. In this work, all the temperature data collected were automatically grouped into 13 different zones and averaged (Fig. 4e), while the main dimensions of each zone were assessed using pixel counting, once the measured values of the pixels had been referred to the true dimensions of a few specific distances selected in the external surface areas of the oven. Such dimensions were used to estimate the external surface area of the generic i-th zone on the assumption that the oven vault was assimilated to a semi-ellipsoidal solid, while the intermediate and inferior parts of the oven to cylinders. All data collected were listed in Table 5 and were used to determine the local heat transfer coefficients h_{Oi} and corresponding heat loss rate (E_{OCi}). The temperature of ambient air was assumed as constant and equal to 24.6 °C (Table 2).

The wood-fired oven under study also dissipated some power by radiation (E_{ORi}) from the generic i-th external surface area of the oven chamber and floor, including the no-flame and flame areas of the entry port and pizza supporting slab, to ambient air. It can be calculated as

$$E_{OR} = \sum_{i=1}^{n_O} \varepsilon_i \, \sigma \, S_{Oi} \, (T_{KOi}^4 - T_{KA}^4) \quad (33)$$

where n_O is the overall number of zones identified via IR thermal mapping, ε_i the emissivity of the i-th component of the radiating surface area (S_{Oi}), σ (= 5.67x10^{-8} W m^{-2} K^{-4}) the Stefan-

Boltzmann constant, while T_{KOi} and T_{KA} are the average absolute temperatures of the i-th zone and ambient air. In particular, the emissivity of the flames (ε_F) resulting from oak log combustion was assumed as equal to about 0.15, being their thickness shorter than 0.25 m, as extracted from an experimental study by Àgueda et al. (2010), who observed that only flames thicker than 3.2 m exhibited an emissivity (0.9) close to that of a blackbody, while the emissivity of the white ceramic refractory tiles covering the external oven chamber, polished stainless-steel molding, firebrick used for the pizza supporting slab and area surrounding the oven mouth were extracted from Anon. (n.d.) and listed in Table 3. Moreover, the emissivity of hot (gray) gases (ε_G) filling the combustion chamber of the wood-fired oven, as viewed from the open oven mouth, was estimated as follows (Alberti et al., 2018):

$$\varepsilon_G = \varepsilon_{H2O} + \varepsilon_{CO2} - \Delta\epsilon_{CO2}^{H2O} + \Delta\epsilon \qquad (34)$$

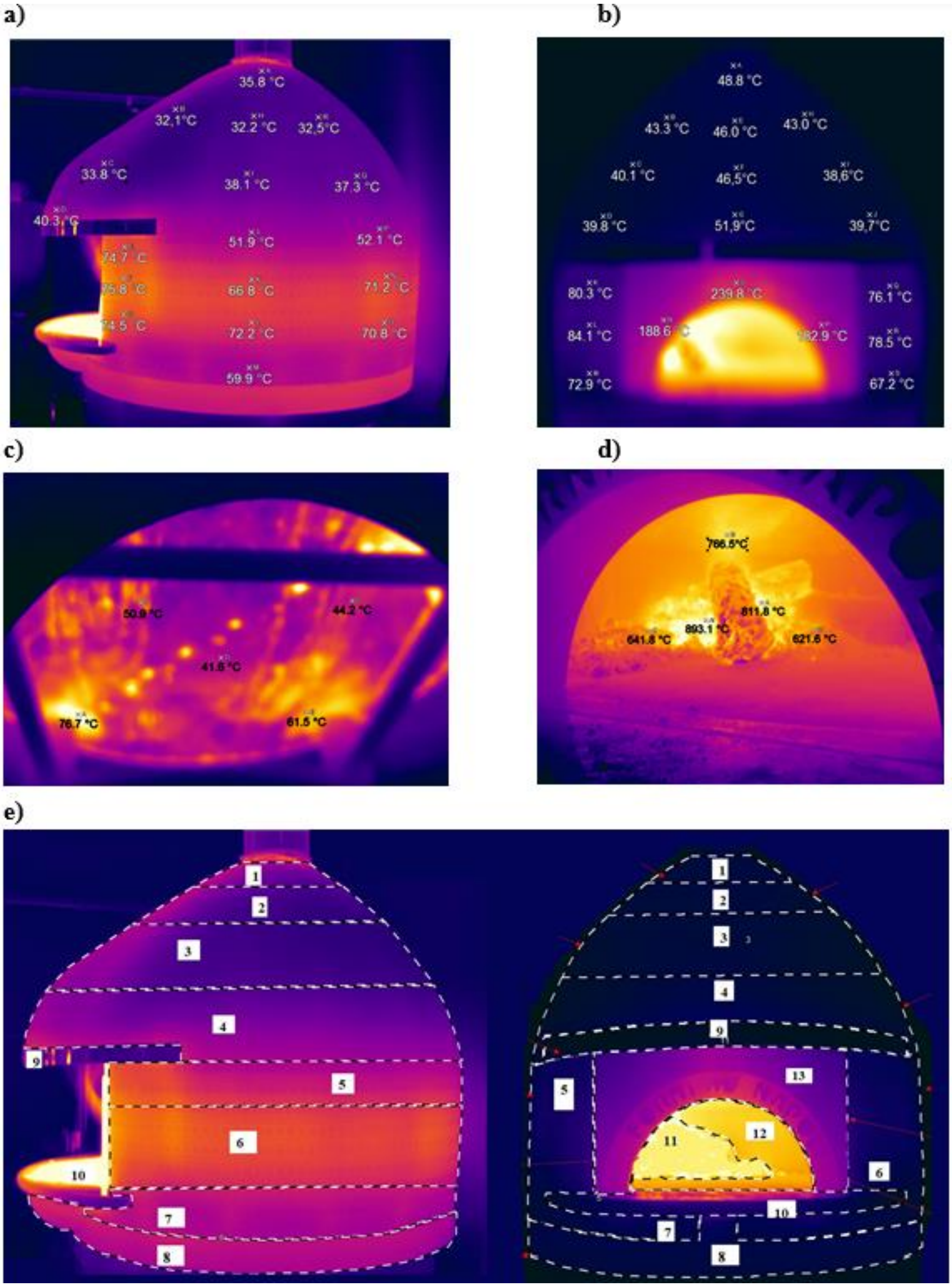

Figure 4. Thermal scanning of the external lateral (**a**), frontal (**b**) and lower (**c**) surface areas and entry port (**d**) of the wood-fired pizza oven operating in quasi steady-state conditions as such (**a-d**) and after attributing the temperature data collected to 13 zones of different surface areas and assessing their temperatures in terms of mean value and standard deviation (**e**).

The single absorbing gas emissivity of species j generally depends on absolute temperature T_K, total pressure P, molar fractions of both the absorbing (x_j) and non-absorbing species (typically

N_2), and optical path length L. This emissivity is calculated as if each gas (i.e., H_2O and CO_2) were to be the only radiatively active species in the mixture. Then, the binary overlap correction $\Delta\epsilon_{CO2}^{H2O}$ accounts for the band overlapping of such gas species and generally depends on temperature T_K, total pressure P, molar fractions of both the absorbing and the non-absorbing species, and optical path length L. Such data allowed the evaluation of the emissivity of a hemispherical volume of gas, as measured by a small surface element positioned in the center of the hemisphere, its radius representing the optical path length L. Thus, the gas emissivity at the average temperature of the no-flame zone of the oven mouth (zone no. 12 in Table 5) was estimated by assuming that the hemispherical gas volume coincided with the oven volume (V_O), this involving that L was equal to

$$L = \sqrt[3]{\frac{3\,V_O}{4\,\pi}} = 0.37 \text{ m} \qquad (35)$$

By using the emissivity data shown in Table 3 and the geometric dimensions of each i-th zone listed in Table 5, use of Eq.s (33), (34) and (35) allowed the i-th heat loss rate by radiation (E_{ORi}) to be estimated, as reported in Table 5.

Table 5. Main dimensions (upper, b_i, and lower, B_i, chord lengths, height, h_i, and surface area, S_{Oi}) and average temperature (T_{Oi}) of the generic i-th thermally mapped zone of the external chamber and floor of the wood-fired oven operating in quasi steady-state conditions ambient air temperature (T_A) and calculated parameters (i.e., z_i, T_{fi}, ΔT_i, Pr_i, Ra_i, Nu_i, h_{Oi}) used to evaluate the generic i-th heat loss rate by convention (E_{OCi}) and radiation (E_{ORi}).

Oven parts	**Zone no.**	**T_{Oi}** [°C]	**b_i** [cm]	**B_i** [cm]	**h_i** [cm]	**S_{Oi}** [cm^2]	**z_i** [m]	**T_{fi}** [°C]	**ΔT_i** [°C]	**Pr_i** [-]	**Ra_i** [-]	**Nu_i** [-]	**h_{Oi}** [W m^{-2} K^{-1}]	**E_{OCi}** [W]	**E_{ORi}** [W]
Lateral scanning															
Semi-ellipsoidal vault	1	40.2±5.2	31	58	8.8	1282	0.45	32	15.6	0.71	1.18×10^{8}	57	3.4	6.9	11.8
	2	34.4±4.9	58	94	13.6	3256	0.76	30	9.8	0.72	3.85×10^{8}	77	2.7	8.5	18.2
	3	33.5±4.2	94	160	25.6	10525	1.27	29	8.9	0.72	1.64×10^{9}	153	3.2	29.8	53.3
	4	39.2±4.4	160	193	28.7	10450	1.77	32	14.6	0.71	6.94×10^{9}	248	3.7	56.9	89.4
Middle cylinder	5	54.4±6.5	151	151	9.75	2305	1.51	40	29.8	0.71	7.89×10^{9}	259	4.7	32.0	43.4
	6	61.7±4.7	151	151	18.0	4255	1.51	43	37.1	0.71	9.34×10^{9}	274	5.0	78.4	103.4
Lower cylinder	7	48.6±2.8	166	166	11.2	2912	1.66	37	24	0.71	8.80×10^{9}	268	4.4	30.5	42.9
	8	48.1±3.6	166	166	7.5	1950	1.66	36	23.5	0.71	8.65×10^{9}	267	4.3	19.8	28.1
Oven metal molding	9	41.2±13.7	68	68	5	1227	1.93	33	16.6	0.71	1.02×10^{10}	282	3.9	7.9	2.0
Pizza supporting slab	10	101±51	-	78	24.5	1501	0.51	63	76.4	0.71	5.84×10^{8}	117	6.5	75.0	75.7
Frontal scanning															
Semi-ellipsoidal vault	1	52±2	31	58	8.8	1282	0.45	38	27	0.71	1.91×10^{8}	65	3.9	13.8	21.9
	2	50.5±2.4	58	94	13.6	3256	0.76	38	26	0.71	9.08×10^{8}	95	3.4	28.5	52.3
	3	48.7±4.1	94	160	25.6	10525	1.27	37	24	0.71	3.99×10^{9}	206	4.4	110.7	155.8
	4	51.1±8.1	160	193	28.7	10450	1.77	38	27	0.71	1.16×10^{10}	294	4.5	124.4	172.1
Middle cylinder	5	72.9±12.8	151	151	9.75	1195	1.51	49	48	0.71	1.13×10^{10}	291	5.4	30.9	39.9
	6	71.2±10.8	151	151	18	3145	1.51	48	47	0.71	1.10×10^{10}	289	5.3	77.8	100.6

Table 6 summarizes the heat balance of the wood-fired pizza oven operating in quasi steady-state conditions. It can be noted that 46% of the power supplied by firewood is lost through flue gas, while 15% and 11% are lost by radiation and convection from the outer surface of the oven walls and floor to the surroundings, respectively. Thus, the energy accumulation rate (E_O), which is stored within the oven chamber, represented about 28% of the oak log combustion power.

Table 6. Main items of the heat balance of the wood-fired pizza oven operating in quasi steady-state conditions.

Power items	**Value**	**Unit**	**%**
Power supplied by firewood ($\eta_{comb}\, Q_{fw}\, LHV$)	12079	W	100
Input air enthalpy rate ($e_A\, Q_A$)	*4658*	W	
Output flue gas enthalpy rate ($e_{FG}\, Q_{FG}$)	*10198*	W	
Heat loss rate through flue gas ($e_{FG}\, Q_{FG}$ - $e_A\, Q_A$)	5540	W	46
Heat loss rate to the surroundings by radiation (E_{OR})	1790	W	15
Heat loss rate to the surroundings by convection (E_{OC})	1344	W	11
Enthalpy accumulation rate within the oven chamber (E_O)	3405	W	28
Estimated power exchanged by radiation from the oven vault and floor	*3488*	W	
Estimated power exchanged by convection from the oven vault and floor	*85*	W	
Overall estimated power exchanged from the oven vault and floor	3573	W	

Heat transfer modes within the wood-fired oven chamber

As firewood was kept burning in quasi steady-state conditions, the aforementioned energy accumulation rate (E_O) in the oven chamber allowed the temperatures of the internal oven vault (T_V) and floor (T_{FL}) to be maintained approximately constant at (546 ± 53) °C and (453 ± 32) °C, respectively, as reported previously (Falciano et al., 2022). Such heat rate was computed as suggested by Kern (1950), the surface of the oven floor free of oak log burning ($S_{FL'}$) being smaller than the projected enclosing vault area (that coincided with the overall floor area, S_{FL}):

$$E_O = S_{FL'} \frac{1}{\frac{1}{\varepsilon_V} + \frac{S_{FL'}}{S_{FL}}\left(\frac{1}{\varepsilon_{FL}} - 1\right)} \sigma \left(T_V^4 - T_{FL}^4\right) + h_c\, S'_{FL}\left(T_V - T_{FL}\right) \quad (36)$$

where the total normal emissivity of refractory bricks used for the oven vault and floor was assumed as a linear decreasing function of their absolute temperature in accordance with Jones et al. (2019), as shown in Table 3. Moreover, the convective heat transfer coefficient (h_C) of hot burnt gases contacting the internal vault and baking floor of the oven was estimated using the correlation relative to a horizontal rectangular cavity (Green & Perry, 2008), as listed in Table 4.

In the circumstances, the energy accumulation rate (E_O) estimated by using Eq. (36) was just 5% greater than that estimated by the heat balance of the wood-fired oven (Eq. 25) and was mainly due to radiation, as shown in Table 6

Simulation of the performance of the wood-fired oven via water heating tests

The wood-fired oven was thus characterized by an almost constant energy accumulation rate (E_O) when operating in quasi steady-state conditions. As an aluminum circular tray filled with deionized water was introduced into the oven chamber, the temperature of the oven vault remained practically unaltered. Similarly, the temperature of the oven floor, as measured at different radial distances larger than 5 cm around each circular tray, was nearly constant. On the contrary, the temperature of the floor area occupied by the sample tended to reduce for a couple of reasons. Firstly, the sample of concern shielded such area from the oven vault irradiation. Secondly, such floor area tended to cool as heat transferred from it to the cooler sample, the upper side of which was still heated by the oven vault via the heat mechanisms of radiation and free convection while some of its moisture was also evaporated. In these conditions, the conductive heat process was assumed to be limited to a restricted floor volume, its base coinciding with the area occupied by the tray itself and its thickness (s_{FB}) being of the order of a few centimeters, respectively. Since the water-containing aluminum tray was not in very intimate contact with the hot oven floor owing to a thin film of hot air, the heat transfer between the tray and oven floor took place largely by natural convection.

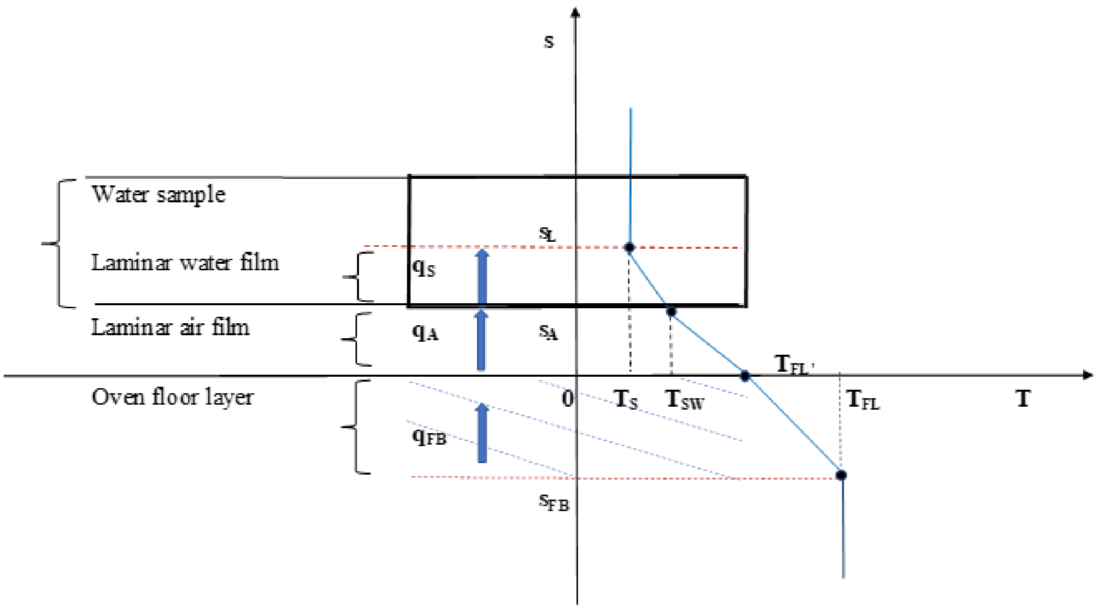

Figure 5. Temperature profiles and heat flux through different layers when a water-containing tray is laid over the oven floor at temperature T_{FL}. All symbols are described in the Nomenclature section.

Fig. 5 shows the temperature profile from the bulk of the oven floor, its temperature (T_{FL}) being almost invariant with respect to the initial value (T_{FL0}), to its upper side ($T_{FL'}$), which was separated from the tray lower side at T_{SW} by a gaseous film, and then from T_{SW} to the average water temperature (T_S) in the tray. The instantaneous heat flux through such three laminar layers was assumed to be constant ($q_{cond} = q_{FB} = q_A = q_S$). The heat flux through the laminar water film contacting the lower side of the tray was of the convective type. By assuming the thermal resistance of the aluminum tray as negligible and the oven floor as a semi-infinite solid at a constant initial temperature ($T_{FL} = T_{FL0}$), the heat flux exchanged was expressed as (Carslaw & Jaeger, 1959; Varlamov et al., 2018):

$$q_S\,dt = -\,h_S\,(T_S - T_{SW})dt = q_A\,dt = -\,h_A\,(T_{SW} - T_{FL'})\,dt = q_{FB}\,dt = -\,k_{FB}\,\frac{T_{FL'} - T_{FL}}{\sqrt{\pi\,\alpha_{FB}\,t}} \qquad (37)$$

Such heat flux was then related to the heat balance of the oven floor section covered by the tray itself as

$$q_{FB}\,dt\; = \;s_{FB}\,\rho_{FB}\,c_{pFB}\,(-dT_{FL'}) \qquad (38)$$

where s_{FB} is the thickness of the oven floor area exhibiting a temperature drop as it contacts the tray initially at room temperature.

By equating the left and central sides of Eq. (37), it was possible to express the temperature (T_{SW}) of the lower tray side as follows:

$$T_{SW} = \frac{T_S + \gamma_{AS}\,T_{FL'}}{1+\gamma_{AS}} \qquad (39)$$

with

$$\gamma_{AS} = h_A/h_S \qquad (40)$$

By referring to the right and central sides of Eq. (37), it was possible to estimate the local floor temperature ($T_{FL'}$) as

$$T_{FL'} = \frac{h_A\,T_{SW}\,\sqrt{\pi\,\alpha_{FB}\,t} + k_{FB}\,T_{FL}}{h_A\,\sqrt{\pi\,\alpha_{FB}\,t} + k_{FB}} \qquad (41)$$

By assuming that at the boundary between the tray and oven floor the instantaneous heat flux ($q_{cond} = q_S = q_A = q_{FB}$) was constant throughout the three laminar layers shown in Fig. 5, it was possible to evaluate its time course as

$$q_{cond} = \frac{T_{FL} - T_S}{\frac{1}{h_S} + \frac{1}{h_A} + \frac{\sqrt{\pi\,\alpha_{FB}\,t}}{k_{FB}}} \qquad (42)$$

Finally, the heat balance for the water-containing tray fed through the entry port of the wood-fired oven operating in quasi steady-state conditions may be written as

$$S_S \left[\frac{1}{\frac{1}{\varepsilon_V} + \frac{S_S}{S_{FL}}\left(\frac{1}{\varepsilon_S} - 1\right)} \sigma \left(T_V^4 - T_S^4\right) + h_c \left(T_V - T_S\right) + q_{cond} \right] dt =$$

$$[m_W(t)\, c_W + m_V\, c_V]\, dT_S + \lambda_e\, dm_e \qquad (43)$$

with

$$m_e = m_{W0} - m_W(t) \qquad (44)$$

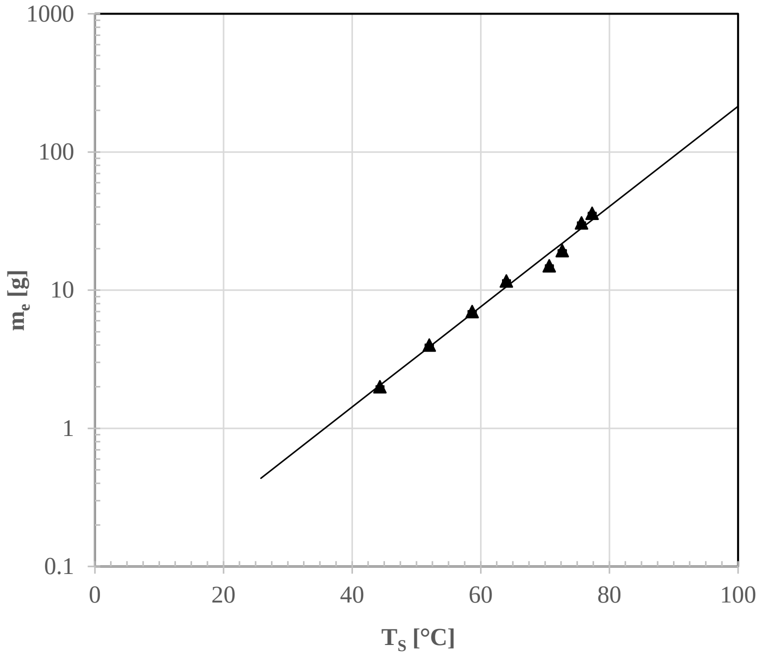

Figure 6. Semilogarithmic plot of the amount of water evaporated (me) against the average temperature of the water in the tray (TS: ▲) during the water heating tests, while the continuous line was plotted using the least squares regression equation (Eq. 45) with the coefficients reported in the text.

The amount of water evaporated during the water heating tests carried out here was found to be a non-linear function of the average water temperature (T_S). By plotting the mass of water evaporated (m_e) against T_S using a semi-logarithmic plot (Fig. 6), it was possible to describe m_e via the following empirical relationship:

$$ln(m_e) = a_0 + a_1\, T_S \qquad (45)$$

where a_0 and a_1 are empirical coefficients that can be determined by fitting [ln(m_e)-vs-T_S] data via the method of least squares:

a_0 = -2.99±0.26; a_1 = 0.084±0.004 °C^{-1} (r^2 = 0.987).

In this way, the derivate of m_e with respect to time may be expressed as

$$\frac{dm_e}{dt} = a_1\, e^{a_0 + a_1 T_S}\, \frac{dT_S}{dt} = a_1\, m_e \frac{dT_S}{dt} \quad (46)$$

In conclusion, once Eq. (46) had been introduced into Eq. (43), it was possible to reconstruct the time course of T_S by integrating numerically the following first-order differential equation:

$$\frac{dT_S}{dt} = \frac{S_S}{m_W(t)\, c_W + m_V\, c_V + \lambda_e\, a_1\, m_e} \left[\frac{\sigma}{\frac{1}{\varepsilon_V} + \frac{S_S}{S_{FL}}\left(\frac{1}{\varepsilon_S} - 1\right)} (T_V^4 - T_S^4) + h_c\, (T_V - T_S) + q_{cond} \right] \quad (47)$$

with the following initial and boundary conditions:

$T_S = T_{S0};\ T_{FL'} = T_{FL0};\ m_e = 0$ for t = 0 (48)

$T_V = T_{V0};\ T_{FL} = T_{FL0}$ for t ≥ 0 (49)

and the physical constraints expressing the amount of water evaporated (Eq. 45), the temperatures of the tray (T_{SW}) and oven floor ($T_{FL'}$) using Eq.s (39) and (41), and the heat flux (q_{cond}) using Eq. (42).

By referring to the above semi-empirical model, it was possible to reconstruct the time course of T_S during the aforementioned water heating tests, as reported below.

Water heating test

As the wood-fired oven had been ignited with 3 kg of oak logs for not shorter than 6 h, several aluminum trays, each one containing 300 g of deionized water, were fed through the oven entry port, and heated for times ranging from 0 to 80 s. While the oven floor temperature was practically constant (448 ± 5 °C), the sample temperature (T_S) increased from T_{S0} (25.8 ± 0.2 °C) to 77.3 ± 1.2 °C and its mass (m_W) decreased from (300 ± 0) g to (264 ± 4) g because of water evaporation.

Since the aluminum tray was just laid upon the hot oven floor, the heat transferred through its base was mainly controlled by the thermal resistance of the gaseous film between both surfaces. In fact, the free convection heat transfer coefficients pertaining to the laminar gaseous (h_A) and water (h_S) films (see Fig. 5) resulted to be of the order of 9 and 500 W m^{-2} K^{-2}, respectively, as calculated via the relationships listed in Table 4 for horizontal heated plates facing up with the physical properties of air and water reported in Table 3.

Fig. 7 shows the time course of the calculated values of the water mass (m_W) and temperature (T_S), as well as the temperature at the tray base (T_{SW}), and oven floor beneath the tray ($T_{FL'}$) using the mathematical model described at §3.4.

It can be noted quite a good reconstruction of the experimental profiles of T_S and m_W. The accuracy of both the calculated profiles was found to be sensitive to the overall heat transfer coefficient h_A. In fact, by increasing it from 9 to 18 W m^{-2} K^{-1}, the average mean percentage errors between the experimental and calculated T_S and m_W values reduced from 8.1 and 1.8% to 4.1% and 0.8%, respectively.

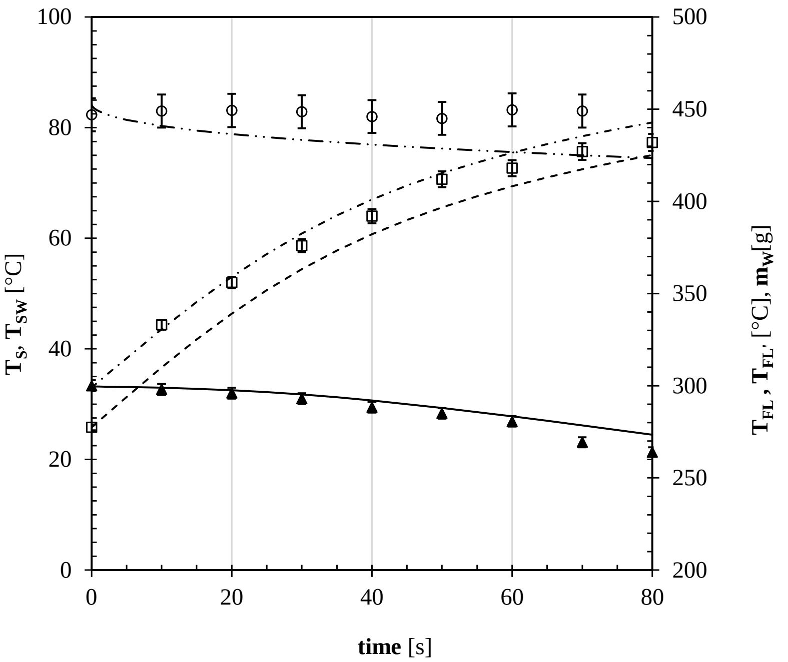

Figure 7. Time course of the experimental temperature (T_S: □) and overall mass of water (m_W: ▲) contained in an aluminum tray, and temperature of the oven floor around the sample itself (T_{FL}: ○), as well as the calculated values of m_W (continuous line), T_S (broken line), T_{SW} (dash-dotted line), and $T_{FL'}$ (dash-double dotted line) using the mathematical model described in the text.

Thus, according to Eq. (43), the overall heat flow to the water contained in an aluminum tray was predominantly represented by radiative heat (72.5±0.9 %), followed by convective heat (15.5±0.3 %) and conductive heat (12.0±0.6 %). Finally, the average power transferred to the water was 1.49±0.03 kW, corresponding to an overall thermal energy of about 118 kJ. Since the enthalpy accumulation rate within the oven chamber (E_O) in the quasi steady-state conditions was about 3.4 kW (Table 6), these tests made use of just 44% of E_O and confirmed that this wood-fired oven might bake just two pizzas at once. Since the enthalpy accumulation rate represented 28% of the overall power supplied by the firewood combustion (Table 6), the water heating test in question revealed an energy efficiency near to 12.2%, as further confirmed by the ratio between the overall energy transferred to the water-containing tray (118 kJ) and the energy released by the combustion of 3 kg/h of oaks logs (966.4 kJ) during the time interval (80 s) accounted for. Such average energy efficiency for the pizza oven examined here was greater than that (6-7%) of gaseous domestic ovens [10, 29], but smaller than that estimated for a metal fired-wood oven by Igo et al. (2020). In such cases, the main energy loss was due to the dispersion of hot fumes (Table 6).

CONCLUSIONS

In this work, the material and energy balances in a pilot-scale wood-fired oven in quasi steady-state operating conditions were established in conjunction with the measurement of the main composition of flue gas and external oven wall and floor temperatures in order to assess the heat loss rates through flue gas and insulated oven chamber. About 46% and 26% of the energy supplied by firewood combustion were dissipated by the exit fumes and external oven surfaces to the surrounding environment. The remaining 28% accumulated in the internal oven chamber, this allowing the temperatures of the oven vault and floor to be kept approximately constant, as well as one or two pizzas to be baked at once. By accounting for the simultaneous heat transfer mechanisms of radiation, convection, and conduction, it was possible to simulate quite accurately a series of water heating tests carried out using water-containing aluminum trays with a diameter near to that of a typical Neapolitan pizza. The overall heat transferred to each pizza-simulating tray was mainly due to radiation (circa 73%), the contribution of the convective heat from the oven vault and conductive heat from the oven floor amounting to about 15 and 12%, respectively.

Further work should be aimed at checking the capability of this semi-empirical model to predict the baking process of typical pizzas differently topped.

Nomenclature

a, b, c	Semi-axes of the semi-ellipsoid vault [m]
a_0, a_1	Empirical coefficients of Eq. (45)
b_i, B_i	Upper and lower chord lengths of the i-th thermally mapped zone of the external oven surface [m]
c_i	Specific heat of the i-th component or solid [J kg^{-1} K^{-1}]
c_V	Specific heat of aluminum tray [J kg^{-1} K^{-1}]
c_W	Specific heat of water [J kg^{-1} K^{-1}]
c_{Wv}	Specific heat of water vapor [J kg^{-1} K^{-1}]
d	Orthogonal distance from the oven mouth [m]
D_i	Diameter of the internal oven chamber [m]
e_i	Specific enthalpy of i-th gaseous stream on dry mass basis [J/kg]

E_O Enthalpy accumulation rate inside the internal oven chamber [W]

E_{OC} Energy rate lost through the external oven surfaces by convention [W]

E_{OR} Energy rate lost through the external oven surfaces by radiation [W]

e_R Specific enthalpy at the standard reference state [J/kg]

g Acceleration of gravity (=9.81 m^2/s)

Gr Grashof number as defined by Eq. (31) [dimensionless]

h_A Convective heat transfer coefficient through the laminar gaseous film [W m^{-2} K^{-1}]

h_c Convective heat transfer coefficient of the gas mixture filling the internal oven chamber [W m^{-2} K^{-1}]

HHV Higher heating value of firewood [MJ/kg]

h_i Height of the i-th thermally mapped zone of the external oven surface [m]

H_i Height of the internal oven chamber [m]

h_{Oi} Convective heat transfer coefficient of ambient air contacting the i-th external surface area of the oven chamber [W m^{-2} K^{-1}]

h_S Convective heat transfer coefficient through the laminar water film [W m^{-2} K^{-1}]

k_i Thermal conductivity of the i-th fluid or solid [W m^{-1} K^{-1}]

L Optical path length of the gas emitting gas as defined by Eq. (35) [m]

LHV Lower heating value of firewood [MJ/kg]

m_e Mass of water evaporated [kg]

MM_{fw} Molecular mass of firewood [g/mol]

m_V Mass of aluminum tray [kg]

m_W Instantaneous mass of water [kg]

n_O Overall number of thermally mapped zones [dimensionless]

Nu Nusselt number as defined by Eq. (29) [dimensionless]

p Empirical exponent of the Knud Thomsen’s formula ($p \approx 1.6075$) [dimensionless]

Pr	Prandtl number as defined by Eq. (32) [dimensionless]
q_A	Instantaneous convective heat flux through the laminar gaseous film [W/m^2]
Q_A	Mass flow rate of input dry air [kg/h]
q_{cond}	Instantaneous heat flux as defined by Eq. (42) [W/m^2]
q_{FB}	Instantaneous conductive heat flux through the firebrick layer [W/m^2]
Q_{FG}	Mass flow rate of output wet flue gas [kg/h]
Q_{FGd}	Mass flow rate of output dry flue gas [kg/h]
Q_{fw}	Wet firewood feed rate [kg/h]
Q_R	Accumulation rate of solid residues over the oven floor [kg/h]
q_S	Instantaneous convective heat flux through the laminar water film [W/m^2]
r^2	Coefficient of determination
Ra	Rayleigh number as defined by Eq. (30) [dimensionless]
R_{fw}	Effective molar dry matter combustion rate [kmol/h]
RH	Relative humidity of ambient air [%]
r_i	Weight generation or consumption rate of the i-th component [kg/h]
s	Vertical axis [m]
s_A	Thickness of the laminar gaseous film [m]
s_{FB}	Thickness of the firebrick layer [m]
S_{FL}	Surface area of the oven floor [m^2]
s_L	Thickness of the laminar water film [m]
S_{OC}	Overall lateral surface of the oven chamber [m^2]
S_{Oi}	Surface area of the i-th thermally mapped zone of the oven chamber [m^2]
S_{OM}	Surface area of the semicircular oven mouth [m2]
SS	Surface area of the circular tray [m2]
S_{SE}	Lateral surface area of the oblate semi-ellipsoidal vault [m^2]

t Baking time [s]

T_A Temperature of ambient air [°C]

T_{fi} Temperature of the i-th laminar film [°C]

T_{FG} Temperature of flue gas [°C]

T_{FL} Temperature of the oven floor [°C]

$T_{FL'}$ Temperature of the oven floor shielded by a tray [°C]

T_{KA} Absolute temperature of ambient air [K]

T_{KOi} Average absolute temperatures of the i-th thermally mapped zone of the oven chamber [K]

T_{Oi} Average temperature of the i-th thermally mapped zone of the oven chamber [°C]

T_S Average temperature of the water contained in the tray [°C]

T_{SW} Average temperature of the tray lower side laid over the oven floor [°C]

T_V Average absolute temperature of the oven vault in quasi steady-state conditions [K]

$U_{W,A}$ Humidity ratio of ambient air [kg of water vapor/kg of dry air]

$U_{W,FG}$ Humidity ratio of flue gas [kg of water vapor/kg of dry flue gas]

v_{FG} Mean superficial velocity of flue gas [m/s]

V_O Volume of the internal oven chamber [m^3]

x'_i Mass fraction of the generic i-th element of wood on dry mass [g/g]

x_A Ash content of firewood on wet matter [g/g]

x_M Moisture content of firewood on wet matter [g/g]

$y_{i,FG}$ Weight fraction of the i-th component of flue gas.

z_i Characteristic dimension of the i-th solid surface area [m]

Greek Symbols

α, β, γ, δ Stoichiometric coefficients of the wood combustion reaction [mol/mol]

α_{FB} Thermal diffusivity of firebrick [m^2/s]

β_V Volumetric coefficient of expansion of fluid [K^{-1}]

$\Delta\epsilon_{CO2}^{H2O}$ Binary overlap correction of the overall gas emissivity due to band overlapping of H_2O and CO_2 gases [dimensionless]

ΔT Temperature difference (=T_{Oi} - T_A) [°C]

ε_{CO2} Emissivity of carbon dioxide in the gas filling the oven chamber [dimensionless]

e_{H2O} Emissivity of water vapor in the gas filling the oven chamber [dimensionless]

ε_F Emissivity of flame [dimensionless]

ε_G Emissivity of flue gas [dimensionless]

ε_i Emissivity of the i-th radiating surface area [dimensionless]

γ_{AS} Ratio of the air-to-water convective heat transfer coefficients as defined by Eq. (40) [dimensionless]

η_{comb} Firewood combustion efficiency [dimensionless]

λ_e Latent heat of water evaporation [J/kg]

μ_i Dynamic viscosity of the i-th fluid [kg m^{-1} s^{-1}]

ρ_i Density of the i-th fluid or solid [kg m^{-3}]

σ Stefan-Boltzmann constant (= 5.67×10^{-8} W m^{-2} K^{-4})

Subscripts

0 Initial

A Referred to air

C Referred to carbon

FG Referred to flue gas

H Referred to hydrogen

N Referred to nitrogen

O Referred to oxygen

S Referred to sulfur

W Referred to tray bottom

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References

Àgueda, A., Pastor, E., & Planas E. (2010). Experimental study of the emissivity of flames resulting from the combustion of forest fuels. *International Journal of Thermal Sciences*, 49(3), 543-554.

Alberti, M., Weber, R., & Mancini, M. (2018). Gray gas emissivities for H_2O-CO_2-CO-N_2 mixtures. *Journal of Quantitative Spectroscopy & Radiative* Transfer, 219, 274–291.

Anon. (n.d.). *Emissivity Table for Infrared Thermometer Readings*. https://ennologic.com/wp-content/uploads/2018/07/Ultimate-Emissivity-Table.pdf (accessed on 20 October 2022).

Barratt, N. (2021). *Different oven types explained!* https://bluenz-3.global.ssl.fastly.net/appliances/ovens/different-types-of-ovens-explained/ (accessed on 21 October 2022).

Carslaw, H.S., & Jaeger, J.C. (1959). *Conduction of heat in solids*. 2nd Edn. Clarendon Press, Oxford, UK, pp. 58-61.

Choi, Y., & Okos, M.R. (1986). Thermal properties of liquid foods: review. In M.R. Okos (Ed.) *Physical and Chemical Properties of Food*. American Society of Agricultural Engineers. St. Joseph, Mich., USA, pp. 35–77.

Ciarmiello, M., & Morrone, B. (2016a). Numerical thermal analysis of an electric oven for Neapolitan pizzas. *International Journal of Heat and Technology*, 34 (Special Issue 2), S351-S358. doi:10.18280/ijht.34S223

Ciarmiello, M., & Morrone, B. (2016b). Why not using electric ovens for Neapolitan pizzas? A thermal analysis of a high temperature electric pizza oven. *Energy Procedia*, 101, 1010-1017. doi: 10.1016/j.egypro.2016.11.128

Earle, R. L., & Earle, M.D. (2004). *Unit Operations in Food Processing*. Web Edn., The New Zealand Institute of Food Science & Technology (Inc.). https://www.nzifst.org.nz/resources/unitoperations/index.htm (accessed on 20 October 2022).

EC. (2010). European Commission Regulation (EU) No. 97/2010, entering a name in the register of traditional SPECIALITIES guaranteed [Pizza Napoletana (TSG)]. *Off. J. Eur. Union*, *34*, 5. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32010R0097 (accessed on 20 October 2022).

EC. (2011). European Commission, preparatory studies for eco-design requirements of EuPs (III): Lot 23 domestic and commercial hobs and grills, included when incorporated in cookers. Final Version. https://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Lots/Final_Documents/Lot_23_Task_3_Final.pdf (accessed on 19 October 2022).

Falciano, A., Masi, P., & Moresi, M. (2022). Performance characterization of a traditional wood-fired pizza oven. *Journal of Food Science*, 87, 4107-4118. https://doi.org/10.1111/1750-3841.16268

Green, D. W., & Perry, R. H. (2008). *Perry's Chemical Engineers' Handbook*. 8th Edn. McGraw-Hill, New York. DOI: 10.1036/0071422943

Hager, T. J., & Morawicki, R. (2013). Energy consumption during cooking in the residential sector of developed nations: A review. *Food Policy*, 40, 54-63.

Heldman, D. R., & Lund, D. B. (2007). *Handbook of Food Engineering*. 2nd Edn. CRC Press, Taylor & Francis Group, Boca Rotan, FL, USA, p. 402 and p. 410.

Henderson-Sellers, B. (1984). A new formula for latent heat of vaporization of water as a function of temperature. *Quart. J. R. Met. Soc.*, 110, 1186-1190.

Igo, S. W., Kokou N., Compaoré, A., Kalifa, P., Sawadogo, G. L., & Namoano, D. (2020). Experimental analysis of the thermal performance of a metal fired-wood oven. *Iranian (Iranica) Journal of Energy and Environment*, 11(3), 225-230.

Jones, J.M., Mason, P.E., & Williams, A. (2019). A compilation of data on the radiant emissivity of some materials at high temperatures. *Journal of the Energy Institute*, 92, 523-534.

Kern, D. Q. (1950). *Process heat transfer*. McGraw-Hill Book Company, Inc., Auckland (USA), p. 82.

Keyest, F.G., & Vines, R. G. (1964). The thermal conductivity of steam. *Int. J. Heat Mass Transfer*, 7, 33-40.

Manhiça, F. A. (2014). Efficiency of a wood-fired bakery oven - Improvement by theoretical and practical. PhD Thesis, Chalmers University of Technology, Gothenburg, Sweden. https://research.chalmers.se/en/publication/203999 (accessed 20 October 2022).

Manhiça, F. A., Lucas, C., & Richards, T. (2012). Wood consumption and analysis of the bread baking process in wood-fired bakery ovens. *Applied Thermal Engineering*, 47, 63-72.

Mukunda, H. S. (2009). *Understanding Combustion*. 2nd Edn. Orient Blackswan, New Delhi, India.

Neutrium. (2012). *Properties of air*. https://neutrium.net/properties/properties-of-air/ (accessed on 20 October 2022).

Singh, R. P., Erdoğdu, F., & Rahman, M. S. (2009). Specific heat and enthalpy of foods. Chp. 16. In Rahman, M. S. (Ed.) *Food Properties Handbook*. 2nd Edn. CRC Press, Boca Raton, FL, USA, pp. 517-543.

The Engineering ToolBox. (n.d.). *Water - Density, Specific Weight and Thermal Expansion Coefficients*. https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html (accessed on 20 October 2020).

Varlamov, A., Glatz, A., & Grasso, S. (2018). The physics of baking good pizza. *Phys. Educ.*, 53(6), 065011. https://doi.org/10.1088/1361-6552/aadc2e.

Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2010). An overview of the chemical composition of biomass. *Fuel*, 89, 913-933.

Zhang, Y., Li, Q., & Zhou, H. (2016). *Theory and Calculation of Heat Transfer in Furnaces*. Chp. 5. Elsevier, Amsterdam, pp. 131-172. https://doi.org/10.1016/B978-0-12-800966-6.00011-9.

Chapter 7

Phenomenology of Neapolitan pizza baking in a traditional wood-fired oven

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Abstract:

Despite Neapolitan pizza is a world-wide renown Italian food, its obligatory baking in wood-fired ovens has so far received little attention in the scientific community. Since heat transfer during pizza baking is not at all uniform, the main aim of this work was to analyze the phenomenology of Neapolitan pizza baking in a pilot-scale wood-fired pizza oven operating in quasi steady-state conditions. The different upper area sections of pizza covered or not by the main topping ingredients (i.e., tomato puree, sunflower oil, or mozzarella cheese), as well the bottom of pizza and growth of its raised rim, were characterized by visual colorimetric analysis, while the time course of their corresponding temperatures was monitored using an infrared thermal scanning camera. All pizza samples tested had an average diameter of 28.2 ± 0.4 cm and a raised rim thick 2.2 ± 0.1 cm. Independently of the garnishment ingredients used, the hedge height increased from 0.8 ± 0.1 cm to 2.3 ± 0.3 cm in as short as 80 s. During pizza baking, the oven floor temperature was practically constant (439 ± 3 °C), while that underneath each pizza reduced as faster as the greater the pizza mass laid on it. The maximum temperature of the pizza bottom was equal to 100 ± 9 °C, the *pizzaiuolo* being quite skill at lifting and rotating the pizza to bake it uniformly around its whole circumference, while that of the upper pizza side ranged from 182 °C to 84 or 67 °C in the case of white pizza as such, tomato pizzas or margherita pizza, mainly because of their diverse moisture content and emissivity. The pizza weight loss was nonlinearly related to the average temperature of the upper pizza side when using no or just one topping ingredient or tomato puree-topped surface area. The overall weight loss was near to 10 g in all pizza types examined. The formation of brown or black colored areas in the upper and lower sides of baked pizza was detected with the help of the IRIS electronic eye using 41 or 16 different decimal color codes in the RGB color space. The upper side exhibited greater degrees of browning and blackening than the lower one, their maximum values of about 26 and 8% being respectively observed in white pizza as such. The formation rate of browned or blackened areas was described using the Bigelow first-order kinetic model and was characterized by a 10-fold increase as the temperature of the upper side of pizza was increased by 16-19 or 9 °C in the case of any white or tomato pizzas. These results are needed to develop an accurate modelling and control strategy to reduce the variability and maximize the quality attributes of Neapolitan pizza.

Keywords: baking characterization; browning and burning kinetics; infrared thermal scanning; Neapolitan pizza; raised rim growth; thermal mapping of pizza crust and bottom; visual color assessment; weight loss; wood-fired oven.

Introduction

Neapolitan pizza is a well-known Italian food recognized as one of the traditional specialties guaranteed (TSG) by the European Commission Regulation no. 97/2010 (EC, 2010). Since it must be baked in wood-fired ovens, its final quality strictly depends on the ability of the Neapolitan pizza maker (*Pizzaiuolo*). In fact, the art of pizza making has been included on the List of Intangible Cultural Heritage of Humanity by the United Nations Education, Scientific and Cultural Organization (UNESCO, 2017).

Even if the pizza production stages (i.e., dough preparation and rising, ball shaping, lamination, garnishing, and baking) have been thoroughly illustrated (Masi et al., 2015), how wood-fired pizza ovens should be appropriately operated to assure a soft, elastic, tender and fragrant Neapolitan-style wood-fired pizza with a crust finely bubbled up and just charred in a few spots is one of Pizzaiolo skills patiently learned after long apprenticeships. The charring is a byproduct of baking the pizza in a blazing-hot oven. It mainly affects the raised edge and underside areas of the crust, which are nearest to the oven heat sources (oven vault and floor, respectively). It would end with burning if the pizza were baked any longer than the recommended 90 s (EC, 2010).

The formation of color in pizza during baking is generally expressed as browning and is the result of non-enzymatic chemical reactions, such as the Maillard reaction and caramelization. Under direct heating the former occurs between reducing sugars and amino acids, proteins, and/or other nitrogenous organic compounds, while latter between carbohydrates, mainly sucrose and reducing sugars (Fennema, 1996). Both reactions only depend on temperature and water activity, this expressing the readiness of water for chemical reactions in food products. Among the numerous methods used to quantify the kinetics of browning via color measurements and chemical analysis, visual color change of bakery products has been successfully described using the CIE-Lab color indices (Purlis, 2010).

During the pizza baking process in a wood-fired oven, simultaneous heat and mass transfer takes place within the product inducing a number of physical, chemical, and biochemical changes besides browning, such as volume expansion and shrinkage, water evaporation, dough/crumb transition owing to protein denaturation and starch gelatinization, and formation of a crust (Masi et al., 2015). The operation of a pilot-scale wood-fired pizza oven from its start-up phase to its operation in quasi steady-state conditions was previously described (Falciano et al., 2022a). Moreover, it was assessed that its average thermal efficiency was 13 ± 4 % independently of different white or tomato pizza products baked. Then, such authors (Falciano et al., 2023) succeeded in quantifying that the heat loss rates through flue gas and insulated oven chamber were respectively equal to 46% and 26% of the energy supplied by burning firewood, while the enthalpy accumulation rate in the oven chamber was near to 3.4 kW. This was sufficient not only to maintain the temperatures of the oven vault and floor practically constant at (546 ± 53) °C and (453 ± 32) °C, respectively, but also to bake one or two pizzas at the same time (Falciano et al., 2023). Such heat flow rate was predicted by accounting for the simultaneous heat transfer mechanisms of radiation and convection between the oven vault and floor surface areas. Moreover, a series of water heating tests were quite accurately reconstructed by accounting for a simultaneous heat flow from the oven vault of the radiative and convective types and from the oven floor of the conductive one, their contribution representing about 73%, 15%, and 12% of the overall heat transferred, respectively.

The main aim of this work was to characterize the phenomenology of Neapolitan pizza baking in a pilot-scale wood-fired oven operating in quasi steady-state conditions. Since heat transfer during pizza baking is not at all uniform, and particularly complex, the temperature of the upper central area of the pizza, being covered by diverse topping ingredients differing in their thermal properties, exhibited a slower rise than that of the external annular rim, this being devoid of any topping. Thus, the rim showed a greater expansion due to yeast fermentation and steam generated by the rapid evaporation of its water content. As temperature continued to increase gluten proteins experienced aggregation and cross-linking, this conferring rigidity to the alveolar structure formed that did not collapse but became permanent. Any further increase in the temperature of the raised rim, as well as the lower side of pizza laid upon the hot oven floor, caused a strong reduction in the moisture content and triggered pyrolysis reactions with the formation of diffuse burns. Thus, the first aim of this work was to measure the different area sections of pizza covered or not by the main topping ingredients (i.e., tomato puree, sunflower oil, or mozzarella cheese), as well the growth of the raised rim, by image analysis. The second and third aims were to monitor the time course of the temperature of the aforementioned areas and pizza weight loss during the baking of pizza samples differently garnished. The final one was to monitor the evolution of the degree of browning or burning of the pizza samples undergoing baking by means of an electronic eye and develop a kinetic model able to describe the extent of browning and blackening areas as a function of time and temperature.

Materials and methods

Raw materials

The Neapolitan pizza bases were prepared using the following ingredients:

i) soft wheat flour type 00 with a nominal moisture content of 12% w/w as kindly supplied by Antimo Caputo Srl (Naples, Italy),

ii) fresh brewer's yeast (Lesaffre Italia, Trecasali, Parma, Italy),

iii) Sicilian fine table salt (Italkali, Petralia, Palermo, Italy), and

iv) deionized water at 16-18 °C.

Each pizza base was baked as such or garnished using sunflower oil (Mepa Srl, Terzigno, Naples, Italy) and/or tomato puree at 7.0±0.2 °Brix (Mutti SpA, Parma, Italy), and Mozzarella cheese (Selex Gruppo Commerciale SpA, Milan, I). The latter had a moisture content of 50% w/w on a wet basis.

The wood-fired oven was fed with seasoned oak logs having weight, length, diameter and moisture and ash contents equal to 600±200 g, 250±20 mm, 40±10 mm, and 5.67±0.17 and 2.9±0.7 % (w/w), respectively.

Pizza preparation

The pizza dough was prepared by mixing 1,600 g of soft wheat flour type 00 and 50 g of table salt with 1 L of deionized water at room temperature, where 1 g of fresh brewer's yeast had been pre-dispersed to allow its re-hydration for about 3 min. Such operation was carried out in a spiral mixer (Grilletta IM5, Famag Srl, Milan, Italy) set at level 1 for 18 min. The resulting dough was left resting at room temperature for 20 min; thereafter, it was partitioned into dough balls of about 250 g each. These were placed over 60 cm x 40 cm plastic trays (Giganplast, Monza and Brianza, Italy), and stored into a climatic chamber (KBF 240, Binder, Tuttlingen, Germany) at 22 °C and 80% relative humidity for 18 h to yield a more extensible and digestible structure.

Each leavened loaf was sprinkled with a pinch of flour, and manually laminated under the pressure of both hands' fingers from the center outwards, the resulting disc being turned several times. The final pizza base was finally baked as such (sample A) or topped as shown in Table 1 (samples B-E).

Table 1 Samples of Neapolitan Pizza submitted to baking tests in the wood-fired oven used in this work.

Sample	Topping	Overall mass [g]
A	No garnishment	250±1
B	Sunflower oil (30 g)	280±2
C	Tomato puree (70 g)	320±2
D	Tomato puree (70 g) and sunflower oil (30 g)	350±3
E	Tomato puree (70 g), sunflower oil (30 g) and Mozzarella cheese (80 g)	430±5

Equipment

The pilot-scale wood-fired pizza oven used in this work is shown in Fig. S1 in the supplement. Its geometry and start-up procedure were described previously (Falciano et al., 2022a). By feeding 3 kg of oak logs per hour (Q_{fw}) for about 6 h, it was possible to put the wood-fired oven in quasi steady-state operating conditions (Falciano et al., 2022a).

Baking tests

Such tests were carried out in triplicate after the oven had been pre-heated at Q_{fw}= 3 kg/h for 6 h. Each pizza sample of the 5 types shown in Table 1 was baked in the wood-fired oven for 20, 40, 60, and 80 or 100 s. As soon as each sample was removed from the oven, the temperature of the oven floor area previously occupied by the sample itself, as well as that of the annular area around the sample itself, was measured by using an infra-red (IR) thermal imaging camera (FLIR E95 42°, FLIR System OU, Estonia) equipped with an uncooled microbolometer thermal sensor with dimension 7.888 x 5.916 mm and resolution 464 x 348 pixels, its pixel pitch being 17 µm, focal length of lens 10 mm, and field of view of 42° x 32°. As soon as the pizza sample had been extracted from the oven, the temperatures of the pizza disc in the rim, and upper and lower central areas were measured using the above thermal imaging camera. Finally, the sample mass was determined to assess its weight loss using an analytical balance (Gibertini, Milan, Italy).

Monitoring of the raised rim height

The variation in the instantaneous height (h) of the raised rim during the baking phase was assessed by using a thermal imaging camera (FLIR E95 42°, FLIR System OU, Estonia) operating in the video mode, which had been fixed on a stand, while a metal reference ruler was positioned near to the pizza sample inside the oven. The images of the pizza sample were extrapolated from the registered video for an overall baking time (t_B) of 80 s. The images were captured every 2 s during the first 20 s, every 4 s as t_B ranged from 20 to 40 s, and finally every 10 s as t_B increased from 40 to 80 s. These were then analyzed using a free, open-source image processing software ImageJ (Java2HTML v. 1.5, National Institutes of Health, USA).

Color visual assessment of baked pizza areas

The variation in the color of each pizza sample undergoing baking in a wood-fired oven was monitored using the IRIS visual analyzer 400 and AlphaSoft software (Alpha MOS, Toulouse, France). The pictures of each pizza sample were taken in a closable light chamber (420 x 560 x 380 mm) to assure controlled light conditions and avoid any influence of external light on the visual analysis. Dual top and bottom LED (Light Emitting Diodes) lighting system was used to prevent any shadow effect. It was characterized by a color temperature of 6700 K, Color Rendering Index (CRI) of 98 (this involving an excellent ability of the light source to accurately reproduce the colors of the object it illuminates, its maximum score being equal to 100), and spectral power distribution of natural daylight close to D65 corresponding to the color temperature of the sky on a clear day around noon. The acA2500-14gc Basler ace GigE camera (Basler AG, Ahrensburg, Germany) equipped with 16-mm diameter lens was used to shoot the pizza sample pictures. Once the instrument had been calibrated with a certified color scale, the pizza samples were placed over a removable white tray, diffusing a uniform light inside the aforementioned light chamber. Measurements on both the upper and lower pizza sides were performed in triplicate using the CIELab color space, which is an international standard for color measurement adopted by *Commission Internationale de l'Eclairage* (CIE) in 1976 (León et al., 2006). L^* describes brightness and extends from 0 (black) to 100 (white), while a^* and b^* represent the green vs. red, and blue vs. yellow coordinates, each one ranging from -100 to +100. For color analysis, once the background of each picture had been removed, the edited image was processed as a color spectrum representing the percentage of each color identified on the pizza surface within a fixed scale of 4096 colors. Each of these colors corresponded to a unique set of 3 values in the RGB (R-Red, G-Green, B-Blue) color space. These coordinates describe the relative amounts of red, green, and blue light mixed to create a particular color, each one ranging from 0 (no color added) to 255 (100% color added). The values for parameters R, G, B were averaged and accounted for the frequency of appearance of each individual color decimal code. The Hierarchical Cluster Analysis (HCA) was used to create clusters of colors corresponding to the degree of browning or blackening of the different pizza samples as a function of the baking time (t_B).

Statistical analysis of data

Each baking test was carried out three times. All parameters were shown as average ± standard deviation and were analyzed by Tukey test at a probability level (p) of 0.05. One-way analysis of variance was carried out using SYSTAT version 8.0 (SPSS Inc., 1998).

Results and discussion

Physically, pizza baking can be described as a process of simultaneous heat and liquid and vapor water transports within the product itself and within the gaseous environment inside the oven chamber. Conduction raises the temperature of the lower pizza surface, which is in contact with the hot oven floor, and then transfers heat from the lower surface to the upward layers of the crust, while radiation and convection transmit heat from the oven vault to the exposed upper surface of the pizza. Hence, these heat transfer mechanisms produce different localized heating effects, which will be monitored as reported below.

Assessment of the different area sections of baked pizza samples

By using the open-source image processing software ImageJ, it was possible to assess the surface area occupied by the ingredients used to top several pizza samples cooked in the pilot-scale wood-fired oven, as shown in Table 2.

Whatever the ingredient type and number used, there was no statistically significant difference among the overall surface areas of all the pizza samples tested at 95% confidence level, this amounting to 623 ± 18 cm^2, equivalent to an average diameter of 28.2 ± 0.4 cm. Also, the surface area of the raised rim was independent of the garnishment used, being the average thickness of this annular section equal to 2.2 ± 0.1 cm.

From Table 2, it can be noted that in the case of a single ingredient (tomato puree or sunflower oil), the surface area over which each ingredient was spread resulted to be practically constant (440 cm^2), this representing about 71% of the overall pizza surface areas. When using both these ingredients, the surface area covered by tomato puree or sunflower oil amounted to 48 or 23%, respectively. When the mozzarella cheese was further put in, the surface areas covered by sunflower oil, tomato puree or mozzarella cheese totaled 7, 28, or 37% of the overall pizza surface areas.

Table 2 - Overall and partial areas of the pizza base as garnished with one or more than one ingredient (SO, sunflower oil; TP, tomato puree; MC, mozzarella cheese) together with its average diameter and thickness of the raised rim.

Topping Ingredient	**no.** **type** Unit	**1** **SO** mean± sd	**1** **TP** mean± sd	**2** **SO+TP** mean± sd	**3** **SO+TP+MC** mean± sd
Rim Area	cm^2	182 ± 12^{a}	179 ± 5^{a}	181 ± 9^{a}	180 ± 11^{a}
SO Area	cm^2	441 ± 25^{a}	-	141 ± 24^{b}	43 ± 5^{c}
TP Area	cm^2	-	440 ± 17^{a}	302 ± 8^{b}	172 ± 21^{c}
MC Area	cm^2	-	-	-	232±13
Overall Area	cm^2	623 ± 14^{a}	619 ± 12^{a}	624 ± 24^{a}	624 ± 24^{a}
Pizza Diameter	cm	28.2 ± 0.3^{a}	28.1 ± 0.3^{a}	28.2 ± 0.5^{a}	28.3 ± 0.7^{a}
Average Rim Thickness	cm	2.2 ± 0.2^{a}	2.2 ± 0.1^{a}	2.2 ± 0.2^{a}	2.2 ± 0.2^{a}

In each row, values with the same letter have no significant difference at $p < 0.05$.

Monitoring of the raised rim growth

During pizza baking in a wood-fired oven, the heat received by the rim makes it expand because of yeast fermentation and local water evaporation. A thermal imaging camera was used to monitor the time course of its height (h) when baking different pizza samples of type A-D (Table 1), as shown for instance for the pizza sample C in Fig. 1. It can be noted a first rapid growth of the edge during the first 40 s followed by quite a slower one in the following 40 s.

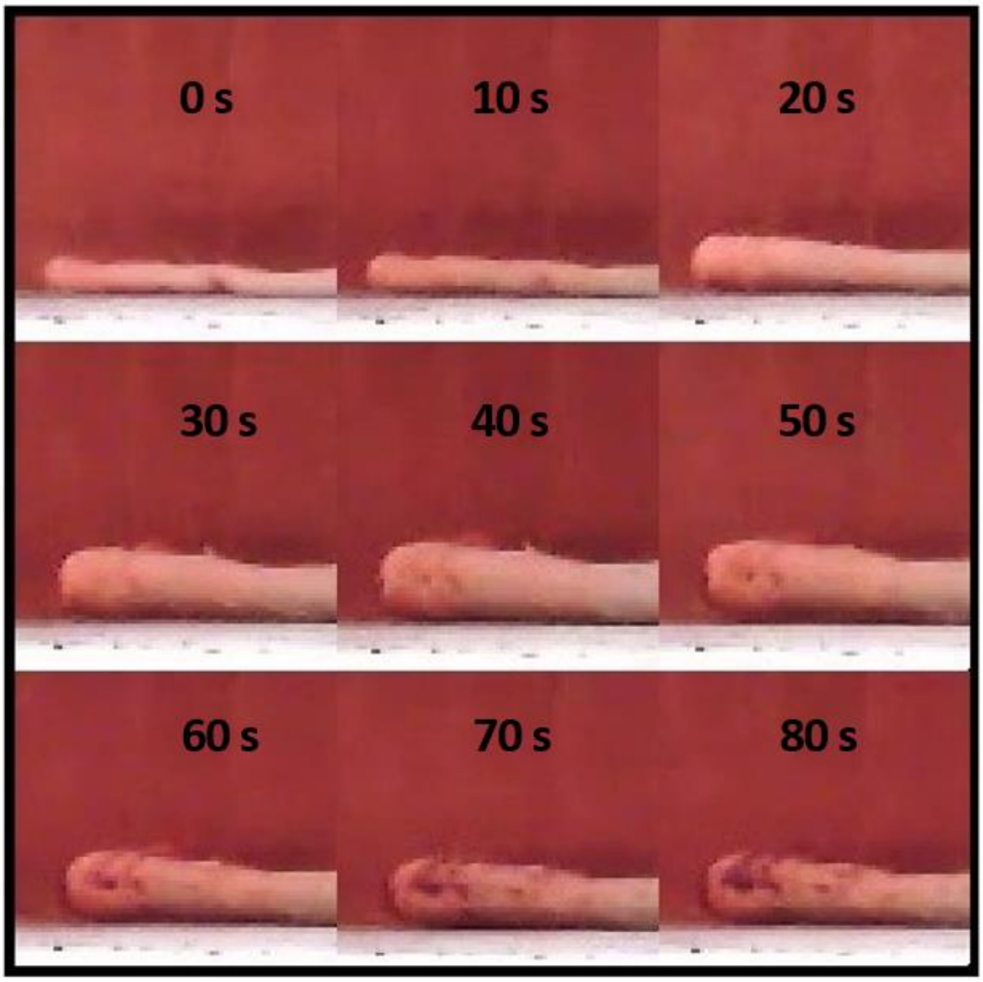


Figure 1: Cross section pictures of the pizza crust topped with tomato sauce and sunflower oil (Pizza sample D: cf. Table 1) at different baking times in the range of 0 to 80 s.

Table S1 in the supplement materials and Figure 2 show the effect of baking time (t_B) on the average value and standard deviation of the instantaneous height (h) of the raised rim of 15 different pizza samples of type A-D (cf. Table 1) during their baking in a pilot-scale wood-fired oven. The rim growth in white pizza samples (A) was not statistically different from that of tomato pizza samples (C) at a probability level of 0.05. This was also observed for the raised rims of white and tomato pizza samples both enriched with sunflower oil (B and D), these being however statistically different from those of pizza samples of types A and C (Table S1). Taken together and accounting for an average data variability of 12%, the raised rim growth might be regarded as approximately independent of the garnishment ingredients used, its height increasing from 0.78 ± 0.09 cm to 2.33 ± 0.34 cm in as short as 80 s (Fig. 2). In reality, a first exponential growth of the raised rim lasting about 20s was followed by a linear growth during the subsequent 20-30 s and then by a declining growth during the remaining 30-40 s.

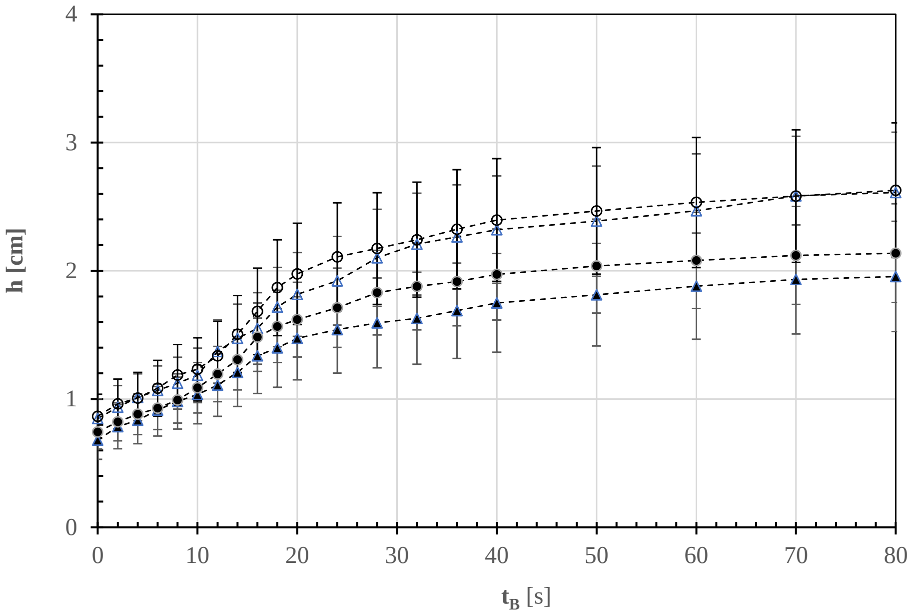


Figure 2 – Effect of baking time (t_B) on the average value and standard deviation of the instantaneous height (h) of the rim of different pizza samples (A, ▲; B, △; C; ●; D, ○) during their baking in a pilot-scale wood-fired oven.

Mapping of the thermal profile of pizza during baking

Table S2 in the supplement shows the mean values and standard deviations of the experimental temperatures of the oven floor exposed to fire and oven vault (T_{FL}) or shielded by the pizza sample undergoing baking (T_{FLbp}), and of different sectors of five pizza types (cf. Table 1), such as raised rim (T_{SR}), upper (T_{SU}) and lower (T_{SL}) central areas, as baked in a wood-fired pizza oven that had been fed with 3 kg/h of oak logs for at least 6 h prior to its use and thus operating in quasi steady-state conditions. Tables S2 also shows the temperatures of the areas covered with tomato puree (TP), sunflower oil (SO) and/or mozzarella cheese (MC) when 2 or 3 ingredients were distributed over the central area of the pizza crust. Each measurement was repeated 12 times for any of the five pizza types listed in Table 1.

Figure 3 shows the time course of the average temperatures of the oven floor as exposed to fire (T_{FL}) or shielded by the pizza sample itself (T_{FLbp}) throughout all the baking tests performed.

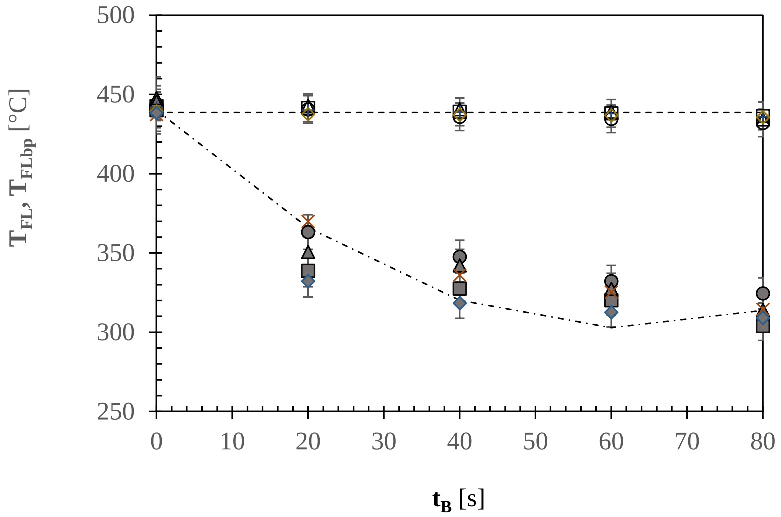


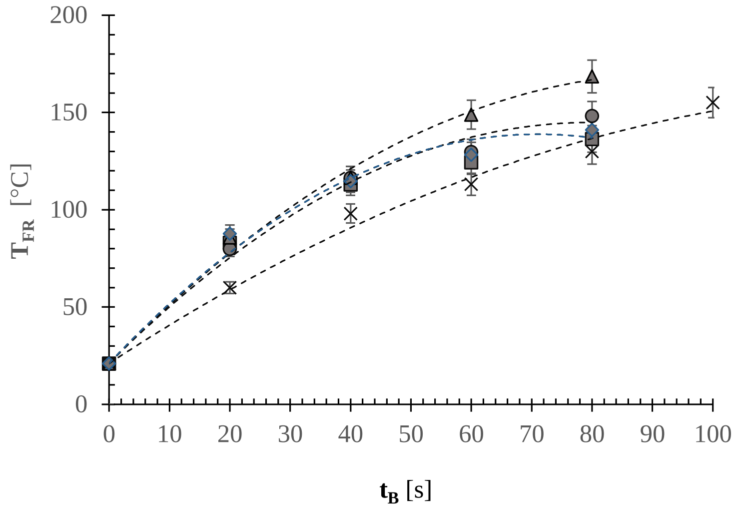
Figure 3 – Time course of the average temperatures of the oven floor as exposed to fire (T_{FL}: open symbols) or shielded by the pizza sample (T_{FLbp}: closed symbols) throughout the baking tests of different pizza types: A, ○, ●; B, △, ▲; C, □, ■); D, ◇, ◆; E, +, ×). The horizontal broken line shows the average temperature of the oven floor around any pizza undergoing baking, while the dash-dotted line shows the quadratic regression line used to simulate the temperature profile of the oven floor under a tomato pizza (C).

First, the oven floor temperature (T_{FL}) exhibited no statistically significant variation around 439 ± 3 °C at the probability level p=0.05, this confirming further that the oven was operating in quasi steady-state conditions. Second, the temperature of the oven floor at direct contact of each pizza showed a decreasing trend, that was accurately simulated by using a quadratic regression equation with coefficients of determination (r^2) ranging from 0.98 to 0.99. The first derivate of T_{FLbp} with respect to t_B for t_B=0 was expressed by a negative number, its modulus apparently increasing with the mass of the pizza sample. The greater the pizza mass per unit surface the most rapid is the cooling of the oven floor surface area over which the raw pizza is laid.

Figure 4 shows the time course of the average temperatures of the raised rim (T_{SR}) and lower area (T_{SL}) of all the pizza samples fed into the wood-fired oven.

As shown in Fig. 4a, after 80 s the raised rim in all the pizza types under study increased to an average temperature (T_{SR}) of 150 ± 13 °C, except for the margherita pizza (E) that reached such a temperature after 100 s owing to its greater mass (Table 1). All these thermal profiles were fitted using quadratic regression equations, their coefficients of determination (r^2) ranging from 0.996 to 0.998 (see broken lines in Fig. 4a). Moreover, in the case of pizza types A-D, for t_B=0 (dT_{SR}/dt_B) and (d^2T_{SR}/dt_B^2) resulted to be approximately constant and equal to 3.2 ± 0.1 °C/s and – 0.041 ± 0006 °C/s^2, respectively. The final temperature of the raised rim was thus about independent of the topping ingredients used and gave rise to quite a crispy area of the pizza crust.

a)



b)

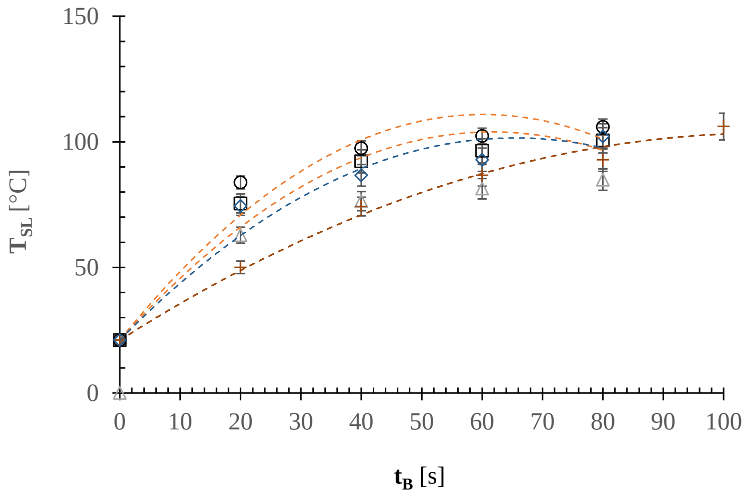


Figure 4 – Time course of the average temperatures of **a**) the raised rim (T_{SR}: closed symbols) and **b**) lower area (T_{SL}: open symbols) of all the pizza samples during the baking tests of different pizza types: A, ●, ○; B, ▲, △; C, ■, □); D, ◆, ◇; E, ×, +). The broken lines were calculated using the specific least squares quadratic regressions.

The lower area of any pizza sample was not uniformly contacting the hot oven floor owing to the presence of a laminar layer made of stagnant air and/or water evaporated. Thus, its temperature (T_{SL}) increased up to an average value of 100 ± 9 °C in as short as 80 s, except for the pizza type E that reached such a temperature after 100 s (Fig. 4b). By using the least squares method, quadratic regression equations were used to reconstruct the T_{SL} profiles, their coefficients of determination (r^2) varying from 0.988 to 0.998 (see broken lines in Fig. 4b). For the pizza types A-D, for t_B=0 (dT_{SL}/dt_B) and (d^2T_{SL}/dt_B^2) were found to be approximately constant and equal to 2.7 ± 0.2 °C/s and – 0.044 ± 0005 °C/s^2, respectively. Probably, because of the *pizzaiuolo*'s ability at lifting and rotating the pizza toward the fire by means of a metal peel, not only was the pizza baked uniformly around its whole circumference, but also was the final temperature of the lower pizza area not so high to burn it. This aspect will be further discussed below.

Figure 5 shows the time course of the average temperature (T_{SU}) of the upper area of the pizza samples examined in this work. This temperature was related to the area devoid of any ingredient in the case of white pizza (A) or spread with sunflower oil (B) or tomato puree (C) only. In the case of pizza D, its central area having been spread with SO and TP, the thermal imaging camera was able to determine the average temperatures T_{SO} and T_{TP} of both areas. In the case of pizza E, the average temperatures of the areas covered with TP, SO or mozzarella cheese pieces were measured.

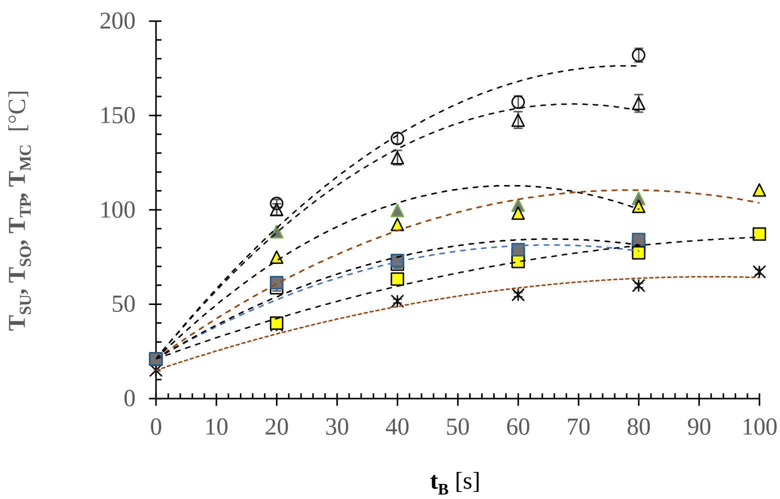


Figure 5 – Time course of the average temperature of the upper area as a whole (T_{SU}) or segmented in the two or three ingredients used to garnish the pizza samples examined in this work: A, ○; B, △; C, □; D: T_{TP},■; T_{SO}, ▲; E: T_{TP}, □; T_{SO}, △; T_{MC}, ✳). The broken lines refer to the quadratic regression lines used to simulate the different temperature profiles.

In the case of white pizza (A), at the end of baking the temperature of the central upper side approached 182 ± 9 °C, probably because the formation of large dark brown colored areas increased the local emissivity and enhance the absorption of the radiative heat from the oven vault. When the central upper area of white pizza (B) was spread with sunflower oil, the increase in the pizza mass from 250 to 280 g limited its temperature raise to 156 ± 4 °C. For the pizzas D and E, the area covered with SO reached a lower temperature of 108 ± 3 °C probably because of its smaller area exposed to the irradiating oven vault. When the whole central area of pizza C was garnished with a tomato puree at 7 °Brix, its great moisture content limited the temperature growth to 81 ± 2 °C. Such a temperature was not statistically significantly different from that of the area equally topped with TP in pizza D or E, their average temperatures being equal to 84 ± 3 °C (Fig. 5). Finally, the temperature of the area topped with white or pale ivory colored mozzarella cheese was definitively smaller (67 ± 2 °C) for its initial temperature (15 °C) was smaller than that of dough, TP, and SO (21 °C), and its emissivity was lesser than that of tomato puree.

Time course of the pizza weight loss

Table S2 lists the instantaneous mean mass (m_S) of any pizza sample studied.

Such data were used to estimate the instantaneous amount of water evaporated during baking and thus calculate the current moisture mass fraction on an oil-free basis (x_W) of the overall pizza sample. It can be noted that the moisture content of white pizza as such (A) or topped with sunflower oil (B) reduced from 0.45 g/g to 0.43 or 0.42 g/g, respectively. On the contrary, x_W for the tomato pizzas as such (C) or topped with SO (D) reduced from 0.555 to 0.542 g/g. The addition of MC in pizza sample E slightly affected x_W, which lessened from 0.554 to 0.536 g/g.

The amount of water evaporated during the baking tests carried out here was found to be a complex function of the average temperature of the sample, as well as its composition and water activity. When using no or just one topping ingredient, such a temperature was assumed as coincident with that of the upper side of the pizza crust (T_{SU}). When the pizza was garnished with two or three ingredients, it was assumed as coincident with that of the surface area topped with tomato puree (T_{TP}), this representing as much as 48 and 28% of the overall surface area of pizza types D and E, respectively.

Thus, by plotting the data collected during the water-heating (Falciano et al., 2022) and pizza-baking tests against the sample temperature (T_S) as above specified (i.e., T_{SU} or T_{TP}) using a semi-logarithmic plot (Fig. 6), it was possible to describe the mass of water evaporated (m_e) by the following empirical relationship:

$$\ln(m_e) = a + b\, T_S \qquad (1)$$

where a and b are empirical coefficients that can be determined by using the least squares method, as shown in Table S3.

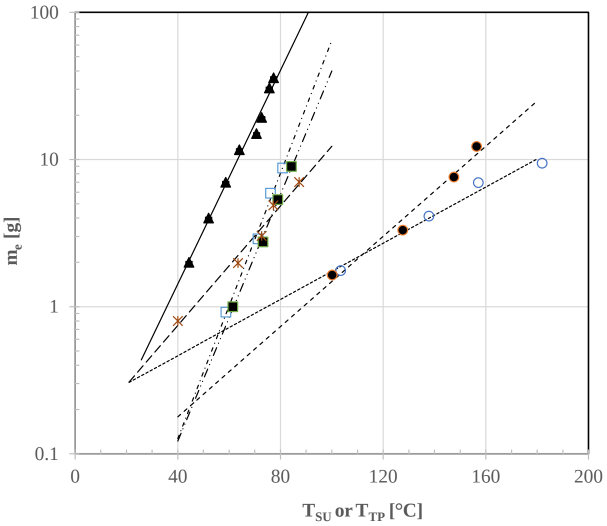


Figure 6 Semilogarithmic plot of the experimental amount of water evaporated (m_e) against the average sample temperature (T_{SU} or T_{TP}) measured during either the water heating test (▲, —) or different pizza baking tests (A: ○, …; B: ●, - - -; C: □, — . —; D: ■, — . . —; D: ∗, — —. Le different regressions lines were calculated using Eq. (1) and the empirical coefficients listed in Table S3.

Obviously, water heating in aluminum trays having a diameter near to that of the pizza samples under study gave rise to the greater water evaporation whatever the sample temperature. The samples C, D, and E, being all garnished with TP and having a greater moisture content around 0.55 g/g, exhibited a slower moisture evaporation. In pizza sample B, garnished with sunflower oil, water evaporation was even smaller. Nevertheless, because at the end of their baking they exhibited quite a higher temperature than that of samples C-E, its overall weight loss was greater than that of all the other pizza samples. The low specific heat of sunflower oil allowed the pizza sample B to reach higher temperatures than that of tomato puree area during baking, the heat transferred by radiation and convection being almost constant (Falciano et al., 2023), with the overall effect of enhancing the overall steam generated. Finally, the evaporation of sample A, being ungarnished, was exclusively related to the physical properties of the dough itself, which has a specific heat greater than sunflower oil but lower than tomato puree and mozzarella cheese.

Altogether, at the end of baking the overall amount of water evaporated was near to 10 g despite the different temperatures achieved by the upper side of the pizza types examined (Fig. 6).

Color visual assessment baled pizza

The formation of brown or black colored areas in pizza during its baking in the wood-fired oven, as due to the appearance of brown or black pigments, was monitored with the help of the IRIS electronic eye. The resulting digital images were processed as a color spectrum on a maximum scale of 4096 colors, each of these corresponding to a unique set of 3 values in the RGB space. For instance, the black color was represented by the decimal code (0,0,0), while the brown one by (165,42,42) (https://www.rapidtables.com/web/color/RGB_Color.html; accessed on 13 January 2023).

As an example, Figure 7 shows the color spectra of the pizza sample A as such and after 80-s baking in the pilot-scale wood-fired oven. By comparing such spectra, it was quite easy to highlight the color differences between these samples, as well as to quantify the area of each significant color and mark it as a percentage.

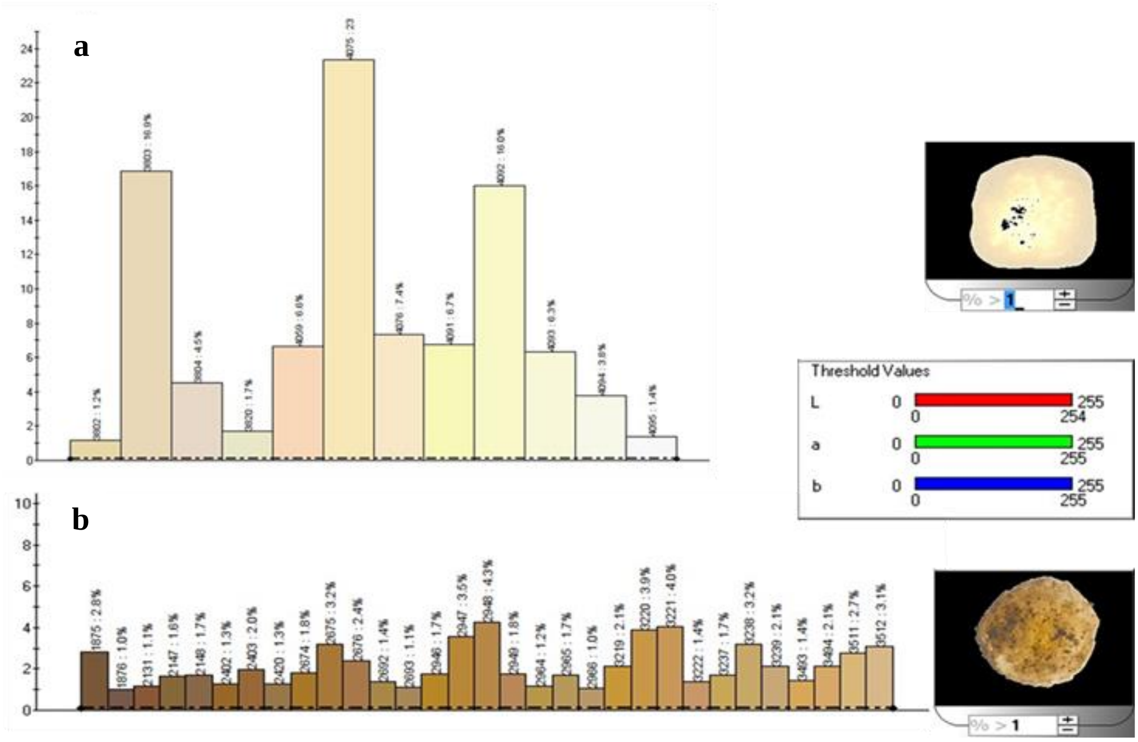


Figure 7: Color spectra of the upper side of pizza sample A (cf. Table 1) as such (**a**) or as baked in the pilot-scale wood-fired oven for 80 s (**b**), reporting the proportion (percentage of surface) of each unique color measured in the RGB color space, if greater than 0.1%.

Table 3: Decimal color codes associated with the browned and blackened areas of a pizza undergoing baking in a wood-fired oven.

Pizza Area	Color Decimal Code
Browned	1857 1858 1859 1873 1874 1875 1876 1891 1892 1893 1894 2128 2129 2130 2131 2132 2145 2146 2147 2148 2149 2165 2166 2400 2401 2402 2403 2404 2405 2417 2418 2419 2420 2421 2422 2438, 2657 2658 2659 2672 2673
Blackened	1075 1091 1092 1331 1346 1347 1348 1364 1365 1602 1603 1604 1618 1619 1620 1621

The effect of the browning or blackening process during the pizza baking was characterized by accounting for the color decimal codes seen as dark brown or black by the human eye. In particular, the browned areas of the pizza were characterized by 41 different decimal codes, while the blackened ones by 16 ones, as shown in Table 3.

By associating such individual colors in two clusters, it was possible to derive the percentage of the pizza surface area denoted as browned (Br) or blackened (Bl).

Figure S2 in the supplement shows the color spectra of the upper and lower sides of pizza samples A-E, as they were extracted from the oven after a baking time of 80 s for samples A-D or 100 s for the margherita pizza E; while Table S4 shows how the proportion of the browned or blackened area in both sides of such pizza samples increased as baking progressed.

As shown in Table S3, the percentage degree of browning or blackening in the lower pizza side was quite smaller than that observed in the upper one. At the end of baking (t_B=80 s), the central upper side of white pizza sample (A) reached a temperature as high as 182 °C (Table S2) and thus exhibited the greatest Y_{Br} and Y_{Bl} values. Since T_{SU} in pizza samples B was around 156 °C, its degree of browning was just near to 9 %. In pizza samples C and D, the presence of tomato puree limited the temperature of the upper area to 81-84 °C, this involving a percentage of browning of about 11%, a value not statistically different from the above one at p=0.05. Finally, pizza samples E were characterized by the smaller degree of browning (7.3%), probably because the higher reflectivity of the mozzarella cheese pieces.

As concerning the degree of burning, its highest value was observed in in the upper side of white pizza A (7.9%), even if the corresponding deviation standard, as high as 6%, made it not statistically different from those observed (1.4-3.9 %) in the other pizza samples.

The degrees of browning and blackening in the lower side of all the pizza samples under study appeared to be unrelated not only to the use or not of topping ingredients, but also to the increase in the overall mass of each pizza. In principle, the greater the overall mass of pizza the more effective the contact between the pizza base and hot oven floor will be. This should enhance the heat transfer through conduction from the bottom of the pizza and thus yield a more extensive blackening. This was in all probability counterbalanced by the pizzaiuolo's ability at turning the pizza in almost the same area of the hot oven floor to limit or avoid burning the pizza bottom.

Although color formation in bakery products is caused by numerous parallel and consecutive reactions with various components, the appearance of brown pigments was generally simulated by assuming either zero order or first order kinetics (Purlis, 2010). To discriminate the mechanism of browning or blackening, the percentage degree Y_{Br} or Y_{Bl} *versus* the upper or lower pizza side temperature was plotted on a semilogarithmic scale, as shown in Figures 8 and 9.

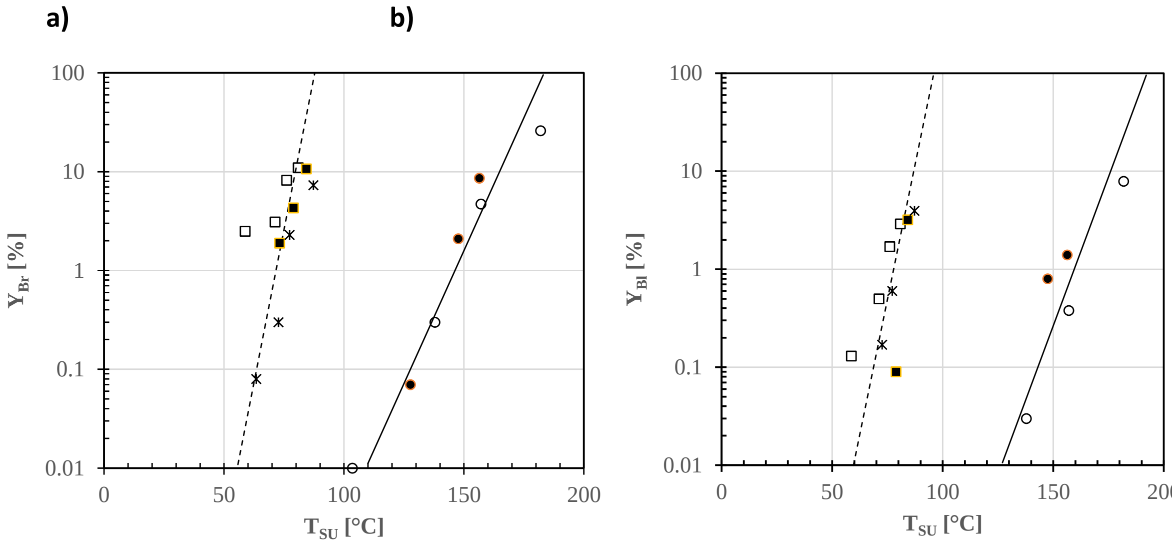


Figure 8 Semilogarithmic plot of the percentage degree of (**a**) browned (Y_{Br}) and (**b**) blackened (Y_{Bl}) areas of the upper surface area of different pizza samples [A: ○; B: ●; C: □; D: ■; E: ∗) during baking in a wood-fired oven *versus* the corresponding temperature (T_{SU}). The continuous and broken lines were the least squares regression lines estimated using Eq. (2).

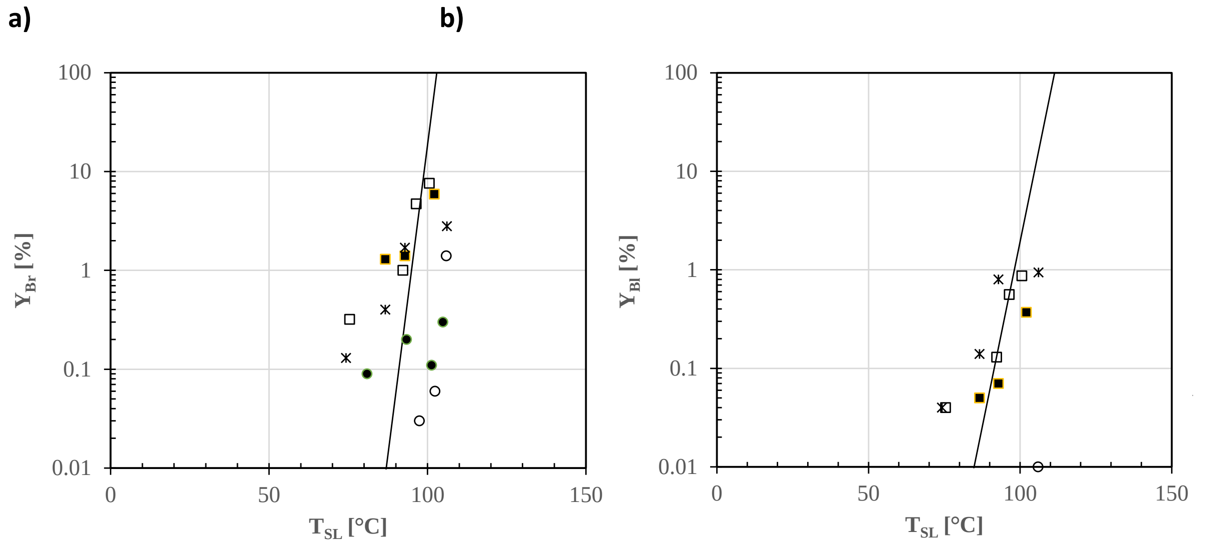


Figure 9 Semilogarithmic plot of the percentage degree of (**a**) browned (Y_{Br}) and (**b**) blackened (Y_{Bl}) areas of the lower surface area of different pizza samples [A: ○; B: ●; C: □; D: ■; E: ∗] during baking in a wood-fired oven *versus* the corresponding temperature (T_{SL}). The continuous and broken lines were the least squares regression lines estimated using Eq. (2).

From Fig. 8, it was observed that the curves of browning and burning on the upper surface area of all pizza samples might be described by straight lines on a semilogarithmic scale. In particular, two distinct straight lines were identified, the first one fitting the color change of white pizzas as such (A) or topped with sunflower oil (B) and the second one that of tomato pizzas as such (C) or garnished with SO only (D) or with mozzarella cheese too (E). From Fig. 9, the browning and burning yields for all the pizza samples under study resulted to be so scattered to be roughly fitted using a single straight line.

In the circumstances, the experimental Y_{Br} and Y_{Bl} data were reconstructed according to Bigelow et al. (1920)'s observations:

$$\log\frac{Y_i}{Y_{iR}} = \frac{T_{Sj} - T_{SjR}}{z_i} \qquad (2)$$

where Y_i is the percentage degree of browning (Br) or blackening (Bl) corresponding to the actual (T_{Sj}) and reference (T_{SjR}) temperatures of the upper or lower side of any pizza sample, and z_i is the temperature increment needed for a ten-fold acceleration of the rate of pizza browning or blackening (i.e., for increasing Y_i by a factor of 10).

By using the least squares method, it was possible to fit the experimental Y_i values, as shown by the continuous and broken lines plotted in Figures 8 and 9. Table 4 lists the empirical coefficients (z_i and T_{SjR}) of the least-squares regressions.

In the literature such a first-order kinetic model has been generally used to describe the death rate of free cells and spores, as well as the inactivation or degradation rate of enzymes, vitamins, and pigments (Ibarz and Barbosa-Cánova, 2003). Whereas the z values characterizing microbial death ranges from 5 to 11 °C, those related to enzyme inactivation varied from 15 to 20 °C (Berk, 2009) and those concerning typical chemical reactions, such as vitamin B_1 and chlorophyll destruction (Ibarz and Barbosa-Cánova, 2003), or the optimal cooking time of different pasta formats (Cimini et al., 2021), were found to fluctuate from 25 to 111 °C.

In this case, the formation rate of browned or blackened areas in baked pizza was 10-fold increased as the temperature of the upper side of pizza was increased by 19 or 16 °C in the case of white pizzas A and B or by about 9 °C in the case of any tomato pizzas C-E. This might be the result of the inertial effect exerted by the addition of an aqueous-rich tomato puree. In fact, the moisture content of white pizzas was definitely smaller than that of tomato pizzas (Table S2). On the contrary, there was no statistically significant difference between the z values characterizing the temperature-sensitivity of the lower side of any white and tomato pizzas to browning and burning, probably as a result of the highly scattered data collected.

Table 4 Least squares estimate of the empirical coefficients (z_i, T_{Rj} and Y_{SjR}) of Eq. (2) as referred to the browned and blackened degrees of different pizza samples undergoing baking in a wood-fired oven, and corresponding coefficients of determinations (r^2).

Browning or Burning Kinetics	**T_{Rj} [°C]**	**z_i [°C]**	**Y_{SjR} [%]**	**r^2**
Browning of the upper pizza side				
White pizza A and B	100	19±3	0.0032	0.90
Tomato pizza C, D, and E	50	8±3	0.0021	0.41
Burning of the upper pizza side				
White pizza A and B	100	16±5	0.00024	0.79
Tomato pizza C, D, and E	50	9±4	0.0009	0.48
Browning of the lower pizza side				
Pizza A-E	100	4±3	18.3	0.08
Burning of the lower pizza side				
Pizza A-E	100	5±5	1.92	0.17

In the circumstances, whatever the pizza type baked the percentage of burning of its bottom was generally by far smaller than that observed in its upper side. This definitively contradicts the general belief that the bottom of pizza baked in wood-fired ovens is more burnt than that cooked in gas or electric ovens. Since the blackened areas observed in tomato pizzas covered up to 4% of total pizza surface areas (Table S4), their wastage would be lower than the amount (~6%) of pizza averagely discarded at the end of a meal in a typical Neapolitan pizzeria (Falciano et al., 2022b). This would avoid the health risk of ingesting charred pizza pieces with high levels of acrylamide, its accumulation in starchy foods baked, fried or roasted at 120-150 °C increasing the risk of developing cancer for consumers in all age groups (Sarion et al., 2021).

Conclusions

In this work Neapolitan pizza baking in a pilot-scale wood-fired pizza oven operating in quasi steady-state conditions was phenomenologically analyzed by using color visual analysis and IR thermal scanning.

First, at the end of baking all pizza samples tested had almost the same diameter (28.2 ± 0.4 cm) and a raised rim, 2.2 cm in thickness and 2.3 cm in height whatever the topping ingredients used.

During pizza baking the oven floor temperature did not change, being practically constant at 439 ± 3 °C; while the area underneath each pizza reduced its temperature as faster as the greater the pizza mass laid on it. The pizza bottom reached a maximum temperature of 100 ± 9 °C, the *pizzaiuolo* being quite skill at lifting and rotating the pizza to bake it uniformly around its whole circumference. By contrast, the upper pizza side was respectively heated up to 182, 84 or 67 °C in the case of white pizza as such, tomato pizzas or margherita pizza, mainly because of their diverse moisture content and emissivity. The pizza weight loss was nonlinearly related to the average temperature of the upper pizza side when using no or just one topping ingredient or that of tomato puree-topped surface area. In all pizza types examined, the overall weight loss was near to 10 g. The formation of brown or black colored areas in the upper and lower sides of baked pizza was detected with the help of the IRIS electronic eye using 41 or 16 different decimal color codes in the RGB color space, these being denoted as dark brown or black, respectively. The upper pizza side exhibited the greater degrees of browning and blackening than the lower one, their maximum values of about 26 and 8% being respectively observed in white pizza as such. The formation rate of browned or blackened areas was described via the Bigelow first-order kinetic model and was characterized by a tenfold increase as the temperature of the upper side of pizza was raised by 16-19 °C or about 9 °C in the case of any white or tomato pizzas. Such a kinetic model was however unable to describe the temperature-sensitivity of all pizza bottoms.

Altogether, the above results expressing the heat and mass transfer dynamics during pizza baking in a wood-fired oven helped to improve the understanding of this process and are preliminary to develop an accurate modelling and control strategy to reduce the variability and maximize the quality attributes of Neapolitan pizza.

Acknowledgements

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Supplement materials

Table S1 – Effect of baking time (t_B) on the average value and standard deviation of the instantaneous height (h) of the rim of different pizza samples (see types A-D in Table 1) during their baking in a pilot-scale wood-fired oven.

Rim height (h) of pizza sample [cm] **t_B [s]**	**A**	**B**	**C**	**D**
0	0.68±0.11 [a]	0.85±0.14 [b]	0.74±0.20 [a]	0.87±0.17 [b]
2	0.78±0.14 [a]	0.94±0.16 [b]	0.82±0.18 [a]	0.96±0.16 [b]
4	0.84±0.18 [a]	1.01±0.19 [b]	0.88±0.17 [a]	1.01±0.16 [b]
6	0.91±0.18 [a]	1.07±0.20 [b]	0.93±0.19 [a]	1.08±0.20 [b]
8	0.98±0.21 [a]	1.12±0.21 [b]	0.99±0.20 [a]	1.19±0.23 [b]
10	1.04±0.21 [a]	1.18±0.22 [a,b]	1.09±0.22 [a]	1.23±0.24 [b]
12	1.11±0.22 [a]	1.37±0.22 [b]	1.20±0.25 [a]	1.34±0.23 [b]
14	1.21±0.26 [a]	1.47±0.22 [b]	1.31±0.22 [a]	1.51±0.28 [b]
16	1.34±0.23 [a]	1.55±0.25 [b]	1.48±0.21 [a]	1.68±0.35 [b]
18	1.40±0.28 [a]	1.72±0.33 [b]	1.57±0.22 [a]	1.87±0.42 [b]
20	1.47±0.33 [a]	1.82±0.37 [b]	1.62±0.21 [a]	1.98±0.43 [b]
24	1.54±0.34 [a]	1.92±0.41 [b]	1.71±0.24 [a]	2.11±0.47 [b]
28	1.59±0.37 [a]	2.10±0.47 [b]	1.83±0.28 [a]	2.17±0.47 [b]
32	1.63±0.39 [a]	2.21±0.45 [b]	1.88±0.29 [a]	2.24±0.47 [b]
36	1.69±0.42 [a]	2.26±0.42 [b]	1.92±0.31 [a]	2.32±0.49 [b]
40	1.75±0.45 [a]	2.32±0.42 [b]	1.97±0.33 [a]	2.40±0.50 [b]
50	1.81±0.49 [a]	2.39±0.38 [b]	2.04±0.35 [a]	2.47±0.50 [b]
60	1.88±0.52	2.47±0.36 [b]	2.08±0.36 [a]	2.53±0.50 [b]
70	1.93±0.50 [a]	2.58±0.34 [b]	2.12±0.35 [a]	2.58±0.45 [b]
80	1.96±0.50 [a]	2.61±0.33 [b]	2.14±0.35 [a]	2.63±0.45 [b]

In each row, values with the same letter have no significant difference at $p < 0.05$.

Table S2: Main results (mean ± sd) of 12 repeated baking tests performed in a wood-fired pizza oven fed with 3 kg/h of oak logs using five pizza types A- E (see Table 1): effect of baking time (t_B) on the instantaneous temperature of the oven floor exposed to fire (T_{FL}) or shielded by the pizza sample (T_{FLbp}), temperatures of the pizza rim (T_{SR}), upper (T_{SU}) and lower (T_{SL}) areas, overall mass of sample (m_S), and estimated moisture fraction on oil-free basis (x_W). When 2 o 3 ingredients were added, T_{SU} was expressed by averaging the temperatures of the areas covered with tomato puree (TP), sunflower oil (SO) and/or mozzarella cheese (MC).

t_B	T_{FL}	T_{FLbp}	T_{SR}	T_{SU}	T_{SL}	m_S	x_W
[s]	[°C]	[°C]	[°C]	[°C]	[°C]	[g]	[g/g]
White pizza							
0	442 ± 9 ^{a}	442 ± 9 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	250.0±1.0 ^{a}	0.450
20	441 ± 7 ^{a}	363 ±10 ^{b}	80.0±3.0 ^{b}	103.0±2.0 ^{b}	84.0±2.0 ^{b}	248.2±0.2 ^{b}	0.446
40	436 ±11 ^{a}	348 ± 5 ^{b}	116.0±3.0 ^{c}	138.0±7.0 ^{c}	97.0±2.0 ^{c}	245.9±0.6 ^{c}	0.440
60	435 ± 7 ^{a}	332 ± 7 ^{c}	130.0±6.0 ^{d}	157.0±6.0 ^{d}	102.0±2.0 ^{d}	243.0±1.0 ^{d}	0.434
80	432 ±10 ^{a}	325 ± 5 ^{c}	148.0±9.0 ^{e}	182.0±9.0 ^{e}	106.0±3.0 ^{d}	240.6±0.7 ^{e}	0.428
White pizza garnished with sunflower oil							
0	446 ± 5 ^{a}	448 ± 7 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	280.0±2.0 ^{a}	0.450
20	443 ± 6 ^{a}	351 ±11 ^{b}	86.0±3.0 ^{b}	100.0±3.0 ^{b}	81.0±2.0 ^{b}	278.4±0.2 ^{a}	0.446
40	441 ± 7 ^{a}	342 ± 9 ^{b}	116.0±7.0 ^{c}	128.0±6.0 ^{c}	93.0±5.0 ^{c}	276.7±0.6 ^{b}	0.442
60	439 ±11 ^{a}	327 ± 7 ^{c}	149.0±7.0 ^{d}	148.0±5.0 ^{d}	101.0±3.0 ^{d}	272.4±1.3 ^{c}	0.432
80	434 ± 8 ^{a}	314 ± 7 ^{b,c}	169.0±9.0 ^{e}	156.0±4.0 ^{d}	105.0±2.0 ^{d}	267.7±1.6 ^{d}	0.421
Tomato pizza							
0	443 ± 8 ^{a}	440 ± 7 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a}	320.0±2.0 ^{a}	0.555
20	442 ± 7 ^{a}	339 ±10 ^{b}	83.0±2.0 ^{b}	59.0±2.0 ^{b}	75.0±2.0 ^{b}	319.1±0.3 ^{a}	0.553
40	439 ± 7 ^{a}	328 ± 6 ^{b}	113.0±4.0 ^{c}	71.0±2.0 ^{c}	92.0±3.0 ^{c}	317.1±0.5 ^{b}	0.551
60	438 ± 8 ^{a}	320 ±10 ^{b,c}	124.0±3.0 ^{d}	76.0±2.0 ^{d}	96.0±2.0 ^{c}	314.1±0.3 ^{c}	0.546
80	436 ± 6 ^{a}	304 ± 5 ^{c}	136.0±3.0 ^{e}	81.0±2.0 ^{e}	101.0±2.0 ^{d}	311.2±0.8 ^{d}	0.542
Tomato pizza garnished with sunflower oil							
				TP area SO area			
0	440 ± 7 ^{a}	438 ±10 ^{a}	21.0±0.1 ^{a}	21.0±0.1 ^{a} 21.0±0.1 ^{a}	21.0±0.1 ^{a}	350.0±3.0 ^{a}	0.555
20	438 ± 5 ^{a}	332 ±12 ^{b}	88.0±3.0 ^{b}	61.0±3.0 ^{b} 89.0±5.0 ^{b}	74.0±3.0 ^{b}	349.4±0.1 ^{a}	0.554
40	437 ± 7 ^{a}	318 ± 5 ^{b,c}	115.0±5.0 ^{c}	73.0±2.0 ^{c} 100.0±4.0 ^{c}	87.0±2.0 ^{c}	347.2±0.5 ^{b}	0.551
60	437 ± 6 ^{a}	313 ± 7 ^{b,c}	128.0±5.0 ^{d}	79.0±2.0 ^{d} 103.0±2.0 ^{c}	93.0±2.0 ^{d}	344.7±0.3 ^{c}	0.547
80	436 ± 6 ^{a}	309 ± 7 ^{c}	141.0±2.0 ^{e}	84.0±2.0 ^{e} 106.0±2.0 ^{c}	102.0±2.0 ^{e}	341.0±1.9 ^{d}	0.542
Tomato pizza garnished with sunflower oil and mozzarella cheese							
				TP area SO area MC area			
0	442 ± 9 ^{a}	437 ±12 ^{a}	21 ± 0.1 ^{a}	21.0±0.1 ^{a} 21.0±0.1 ^{a} 15.0±0.1 ^{a}	21.0±0.1 ^{a}	430.0±4.0 ^{a}	0.554
40	439 ± 4 ^{a}	336 ±10 ^{b}	98 ± 3 ^{b}	63.0±2.0 ^{b} 92.0±4.0 ^{b} 51.6±1.8 ^{b}	74.3±2.6 ^{b}	428.0±0.6 ^{a}	0.542

60	438 ± 7 ^{a}	325 ± 6 ^{b,c}	113 ± 3 ^{c}	73.0±2.0 ^{c}	98.0±3.0 ^{c}	55.0±2.0 ^{c}	86.7±2.0 ^{c}	427.0±0.6 ^{b}	0.540
80	436 ± 6 ^{a}	314 ± 7 ^{b,c}	130 ± 5 ^{d}	77.0±3.0 ^{c}	101.0±2.0 ^{c}	59.9±1.6 ^{d}	92.8±2.1 ^{d}	425.1±0.6 ^{c}	0.538
100	436 ± 5 ^{a}	307 ± 6 ^{c}	155 ± 5 ^{e}	87.0±2.0 ^{c}	110.6±3.4^{d}	67.2±2.4 ^{e}	106.1±3.7 ^{e}	423.0±0.3 ^{d}	0.536

Mean values within the same parameter at different baking times followed by different superscript letters significantly differ by the Tukey test ($p<0.05$).

Table S3 Mean value and standard deviation of the empirical coefficients a and b of Eq. (1) and coefficient of determinations (r^2) for the water heating and pizza baking tests carried out in this work.

Sample	**a**	**b**	**r^2**
Water	-2.99±0.26	0.084±0.004	0.987
A) Pizza as such	-1.65±0.34	0.022±0.002	0.979
B) Pizza topped with SO	-3.13±0.52	0.035±0.004	0.977
C) Pizza topped with TP	-6.22±0.48	0.104±0.007	0.992
D) Pizza topped with TS and SO	-5.96±0.31	0.097±0.004	0.996
E) Pizza topped with TS, SO, and MC	-2.16±0.27	0.047±0.004	0.980

Table S4 Effect of baking time (t_B) on the percentage degree of browned (Y_{Br}) and blackened (Y_{Bl}) areas of the upper and lower area of different pizza samples A-E (cf. Table 1) during baking in a wood-fired oven. Each percentage is expressed as mean ± sd (n = 3).

Pizza sample	A	B	C	D	E	A	B	C	D	E
t_B (s)	**Browned area percentage Y_{Br} [%]**					**Blackened area percentage Y_{Bl} [%] (%)**				
Upper pizza side										
20	0.01±0.0	0.00±0.0	2.5±1.0			0.00±0.0	0.00±0.0	0.13±0.2		
40	0.3±0.2	0.07±0.1	3.1±1.2	1.9±0.3	0.08±0.1	0.03±0.1	0.00±0.0	0.5±0.3	0.00±0.0	0.00±0.0
60	4.7±1.0	2.1±1.5	8.2±2.0	4.3±0.5	0.3±0.1	0.38±0.1	0.8±1.7	1.7±0.8	0.09±0.1	0.17±0.0
80	26±5 ^{a}	8.6±1.6 ^{c,b}	11±2 ^{b}	10.7±5 ^{b}	2.3±0.1	7.9±6 ^{a}	1.4±1.1 ^{a}	2.9±0.1 ^{a}	3.2±2.0 ^{a}	0.6±0.1
100					7.3±0.3 ^{c}					3.95±0.3 ^{a}
Lower pizza side										
20	0.00±0.0	0.09±0.1	0.32±0.3			0.00±0.0	0.00±0.0	0.04±0.0		
40	0.03±0.0	0.2±0.3	1.0±0.4	1.3±0.9	0.13±0.0	0.00±0.0	0.00±0.0	0.13±0.1	0.05±0.0	0.04±0.0
60	0.06±0.1	0.11±0.5	4.7±1.7	1.4±1.4	0.40±0.0	0.00±0.0	0.00±0.0	0.56±0.1	0.07±0.0	0.14±0.0
80	1.4±1.2 ^{b}	0.3±0.2 ^{a}	7.6±1.2 ^{c}	5.9±1.0 ^{c}	1.7±0.1	0.01±0.0 ^{c}	0.00±0.0 ^{c}	0.87±0.4 ^{a,b}	0.37±0.2 ^{b}	0.80±0.1
100					2.8±0.1 ^{b}					0.94±0.1 ^{a}

Mean values within the same parameter at different baking times followed by different superscript letters significantly differ by the Tukey test ($p<0.05$).

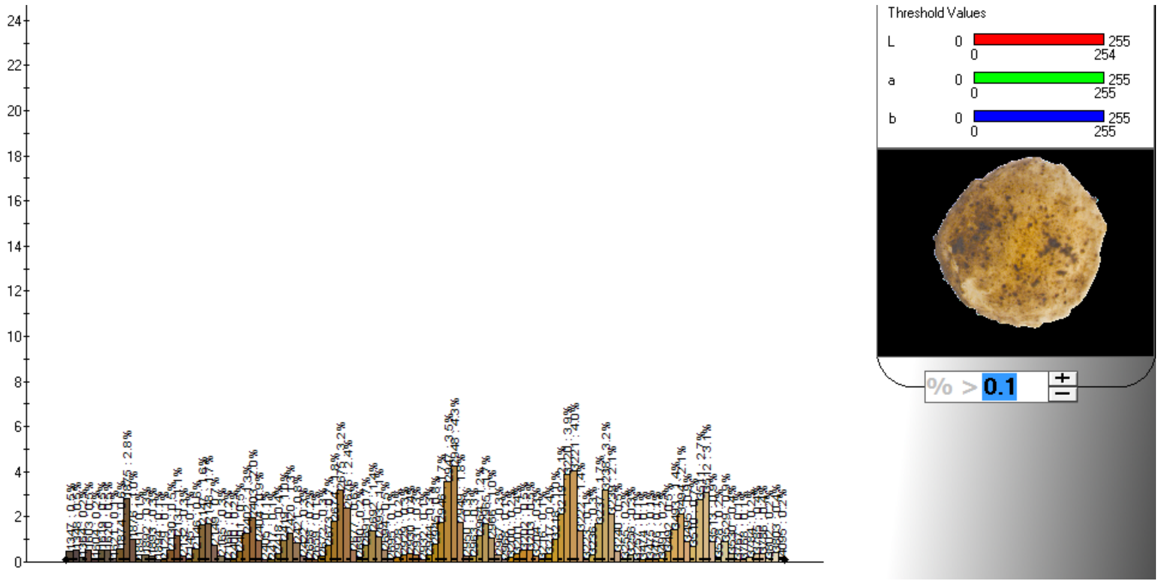
Figure S1

Front picture of the wood-fired pizza oven used in this work.

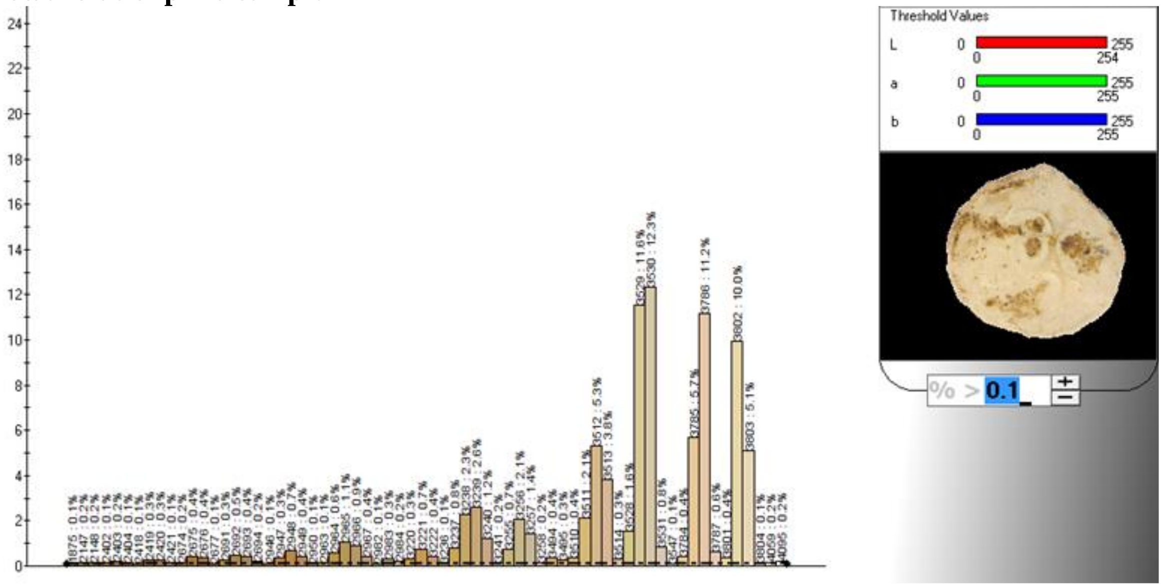
Figure S2

Color spectra of the upper and lower sides of pizza samples A-E (cf. Table 1) as baked in the pilot-scale wood-fired oven for 80 s showing the proportion (percentage of surface) of each unique color measured in a 4096-color space if greater than 0.1%.

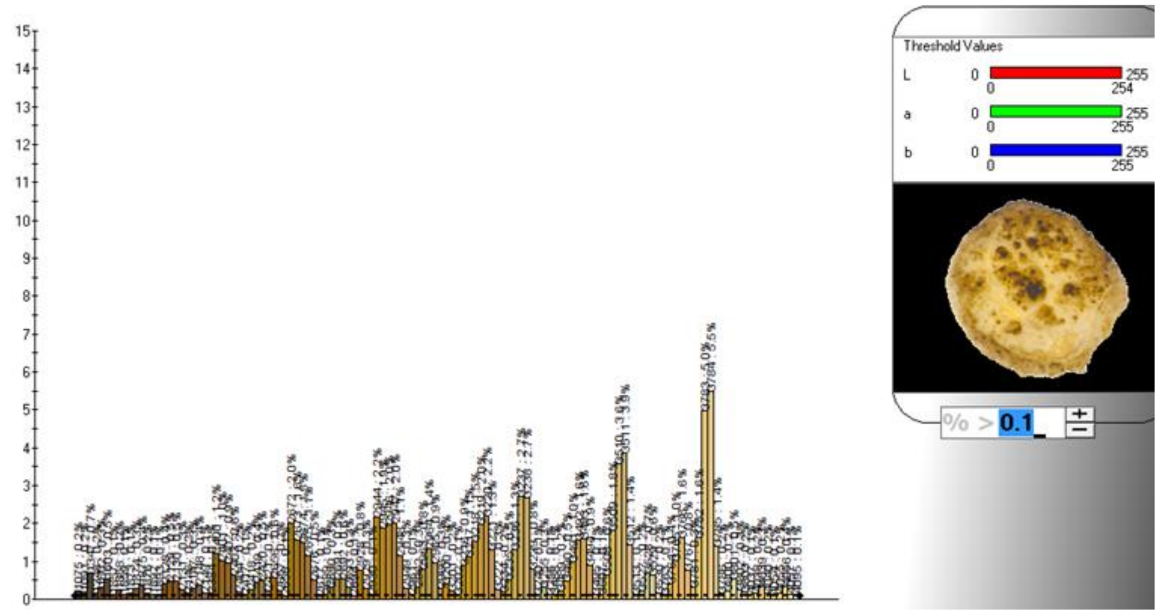
Upper side of pizza sample A



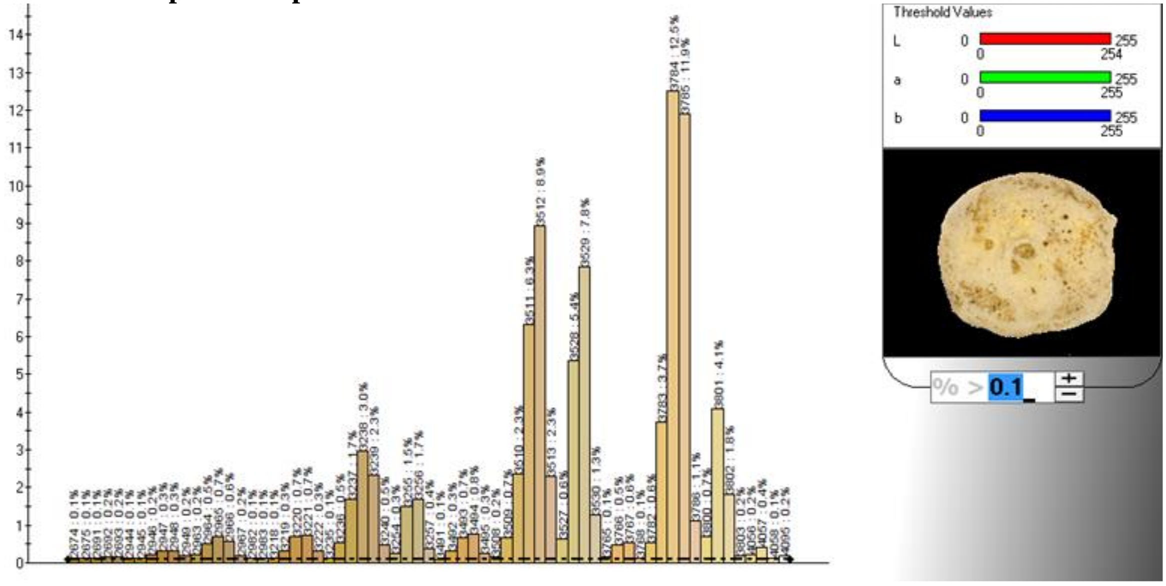
Lower side of pizza sample A



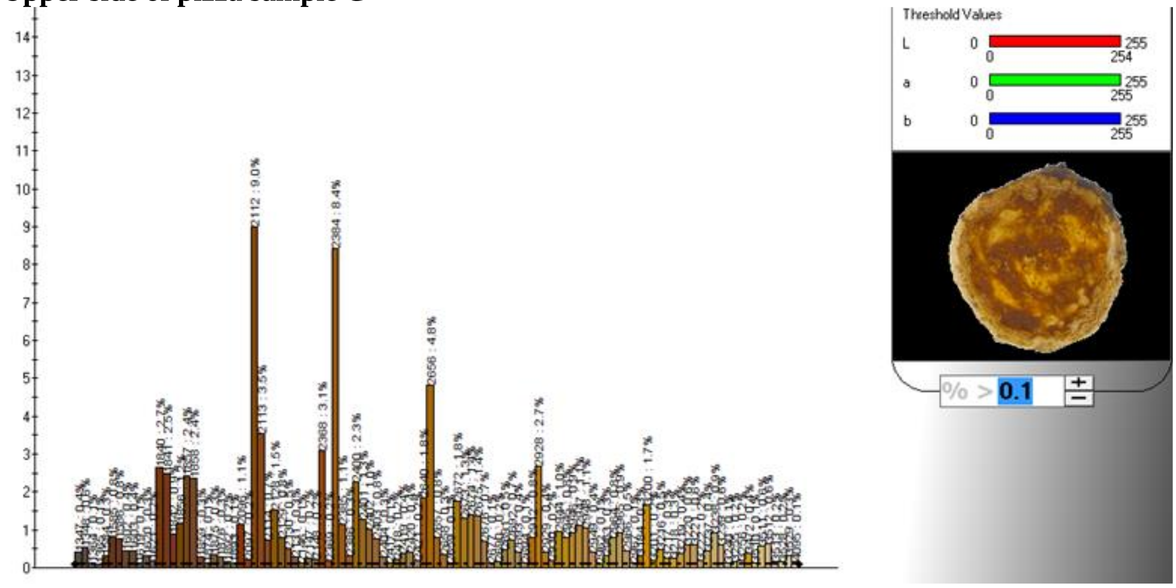
Upper side of pizza sample B



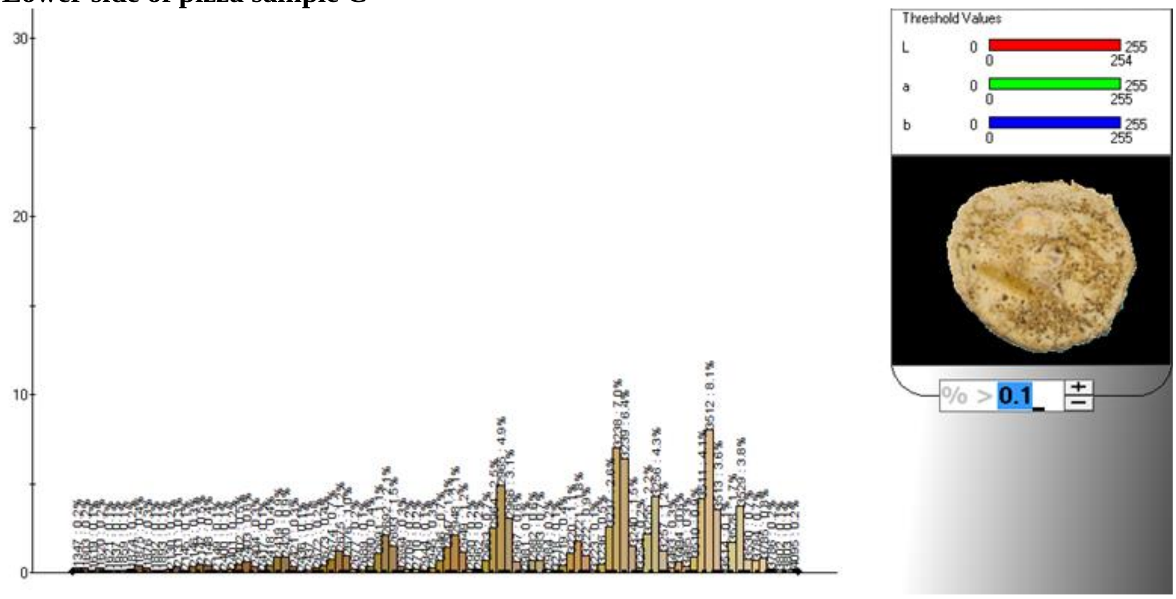
Lower side of pizza sample B



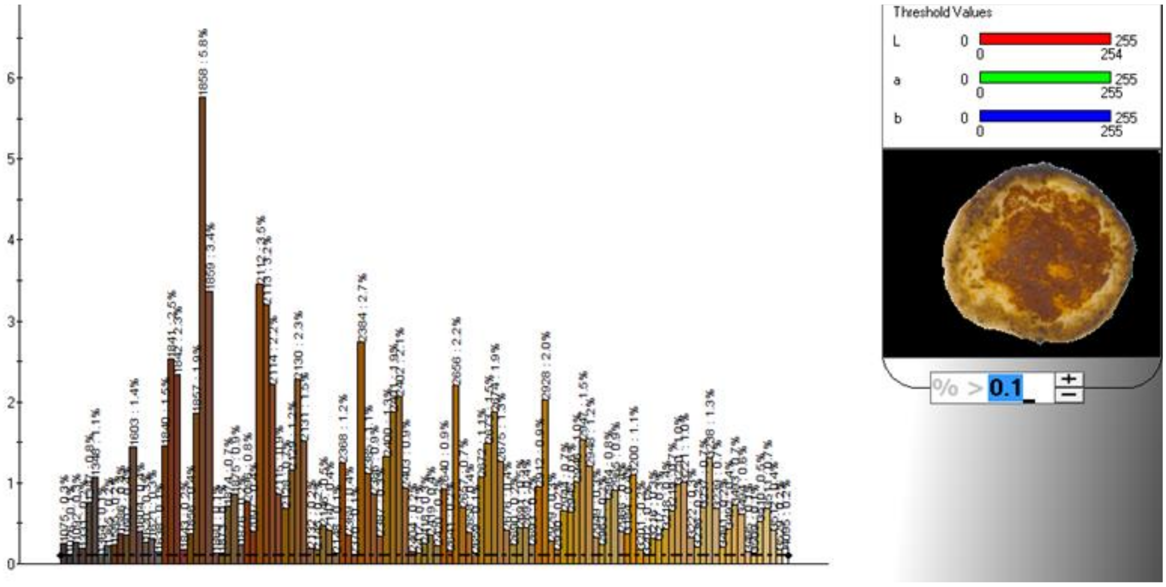
Upper side of pizza sample C



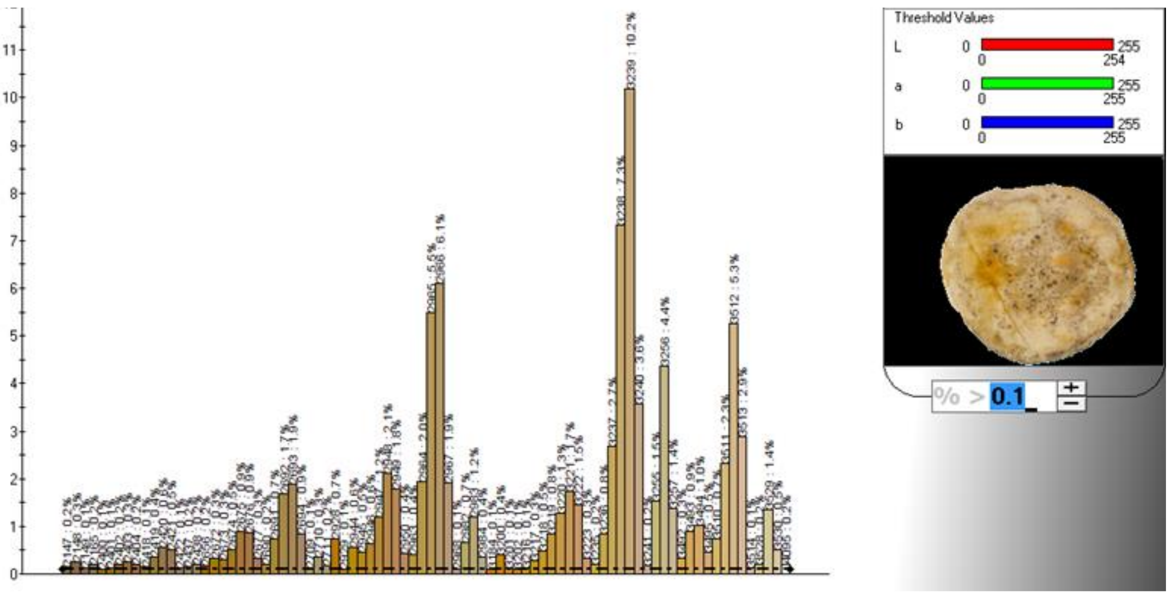
Lower side of pizza sample C



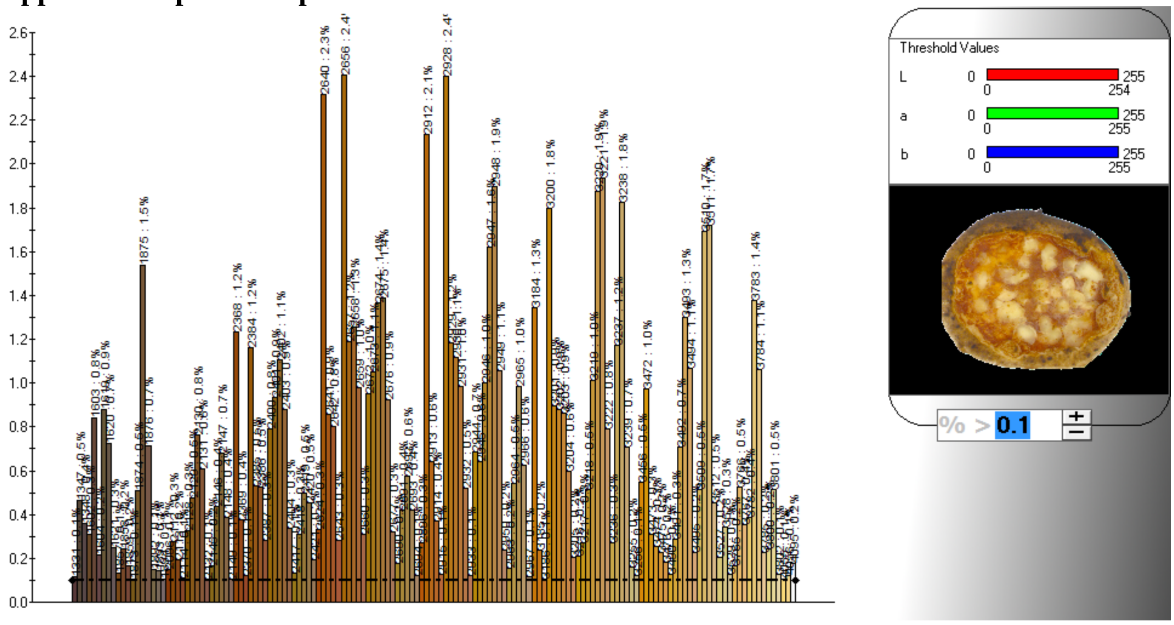
Upper side of pizza sample D



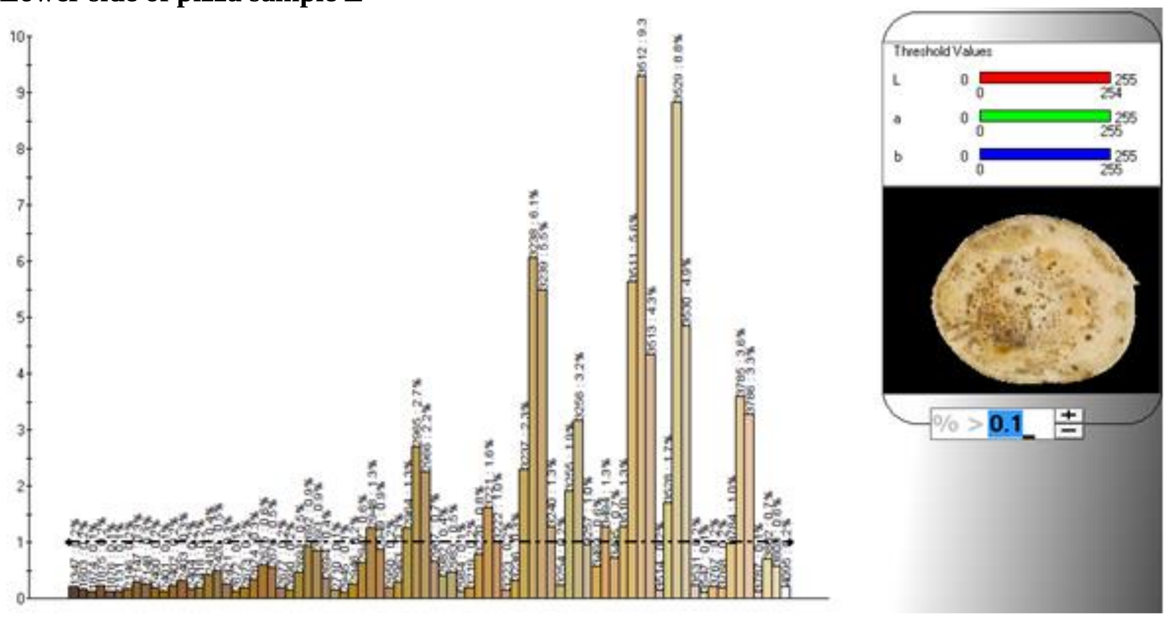
Lower side of pizza sample D



Upper side of pizza sample E



Lower side of pizza sample E



References

Berk Z (2009) Thermal processing, in Food Process Engineering and Technology, Chp 17. Academic Press, San Diego, CA, pp. 355–373 (2009).

Bigelow WD, Bohart GS, Richardson AC and Ball CO (1920) Heat penetration in processing canned foods, in Bulletin (National Canners Association) no. 16L. National Canners Association, Research Laboratories, Washington, D.C.

Cimini A, Cibelli M, Taddei AR, Moresi M (2021) Effect of cooking temperature on cooked pasta quality and sustainability. Journal of the Science of Food and Agriculture, 101: 4946–4958.

EC (2010). Commission Regulation (EU) No. 97/2010. Entering a Name in the Register of Traditional SPECIALITIES guaranteed [Pizza Napoletana (TSG)]. Off. J. Eur. Union 2010. 34. 5. Available online: https://eur-lex.europa.eu/legalcontent/ EN/TXT/HTML/?uri=OJ:L:2010:034:FULL (accessed on 26 January 2022).

Falciano A, Cimini A, Masi P, Moresi M (2022b) Carbon Footprint of a Typical Neapolitan Pizzeria. Sustainability, 14(5), 3125.

Falciano, A., Masi, P., Moresi, M. (2022a). Performance characterization of a traditional wood-fired pizza oven. Journal of Food Science, 87: 4107-4118.

Falciano, A., Masi, P., Moresi, M. (2023). Semi-empirical modelling of a traditional wood-fired pizza oven in quasi steady-state operating conditions. Journal of Food Science, submitted.

Fennema, O.R. (1996). Food Chemistry, third ed. Marcel Dekker, New York.

Ibarz A and Barbosa-Cánova GV (2003). Unit Operations in Food Engineering. CRC Press, Boca Raton, FL.

León, K., Mery, D., Pedreschi, F., León, J. (2006). Color measurement in $L^*a^*b^*$ units from RGB digital images. Food Research International 39 (10), 1084-1091.

Purlis E. (2010) Browning development in bakery products – A review. Journal of Food Engineering 99, 239-249.

Sarion C, Codină GG, Dabija A. (2021) Acrylamide in Bakery Products: A Review on Health Risks, Legal Regulations and Strategies to Reduce Its Formation. Int J Environ Res Public Health. 2021 Apr 19;18(8):4332.

UNESCO (United Nations Education. Scientific and Cultural Organization) (2017). Decision of the Intergovernmental Committee: 12.COM 11.B.17. 2017. Available online: https://ich.unesco.org/en/decisions/12.COM/11.B.17 (accessed on 26 January 2022).

Chapter 8

Carbon Footprint of a typical Neapolitan Pizzeria

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Abstract

Neapolitan Pizza is very popular worldwide and is registered in the list of the traditional specialities guaranteed. 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 CO2e/diner was estimated, about 74% of which being due to the production of the ingredients used (the only buffalo mozzarella cheese 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), and Grana Padano cheeses, or electricity was varied by +50% with respect to each corresponding default value, respectively. The specific carbon footprint for the Marinara pizza was equal to ~4 kg CO2e/kg, while that for the Margherita pizza was up to 5.1 or 10.8 kg CO2e/kg when topped with fresh cow or buffalo mozzarella cheese, respectively. To help pizza restaurant operators selecting the most rewarding mitigation strategy, it was 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 the traditional wood-fired ones, as well as renewable electricity sources.

Keywords: Carbon Footprint; Life Cycle Assessment; Standard Method PAS 2050; Neapolitan Pizza restaurant, pizza, sensitivity analysis, mitigation strategy.

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 × 106 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 PM2.5 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 (CO2e) 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 CO2e/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 CO2e/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 CO2e/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 CO2e, 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 CO2e, 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 CO2e), 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 CO2e, while a pizza contained in a cardboard box to 0.20 kg CO2e [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 m3 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].

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].

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) [20], as well as personnel travel, and transport of consumers to and from the restaurant gate (Section 6.5) [20], were not included in the system boundary.

In accordance with Section 7.2, 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.

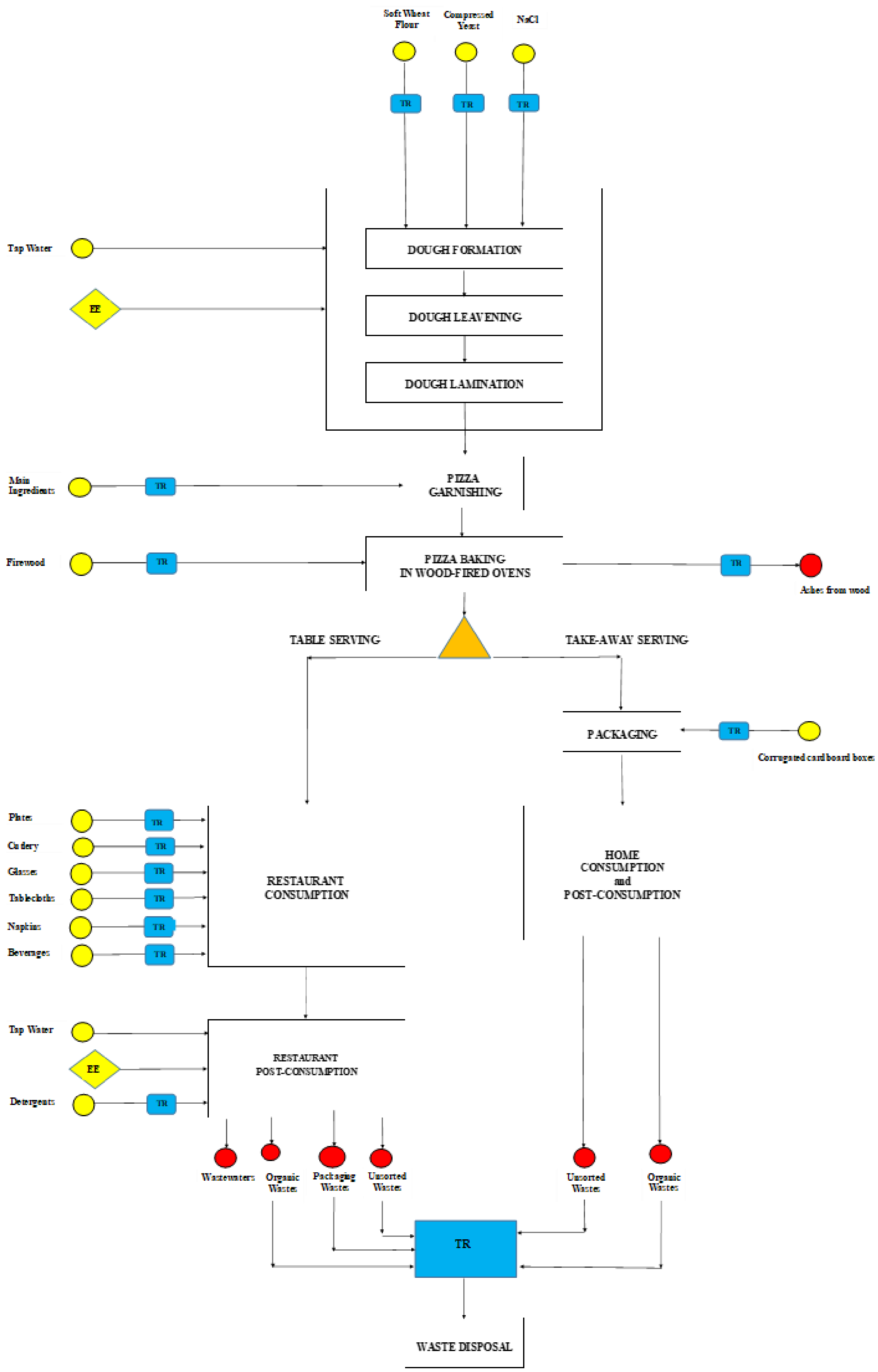

Figure 1. System boundary of the study carried out to assess the carbon footprint of a typical Neapolitan Pizza restaurant: EE - electric energy; TR - transportation.

Life cycle inventory analysis

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

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]. Fig. S1 in the 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, Oregon, 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.

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 Fig. S2 in the 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-□m 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 & 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 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 factor	yieldUnit
Utility sources				
Electricity	37,600	kWh	0.44	kWh/pizza
Tap water	2,930	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	6,390	kg	74.48	g/pizza
Fresh cow mozzarella cheese TSG	4,198	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	5,900	L	0.08	L/pizza
Coca-Cola	3,700	L	0.05	L/pizza
Coca-Cola Zero	470	L	0.01	L/pizza
Fanta	2,600	L	0.04	L/pizza
Packaging materials				
Corrugated cardboard pizza boxes	2,531	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	1,136	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

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 #	**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
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}).

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 ± 20 mm with a diameter smaller than 5 cm, being characterized by moisture and ash contents of 5.67 ± 0.17 and 2.9 ± 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.

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].

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.

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]

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:

$$\mathbf{CF} = \sum_{\mathbf{i}} (\boldsymbol{\Psi}_{\mathbf{i}}\ \mathbf{EF}_{\mathbf{i}}), \qquad (1)$$

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 supplement.

Sensitivity analysis

Firstly, the sensitivity of the LCA model defined by Eq. (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≠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:

$$\frac{\Delta CF}{CF_R}\bigg|_{EF_{j\neq i}} = \frac{1}{CF_R}\ EF_{iR}\ \left(\frac{\Delta EF_i}{EF_{iR}}\right)\ \Psi_i \qquad (3)$$

with

$$\Delta EFi = EF_i - EF_{iR} \qquad (4)$$

and

$$\Delta CF = CF - CF_R \qquad (5)$$

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.

Results and Discussion

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.

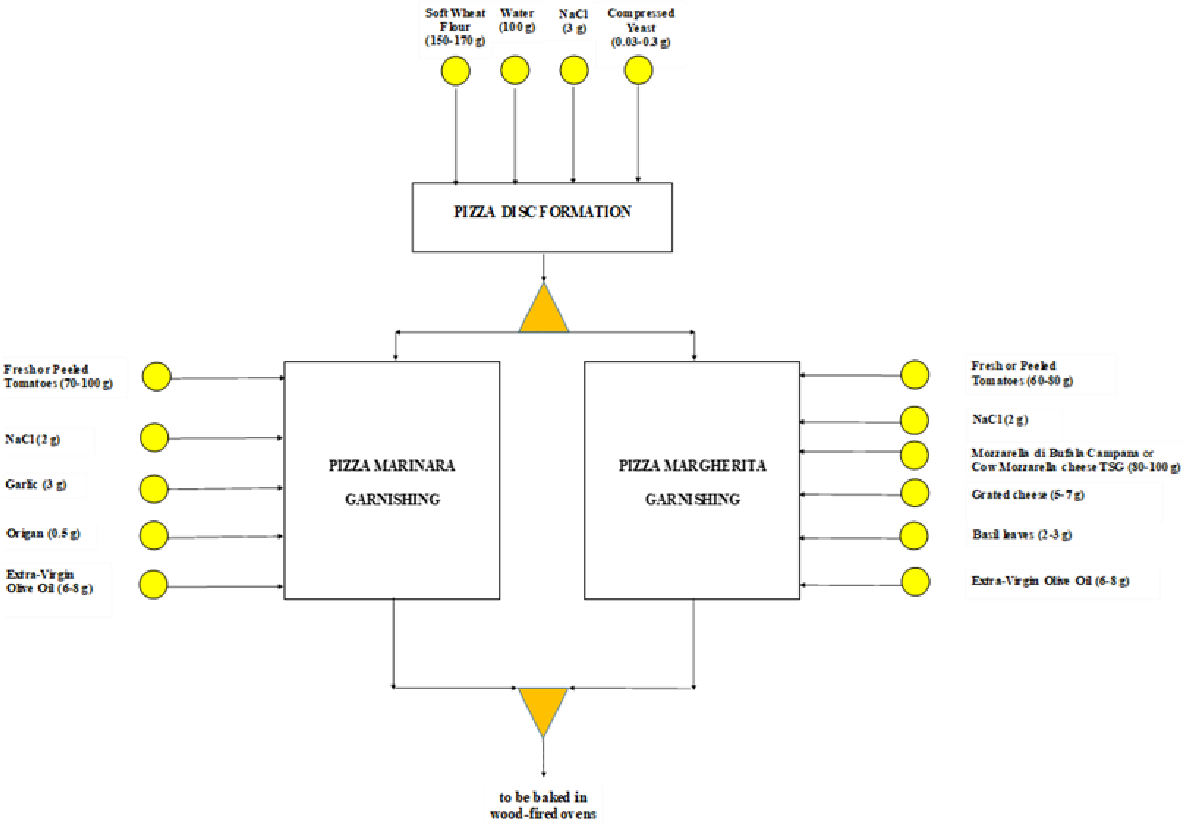

Figure 2. Minimum and maximum quantities of the ingredients needed to garnish the Pizza Napoletana (TSG) of the Marinara or Margherita type according to the EC Regulation no. 97/2010 [4].

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		3,458.0		73.73	73.00
Beverage production	27,299		318.2		6.78	6.72
Production of used table setting	3,040		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	1,295	0	0.32	0	0.32	0
Refrigerant leakage	2,059		24.0		0.51	0.51
Wastewater Treatment	1,395		16.3		0.35	0.34
Waste Disposal	4,349		50.8	50.7	1.08	1.07
Carbon Footprint (CF)	***402,424***	***406,400***	***4,690***	***4,737***	***100.00***	***100.00***

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.

Quite limited inventories for the GHGs emitted by restaurants have been so far published, generally in non-peer reviewed sources [39]. 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 [40]. 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 [39].

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 [41].

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 Fig. 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 supplement. The average mass of the raw Marinara (350±4 g) or Margherita (417±6 g) pizza fell within the range of 335-387 g or 408-473 g, respectively, prefixed by the Neapolitan Pizza production disciplinary [42] and summarized in Fig. 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.

Sensitivity analysis

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}.

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
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

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 [43] 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 [44-45].

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. [46], 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%. Also, any further increase in buffalo meat utilization would improve the sustainability of such an ingredient of the Margherita pizza [46].

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 [47], 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 [48], or 30-L KeyKegs, made from 100% recycled PET (https://www.keykeg.com) [47]. 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 [49] 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 1,210 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) [50], 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 [51]. 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 [52]. 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.

Like the guideline suggested by Messier [39], 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.

Electric versus wood-fired ovens

The wood-fired ovens are worldwide used in restaurants, bakeries, and rotisserie shops. According to Lima et al. [53], 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 $\mu g/m^3$), while in indoor areas it was around 68 $\mu g/m^3$. 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. [54] measured that the indoor $PM_{2.5}$ concentration ranged from 12 to 368 $\mu g/m^3$ with an average value of 95 $\mu g/m^3$. Similarly, grilling different foods on a gas stove gave rise to indoor $PM_{2.5}$ concentrations varying from 78 and 389 $\mu g/m^3$, while frying chips using different oils on a gas stove or an electric fryer to 60-118 $\mu g/m^3$ or 12-27 $\mu g/m^3$, respectively [55]. In such pizzerias, the indoor $PM_{2.5}$ concentrations definitively exceeded the indoor 24-h mean level of 15 $\mu g/m^3$ 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 [53], 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 [56].

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 hours 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 x 2 + (8 x 0.7+ 3 x 0.3) x 5 = 54.5 kWh/day

or

54.5 x 312 = 17,004 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).

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

Table S1: Emission factors for the energy sources, means of transport, production of raw and packaging materials, and disposal of processing and post-consumer wastes used to assess the cradle-to-grave carbon footprint of a Neapolitan pizzeria, as extracted from Ecoinvent v. 3.7 database of the LCA software Simapro (Prè Consultants, Amersfoort, NL) and other papers.

Emission Factor	Value	Unit	Ref.

Energy source			
Electricity, low voltage (<1kV), grid/IT	0.452	kg CO_{2e} kWh^{-1}	Ecoinvent v. 3.7
Electricity production, wind, >3MW turbine onshore{IT}| Cut-off, S	0.0293	kg CO_{2e} kWh^{-1}	Ecoinvent v. 3.7
Electricity production, hydro, reservoir, alpine region{IT}| Cut-off, S	0.00594	kg CO_{2e} kWh^{-1}	Ecoinvent v. 3.7
Woodfire	0.0406	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
Means of transport			
Transport, lorry 3.5-7.5Mg, Euro5	0.506	kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent v. 3.7
Transport, lorry 7.5-16 Mg, Euro5	0.212	kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent v. 3.7
Transport, freight, light commercial vehicle {EU without CH}| Cut-off, S	1.83	kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent v. 3.7
Municipal waste collection service by 21-Mg ton lorry {RoW}| Cut-off, S	1.27	kg CO_{2e} Mg^{-1} km^{-1}	Ecoinvent v. 3.7
Raw Materials			
Tap Water {EU without CH}| Cut-off, U	0.278	kg CO_{2e} m^{-3}	Ecoinvent v. 3.7
Soft wheat flour	0.61±0.23	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Compressed yeast	0.82	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Peeled tomatoes	1.28±0.4	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Fresh tomatoes	0.48±0.30	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Water Buffalo Mozzarella cheese	32.7±0.1	kg CO_{2e} kg^{-1}	Berlese et al. (2019) [53]
Mozzarella cheese	8.5±1.4	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Grana Padano cheese	14.3±2.8	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Ricotta cheese	3.4	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Provola cheese	10.82	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Pecorino Romano cheese	18.9±2.4	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Naples salami	11.3	kg CO_{2e} kg^{-1}	[38]
Baked ham	10.7	kg CO_{2e} kg^{-1}	[38]
Deboned pressed dry-cured ham	12.7±4.0	kg CO_{2e} kg^{-1}	[38]

Cracklings	0.82	kg CO_{2e} kg^{-1}	Animal meal, from dry rendering, at plant/NL Economic: Agri-footprint Economic Allocation
Baby artichokes	0.41±0.11	kg CO_{2e} kg^{-1}	[36], [35]
Mushrooms	1.8±1.1	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Rucola leaves	0.40±0.15	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Escarole	0.40±0.15	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Eggplant	1.35±0.07	kg CO_{2e} kg^{-1}	[35, 36]
Peppers	1.18±0.08	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Broccoli	0.67±0.36	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Table salt	0.159	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Extra-virgin olive oil	3.8±2.8	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Oregano	1.6	kg CO_{2e} kg^{-1}	[39]
Garlic	0.67±0.07	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Extra-virgin olive oil	3.8±2.8	kg CO_{2e} kg^{-1}	SUEATABLE_LIFE database [35]
Basil leaves	1.6	kg CO_{2e} kg^{-1}	[40]
Beverages			
Mineral water in 75-cL glass bottles	0.63±0.02	kg CO_{2e} L^{-1}	[41-42]
Beer in 75-cL glass bottles	0.69±0.52	kg CO_{2e} L^{-1}	[35, 55]
Beer in 33-cL glass bottles	0.79±0.52	kg CO_{2e} L^{-1}	[35, 55]
Coca-Cola in 33-cL glass bottles	1.09	kg CO_{2e} L^{-1}	[43]
Coca-Cola Zero in 33-cL aluminum cans	0.45	kg CO_{2e} L^{-1}	[43]
Fanta in 33-cL aluminum cans	0.52	kg CO_{2e} L^{-1}	[43]
Packaging Materials			
EPA wooden pallet	0.244	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
25-kg paper bags	1.51	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
25-g multilayer foil	3.21	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
400-g metal can	2.47	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2

5.0-kg wooden box	1.5	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
3.0-kg polystirene box	4.13	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
PE bag of different capacities	2.53	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
1.5-kg paper layer	0.557	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
0.6-kg twine net	12.4	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
1-kg glass jar	1.07	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
1 metal lid	2.82	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
100-g bunches using plasticized wire	2.2	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
0.6-kg wooden cassette	1.5	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
15-kg PP box	3.14	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
1-kg light cardboard box	1.40	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
5-L metal can	4.28	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
1-kg PET jar	3.80	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
100-g PE net	2.84	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
300-g PE tray	2.84	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
Al-PET coated cardboard pizza box	1.41	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
PET tanks or bottles of different volumes	1.94	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
Detergents			
Dishwashing liquid detergent	0.62	kg CO_{2e} kg^{-1}	[26]; Ecoinvent v. 3.7+ SimaPro 9.2
Floor washing liquid detergent	0.66	kg CO_{2e} kg^{-1}	[26]; Ecoinvent v. 3.7+ SimaPro 9.2
Glass window cleaner detergent	0.64	kg CO_{2e} kg^{-1}	[26]; Ecoinvent v. 3.7+ SimaPro 9.2
Toilet detergent	2.56	kg CO_{2e} kg^{-1}	[26]; Ecoinvent v. 3.7+ SimaPro 9.2
Table set			
Ceramic plates	1.83	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
Stainless steel cutlery	7.91	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
Glasses	1.07	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
Paper tablecloths	1.59	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2

Paper napkins	1.59	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7+ SimaPro 9.2
Wastewater treatment and waste disposal			
Wastewater treatment, av. {EU without CH}| capacity 1E9 l/yr | Cut-off, S	0.476	kg CO_{2e} m^{-3}	Ecoinvent v. 3.7
Landfill			
Waste Paperboard {RoW} treatment of sanitary landfill| Cut-off, S	1.52	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste plastic, mixture {RoW}| treatment of sanitary landfill| Cut-off, S	0.102	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste aluminum {RoW}, treatment of sanitary landfill| Cut-off, S	0.0383	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste wood, untreated {RoW}| treatment of sanitary landfill| Cut-off, S	0.0747	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Sludge from pulp&paper production{RoW}|treatment of, sanitary landfill| Cut-off, S assumed as equivalent to landfilling of organic waste	1.14	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Glass waste {CH}| treatment of inert material landfill Cut-off, S	0.00418	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Scrap steel {EU without CH}| inert material landfill| Cut-off, S	0.00516	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Wood ash mixture, pure {RoW}| treatment of, sanitary landfill | Cut-off, S	0.0184	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Municipal solid waste {RoW}| treatment of, sanitary landfill | Cut-off, S	0.626	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Recycling			
Paper (waste treatment) {GLO}| recycling of paper | Cut-off, S	0	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Paper (waste treatment) {GLO}| recycling of paper | APOS, S	-0.139	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Cut-off, S	0	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | APOS, S	-1.73	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Aluminum (waste treatment) {GLO}| recycling of aluminium | Cut-off, S	0	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Aluminum (waste treatment) {GLO}| recycling of aluminium | APOS, S	-21.8	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Packaging glass, white {GLO}| recycling of packaging glass| Cut-off, S	0	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Packaging glass, white {GLO}| recycling of packaging glass| APOS, S	-1.26	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S	0	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Steel and iron (waste treatment) {GLO}| recycling of steel and iron | APOS, S	-1.73	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste wood, untreated {IT}| market for waste wood, untreated | Cut-off, S	0.0585	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste wood, untreated {IT}| market for waste wood, untreated | APOS, S	0.0776	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7

Biowaste {RoW}| treatment of biowaste, industrial composting | Cut-off, S	0.0588	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Biowaste {RoW}| treatment of biowaste, industrial composting | APOS, S	0.0589	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Biowaste {RoW}| treatment of biowaste by anaerobic digestion | Cut-off, S	0.118	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Biowaste {RoW}| treatment of biowaste by anaerobic digestion | APOS, S	0.148	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Incineration			
Waste paperboard {RoW}| treatment of, municipal incineration | Cut-off, S	0.0316	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste plastic, mixture {RoW}| treatment of, municipal incineration | Cut-off, S	2.38	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste wood, untreated {RoW}| treatment of, municipal incineration | Cut-off, S	0.0145	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Scrap aluminum {RoW}| treatment of, municipal incineration | Cut-off, S	0.0135	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Raw sewage sludge {RoW}| treatment of, municipal incineration | Cut-off, S	0.0772	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Scrap steel {EU without CH}| treatment of, municipal incineration | Cut-off, S	0.0102	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Waste glass {RoW}| treatment of, municipal incineration | Cut-off, S	0.0175	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Municipal solid waste {IT}| treatment of, incineration | Cut-off, S	0.519	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7
Municipal solid waste {IT}| treatment of, incineration | APOS, S	0.520	kg CO_{2e} kg^{-1}	Ecoinvent v. 3.7

Table S2: Details of the LCA model used to estimate the carbon footprint of the 168-g cardboard pizza box using the software SimaPro and embedded databases.

Documentation | **Input/output** | Parameters | System description

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocatic	Waste type	Category	Comment
Pizza- Cardboard box	168	g	Mass	100 %	Cardboard	...\Transformation	
Add							

Outputs to technosphere: Avoided products	Amount	Unit	Distributior	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distributior	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribi	SD2 o	Min	Max	Comment
Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| production | Cut-off, S	11.11	g	Undefi				
Corrugated board box {RER}| production | Cut-off, S	168-11.11-5.12 = 152	g					
Polyethylene terephthalate, granulate, amorphous, recycled {RoW}| polyethylene terephthalate productic	5.12	g	Undefi				
Add							

Inputs from technosphere: electricity/heat	Amount	Unit	Dis	SD2 or	Min	Max	Comment
Sheet rolling, aluminium {RER}| processing | Cut-off, S	11.11	g	Un				
Laminating service, foil, with acrylic binder {RER}| processing | Cut-off, S	2925	cm2	Un				
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, S	0/1000*300 = 0	kgkm					PS - FG
Extrusion, plastic film {RER}| extrusion, plastic film | Cut-off, S	5.12	g	Un				

Table S3: Details of the LCA model used to estimate the carbon footprint of the 5-L metal can containing extra-virgin olive oil using the software SimaPro and embedded databases.

Documentation | **Input/output** | Parameters | System description

Products

Outputs to technosphere: Products and co-products	Amount	Unit	Quantity	Allocatic	Waste type	Category	Comment
Pizza- EVOO 5-kg can	1	kg	Mass	100 %	Steel	...\Transformation	
Add							

Outputs to technosphere: Avoided products	Amount	Unit	Distributior	SD2 or 2SD	Min	Max	Comment
Add							

Inputs

Inputs from nature	Sub-compartment	Amount	Unit	Distributior	SD2 or 2SD	Min	Max	Comment
Add								

Inputs from technosphere: materials/fuels	Amount	Unit	Distribi	SD2 o	Min	Max	Comment
Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Cut-off, S	1	kg	Undefi				
Add							

Inputs from technosphere: electricity/heat	Amount	Unit	Dis	SD2 or	Min	Max	Comment
Transport, freight, lorry 7.5-16 metric ton, EURO5 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO5 | Cut-off, S	0/1000*300 = 0	kgkm					PS - FG
Metal working, average for steel product manufacturing {RoW}| processing | Cut-off, S	1	kg	Un				
Add							

Table S4: Mass of several Marinara and Margherita pizza types as weighted at the inlet and outlet of the wood-fired oven, or just 2 minutes later when put in a plate or cardboard to be served.

Pizza Mass	**Marinara Pizza**	**Margherita Pizza**	**Unit**
As entering the wood-fired oven	350±4	417±6	g
As exiting from the wood-fired oven	313±2	377±5	g
As dished to be served	311±2	375±5	g

Figure S1: Radial profiles of the temperature of the wood-fired oven floor, as measured using a non-contact infrared thermometer.

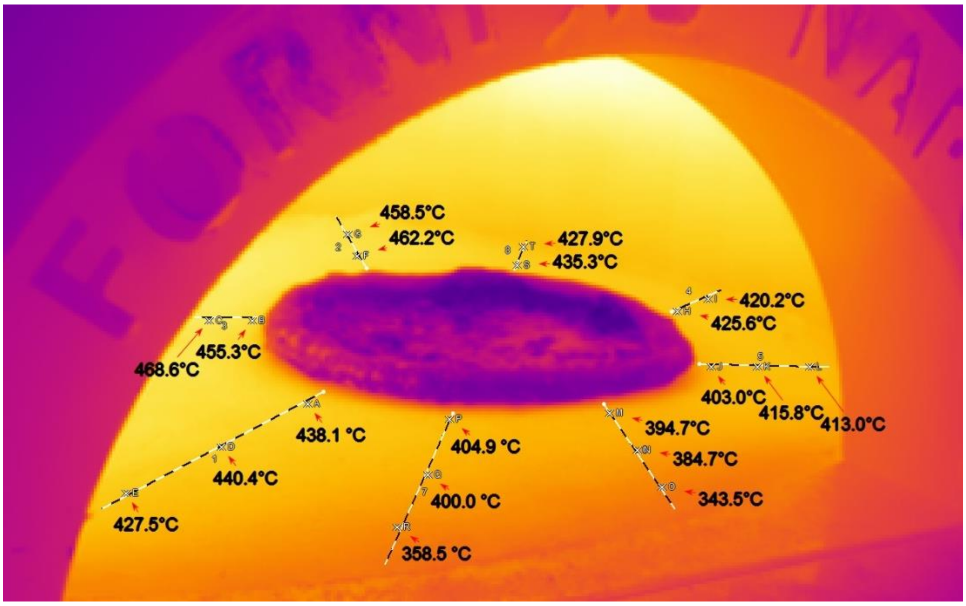

Figure S2: Pictures of the empty open (a) and closed (b) pizza corrugated cardboard boxes used in the pizzeria examined in this work.


a)


b)

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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
EFi	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 ≤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)
ΔEFi	Relative variation for the i-th emission factor EFi, as defined by Equation (4)
Ψi	Entity of the i-th activity parameter [kg, kWh, or kg km]

References

1. Kuscer, L. Slice of the pie: pizza consumption trends & industry statistics, 2022. Available online: https://muchneeded.com/pizza-consumption-statistics/ (accessed on 8 February 2022).

2. UDiCon (Unione per la Difesa dei Consumatori) Giornata mondiale della Pizza: festa per i consumatori, 2020. Available online : https://www.udicon.org/2020/01/17/giornata-mondiale-della-pizza-festa-per-i-consumatori/ (accessed on 26 January 2022).

3. Anon. Pizza, un business che lievita anno per anno, 2020. Available online : https://www.cna.it/pizza-un-business-che-lievita-anno-per-anno/ (accessed on 26 January 2022).

4. EC. Commission Regulation (EU) No. 97/2010, “entering a name in the register of traditional specialities guaranteed [Pizza Napoletana (TSG)]”. Official Journal of the European Union, L 34, 05 February 2010. Available online : https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L:2010:034:FULL (accessed on 26 January 2022).

5. UNESCO (United Nations Education, Scientific and Cultural Organization). Decision of the Intergovernmental Committee: 12.COM 11.B.17, 2017. Available online : https://ich.unesco.org/en/decisions/12.COM/11.B.17 (accessed on 26 January 2022).

6. Masi, P., Romano, A., Coccia, E. The Neapolitan pizza. A scientific guide about the artisanal process. Doppiavoce: Napoli, Italy, 2015.

7. AVPN (Associazione Verace Pizza Napoletana). Disciplinare internazionale per l’ottenimento del Marchio collettivo “Verace Pizza Napoletana” - (Vera Pizza Napoletana), 2004. Available online: https://www.pizzanapoletana.org/public/pdf/Disciplinare_AVPN.pdf (accessed on 26 January 2022).

8. Kumar, P., de Fatima Andrade, M., Yuri Ynoue, R., Fornaro, A., Dias de Freitas, E., Martins, J., Martins, L.D., Albuquerque, T., Zhang, Y., Morawska, L. New directions: From biofuels to wood stoves: The modern and ancient air quality challenges in the megacity of São Paulo. Atmospheric Environment 2016, 140, 364-369.

9. Apurva. Tandoors, burning of solid waste adding to dirty Delhi air: IIT study. The Indian Express, 2016. Available online : https://indianexpress.com/article/india/india-news-india/tandoors-burning-of-solid-waste-adding-to-dirty-delhi-air-iit-study/ (accessed on 8 February 2022).

10. WHO (World Health Organization). Ambient (outdoor) air pollution, 2018. Available online: http://www.who.int/mediacentre/factsheets/fs313/en/index.html (accessed on 26 January 2022).

11. Singh, B., Highway, D. What is your restaurant's carbon footprint?, 2016. Available online: https://www.pizzamarketplace.com/articles/what-is-your-restaurants-carbon-footprint/ (accessed on 26 January 2022).

12. Fucito, A. Forno elettrico e pizza napoletana: parola ai pizzaioli, tecnici, associazioni, 2019. Available online: https://garage.pizza/rubriche-sulla-pizza/forno-elettrico-e-pizza-napoletana-parola-ai-pizzaioli-tecnici-associazioni/ (ac-cessedon 26 January 2022).

13. Stylianou, K., Nguyen, V.K., Fulgoni, V.L., Jolliet, O. Environmental impacts of mixed dishes: A case study on pizza. The FASEB Journal, 2018. Available online: https://faseb.onlinelibrary.wiley.com/doi/abs/10.1096/fasebj.31.1_supplement.lb386 (accessed on 26 January 2022).

14. Hofmann, S., Gensch, C.-O. Carbon footprint – Frozen Food. Final Report: Life cycle assessment of various product options and identification of optimization potentials for selected frozen food products. German Institute for Frozen Food- Oeko-Institute, 2012. Available online: https://www.tiefkuehlkost.de/download/finalreport-cf-frozenfood-final.pdf.pdf (accessed on 26 Jan-uary 2022).

15. WRAP (Waste and Resources Action Programme). Hotspots, opportunities & initiatives. Pizza (fresh and frozen), 2013. Available online: http://www.wrap.org.uk/sites/files/wrap/Pizza%20(fresh%20and%20frozen)%20v1.pdf (accessed on 3 February 2021).

16. ARAlimentare (Attività Riunite Alimentare SpA). Carbon footprint per pizza Sorrento 4 formaggi 120 g di Attività Riunite Ali-mentare Spa. CFP – ECR 013-A01. External Communication Report, 2013. Available online: https://www.minambiente.it/sites/default/files/archivio/allegati/trasparenza_valutazione_mer/18_Ar_Alimentare_SPA.pdf (accessed on 26 January 2022).

17. Davies, T., Konisky, D. M. Environmental implications of the foodservice and food retail industries. Discussion Paper 00-11, 2000. Available online: https://media.rff.org/documents/RFF-DP-00-11.pdf (accessed on 26 January 2022).

18. Crawford, R. Home-delivered food has a huge climate cost. So which cuisine is the worst culprit?, 2021. Available online : https://theconversation.com/home-delivered-food-has-a-huge-climate-cost-so-which-cuisine-is-the-worst-culprit-151564 (accessed on 8 February 2022).

19. Aldaya, M.M., Hoekstra, A.Y. The water needed to have Italians eat pasta and pizza. Report Series No. 36. Unesco-IHE, Delft, NL, 2009. Available online: https://ris.utwente.nl/ws/portalfiles/portal/5147321 (accessed on 26 January 2022).

20. BSI. PAS 2050: 2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. British Standards Institution, London, UK, 2011.

21. ISO. 14040-Environmental management e Life Cycle Assessment - Principles and framework. International Organization for Standardization, Genève, CH, 2006.

22. ISO. 14044-Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization, Genève, CH, 2006.

23. Wikipedia. COVID-19 pandemic in Italy, 2022. Available online: https://en.wikipedia.org/wiki/COVID-19_pandemic_in_Italy (accessed on 26 January 2022).

24. Saouter, E., van Hoof, G. A database for the Life-Cycle Assessment of Procter & Gamble laundry detergents. Int J Life Cycle Assess 2002, 7(2), 103-114.

25. Martin, S., Bunsen, J., Ciroth, A. Openlca 1.7.2. Case study: ceramic cup vs paper cup, 2018. Available online: https://www.openlca.org/wp-content/uploads/2018/09/comparative_assessment_openLCA_coffee_mugs.pdf (accessed on 26 January 2022).

26. Koehler, A., Wildbolz, C. Comparing the environmental footprints of home-care and personal-hygiene products: The relevance of different life-cycle phases. Environ. Sci. Technol. 2009, 43, 8643–8651.

27. Johnson, A. R-404A refrigerant fact & info sheet, 2019. Available online: https://refrigeranthq.com/r-404a-refrigerant-fact-info-sheet/ (accessed on 26 January 2022).

28. Fusi, A., Guidetti, R., Azapagic, A. Evaluation of environmental impacts in the catering sector: the case of pasta. J Cleaner Prod. 2016, 132, 146-160.

29. Ronchi, E., Nepi, M.L. L'Italia del riciclo 2020. Fondazione per lo sviluppo sostenibile, FISE UNICIRCULAR, Rome, Italy, 2020. Available online: https://www.fondazionesvilupposostenibile.org/wp-content/uploads/dlm_uploads/Italia-del-riciclo-2020-Rapporto.pdf (ac-cessed on 26 January 2022).

30. Tricase, C., Lombardi, M. State of the art and prospects of Italian biogas production from animal sewage: technical-economic considerations. Renew. Energ. 2009, 34 (3), 477-485.

31. Adella, L., Aragona, G., D'Alessandro, P., Ermili, S., Frittelloni, V., Lanz, A. M., Lupica, I., Minniti, F. Gestione dei rifiuti urbani. In: Rapporto Rifiuti Urbani. Edizione 2020. Rapporti 331/2020. ISPRA, Rome, Italy, 2020, pp. 73-175.

32. SRD (Statista Research Department) Treatment of municipal solid urban waste in Italy 2019, by method, 2021. Available online: https://www.statista.com/statistics/682944/management-of-solid-urban-waste-in-italy-by-treatment/#statisticContainer. (ac-cessed on 26 January 2022).

33. Demichelis, F., Piovano, F., Fiore, S. Biowaste management in Italy: Challenges and perspectives. Sustainability 2019, 11, 4213, 1-21, <doi:10.3390/su11154213>.

34. Legambiente. Rifiuti zero, impianti mille. Dossier di Lega Ambiente, 2019. Available online: https://www.legambiente.it/wp-content/uploads/dossier-Rifiuti-zero-Impianti-mille-2019.pdf (accessed on 26 January 2022).

35. Petersson, T., Secondi, L., Magnani, A., Antonelli, M., Dembska, K., Valentini, R., Varotto, A., Castaldi, S. A multilevel carbon and water footprint dataset of food commodities. Scientific Data 2021, 8, 127. https://doi.org/10.1038/s41597-021-00909-8.

36. Clune, S., Crossin, E., Verghese, K. Systematic review of greenhouse gas emissions for different fresh food categories. J Cleaner Prod. 2017, 140, 766-783.

37. EcoInvent. System models, n.d. Available online: https://ecoinvent.org/the-ecoinvent-database/system-models/#!/allocation (accessed on 26 January 2022).

38. Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H. Anthropogenic and natural radiative forcing. Chp. 8. In Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.) Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013, pp. 731-738. Available online: //www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf (accessed on 26 January 2022).

39. Messier, J. M. The restaurant GHG guidelines: An operational greenhouse gas emissions accounting protocol for restaurants. Master Science thesis, University of Minnesota, Minneapolis, USA, 2016. Available online : https://conservancy.umn.edu/bitstream/handle/11299/191254/Messier_umn_0130M_16992.pdf?sequence=1 (accessed on 26 January 2022).

40. Ying, C., Freed, P. Knowing is half the battle, 2016. Available online: https://www.youtube.com/watch?v=l2IP1Y_Nd4I (accessed on 26 January 2022).

41. Moresi, M. Assessment of the life cycle greenhouse gas emissions in the food industry. Agro Food Industry Hi-Tech 2014, 25 (3) May/June, 53-62.

42. Gazzetta Ufficiale. Disciplinare di produzione della specialità tradizionale garantita “pizza napoletana. Gazzetta Ufficiale della Repubblica Italiana, Serie generale n. 56, 9 marzo 2010, pp. 42-47.

43. Morawicki, R.O. Handbook of Sustainability for the Food Sciences. Wiley-Blackwell, Chichester, UK, 2012.

44. Cimini, A., Moresi, M. Are the present standard methods effectively useful to mitigate the environmental impact of the 99% EU food and drink enterprises? Trends in Food Science and Technology 2018, 77, 42-53.

45. Cimini, A., Moresi, M. Product Carbon Footprint: Still a proper method to start improving the sustainability of food and bev-erage enterprises. It. J. Food Sci. 2019, 31, 808-826

46. Berlese, M., Corazzin, M., Bovolenta, S. Environmental sustainability assessment of buffalo mozzarella cheese production chain: A scenario analysis. J. Cleaner Prod. 2019, 238, 117922; https://doi.org/10.1016/j.jclepro.2019.117922.

47. Cimini, A., Moresi, M. Circular economy in the brewing chain. It. J. Food Sci. 2021, 33 (3), 47–69.

48. Cimini, A., Moresi, M. Carbon footprint of a pale lager packed in different formats: assessment and sensitivity analysis based on transparent data. J. Cleaner Prod. 2016, 112, 4196-4213.

49. European Union (EU). Regulation (EU) 2019/631 of the European Parliament and of the Council of 17 April 2019 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles and repealing Regulations (EC) No 443/2009 and (EU) No 510/2011. Official Journal of the European Union, 111/13, 25.4.2019, p. 13-53. Available online: http://data.europa.eu/eli/reg/2019/631/oj (accessed on 26 January 2022).

50. Terna. Dati statistici sull’energia elettrica in Italia, 2020. Available online: https://www.terna.it/it/sistema-elettrico/statistiche/pubblicazioni-statistiche (accessed on 6 February 2022).

51. Cimini, A., Moresi, M. Environmental impact of the main household cooking systems – a review. It. J. Food Sci. 2022, in press.

52. Senthil Kumar, K., Rajagopal, K. Computational and experimental investigation of low ODP and low GWP HCFC-123 and HC-290 refrigerant mixture alternate to CFC-12. Energy Conversion and Management 2007, 48, 3053-3062.

53. Lima, F.D.M., Pérez-Martínez, P.J., de Fatima Andrade, M., Kumar, P., de Miranda, R.M. Characterization of particles emitted by pizzerias burning wood and briquettes: a case study at Sao Paulo, Brazil. Environmental Science and Pollution Research 2020, 27, 35875–35888.

54. Buonanno, G., Morawska, L., Stabile, L., Viola, A. Exposure to particle number, surface area and PM concentrations in pizze-rias. Atmospheric Environment 2010, 44, 3963-3969.

55. Buonanno, G., Morawska, L., Stabile, L. Particle emission factors during cooking activities. Atmospheric Environment 2009, 43, 3235-3242.

56. Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Verones, F., Vieira, M.D.M., Hollander, A., Zijp, M., van Zelm, R., Stam, G. ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. RIVM Report 2016. National Institute for Public Health and the Environment, Bilthoven, NL, 2016.

57. Petersson, T., Secondi, L., Magnani, A., Antonelli, M., Dembska, K., Valentini, R., Varotto, A., Castaldi, S. SUEATABLE_LIFE: a comprehensive database of carbon and water footprints of food commodities, 2021. Available online: https://doi.org/10.6084/m9.figshare.13271111 (accessed on 26 January 2022).

58. Noya, I., Aldea, X., Gasol, C.M., González-García, S., Amores, M.J., Colón, J., Ponsá, S., Roman, I., Rubio, M.A., Casas, E., Moreira, M.T., Boschmonart-Rives J. Carbon and water footprint of pork supply chain in Catalonia: From feed to final products. Journal of Environmental Management 2016, 171, 133-143.

59. HEALabel. The impact of oregano, n.d. Available online: https://healabel.com/o-ingredients/oregano (accessed on 26 January 2022).

60. HEALabel. The impact of basil, n.d. Available online: https://healabel.com/b-ingredients/basil (accessed on 26 January 2022).

61. Cerelia. Environmental Product Declaration of Cerelia natural mineral water bottled in PET 1.5 L and glass non-returnable 1 L. Rev. 0. Registration no. S-P-00123, 2008.

62. Ferrarelle. Dichiarazione ambientale di prodotto dell’acqua minerale Ferrarelle. Rev. 0. Registration no. S-P-00281, 2011.

63. Campaign Staff. Coca-Cola reveals carbon footprints of Coke brands, 2009. Available online: https://www.campaignlive.co.uk/article/coca-cola-reveals-carbon-footprints-coke-brands/888281 (accessed on 26 January 2022).

Chapter 9

Novel high-quality takeaway Neapolitan pizza from unused dough balls: sensory and textural properties, and carbon footprinting assessment.

This chapter has been submitted and is under review as:

Falciano, A., Puleo S., Colonna F., Moresi, M. Di Monaco R., and Masi, P. (2023). Novel high-quality take-away or home-delivery Neapolitan pizza product from unused dough balls: sensory and textural properties and carbon footprinting assessment.

Chapter 10

Conlusions and future perspective

Not only is the Neapolitan pizza one of the most popular and well-known products of the Italian gastronomy, but is also one of the pillars of the catering industry and the circular economy.

The introduction of some innovations in the Neapolitan pizza production process such as the use of sourdough, alternative flours, medium-long shelf life pizza doughs balls ready to use, new pizza service systems, and the scientific knowledge on the phenomena that occur during the cooking phase of the Neapolitan pizza in the traditional wood-burning oven, also useful for developing alternative cooking systems, can further improve the qualitative aspects of the Neapolitan pizza and further strengthen the circular economy.

In **Chapter 2** the effect of refreshments on the growth of endogenous microorganisms and their effects on the physical-chemicals properties during the preparation of liquid sourdough (DY 200) was investigated, using wheat flours from two different geographical locations (Italian and Mexican flour). The results showed that the microbial population was higher in sourdough made from Mexican wheat flour. After 6 days of incubation, the microbial populations were not significantly different in both types of sourdoughs, either refreshed or not, and therefore no significant differences in the pizza physico-chemical properties were detected. In summary, daily refreshments are not necessary during the first 6 days of preparing the liquid sourdough. Future studies will concern the development and characterization of the liquid acid mother to apply it to the production process of Neapolitan pizza.

In **Chapter 3** it was proposed to exploit the beneficial properties of jujube powder by using it to make composite flours for the development of a functional pizza base. The incorporation of jujube flour in the formulation of the pizza base significantly increased the fiber, total phenolic and flavonoid contents, and the radical scavenging activity without significantly changing the overall acceptability of the products. Therefore, jujube powder could be considered as a potential healthy functional ingredient, without promoting negative effects and without modifying the desirable physical and sensory characteristics of pizza and future studies will be aimed at verifying its *in vivo* health properties, after ingestion. and complete digestion.

The study shown in **Chapter 4** represents an important starting point for a large-scale marketing of ready-to use dough balls which can find a valid application in allowing the tasting a “Pizza Napoletana” (TSG) product even in pizzerias not necessarily present in the Campania region. The dough balls were evaluated as a function of the leavening time and in any case the refrigerated conditions at 2 ± 0.5 °C did not affect the microbiological and chemical-physical parameters in ready-to-use dough balls after 28 days of storage, and the dough ball with a longer leavening time (16 h) exhibited similar characteristics to the fresh product and good property for rolling.

In **Chapter 5** the performance of a pilot-scale wood-fired pizza oven like those commonly used in Neapolitan pizzerias in Italy was assessed. Firstly, its start-up procedure was performed. Second, it was studied how, independently of the operator’s ability, the oven can be put in quasi-steady-state conditions with its dome and floor temperatures exhibiting no appreciable fluctuations by varying firewood feed rate from 3 to 9 kg/h. Third, two different baking tests were carried out using either just water or 4 pizza types as such or topped with tomato puree and/or sunflower oil. In both tests the thermal efficiency was around 13% of the energy supplied by oak log burning. In the circumstances, the use of such equipment leads to an inefficient use of wood as well as poor indoor and outdoor air quality. Subsequently, in **Chapter 6** the material and energy balances in a pilot-scale wood-fired oven in quasi steady-state operating conditions were established in conjunction with the measurement of the main composition of flue gas and external oven wall and floor temperatures in order to assess the heat loss rates through flue gas and insulated oven chamber. About 46% and 26% of the energy supplied by firewood combustion were dissipated by the exit fumes and external oven surfaces to the surrounding environment. The remaining 28% accumulated in the internal oven chamber, this allowing the temperatures of the oven vault and floor to be kept approximately constant, as well as one or two pizzas to be baked at once. By accounting for the simultaneous heat transfer mechanisms of radiation, convection, and conduction, it was possible to simulate quite accurately a series of water heating tests carried out using water-containing aluminum trays with a diameter near to that of a typical Neapolitan pizza. The overall heat transferred to each pizza-simulating tray was mainly due to radiation (circa 73%), the contribution of the convective heat from the oven vault and conductive heat from the oven floor amounting to about 15 and 12%, respectively.

Pizza baking can be described as a process of simultaneous heat and liquid and vapor water transports within the product itself and within the gaseous environment inside the oven chamber. Conduction raises the temperature of the lower pizza surface, which is in contact with the hot oven floor, and then transfers heat from the lower surface to the upward layers of the crust, while radiation and convection transmit heat from the oven vault to the exposed upper surface of the pizza. Hence, these heat transfer mechanisms produce different localized heating effects, and in **Chapter 7** was reported the phenomenologically results of Neapolitan pizza baking in a pilot-scale wood-fired pizza oven operating in quasi steady-state conditions. Specifically, the evolution of the rim, the heat and mass transfer, and finally the degree of browning and burning of pizza samples garnished in different ways were evaluated. Pizza samples tested had almost the same diameter (28.2 ± 0.4 cm) and a raised rim, 2.2 cm in thickness and 2.3 cm in height whatever the topping ingredients used after cooking. During pizza baking the oven floor temperature did not change, being practically constant at 439 ± 3 °C; while the area underneath each pizza reduced its temperature as faster as the greater the pizza mass laid on it. The pizza bottom reached a maximum temperature of 100 ± 9 °C, by contrast, the upper pizza side was respectively heated up to 182, 84 or 67 °C in the case of white pizza as such, tomato pizzas or margherita pizza, mainly because of their diverse moisture content and emissivity. In all pizza types examined, the overall weight loss was near to 10 g and was nonlinearly related to the average temperature of the upper pizza side when using no or just one topping ingredient or that of tomato puree-topped surface area. Thanks to the use of the IRIS electronic eye it was possible to identify color codes in order to quantify the formation of brown or black areas on the upper and lower sides of the various cooked pizza samples. The upper pizza side exhibited the greater degrees of browning and blackening than the lower one, their maximum values of about 26 and 8% being respectively observed in white pizza as such. The formation rate of browned or blackened areas was described via the Bigelow first-order kinetic model and was characterized by a tenfold increase as the temperature of the upper side of pizza was raised by 16-19 °C or about 9 °C in the case of any white or tomato pizzas. Such a kinetic model was however unable to describe the temperature-sensitivity of all pizza bottoms. Altogether, the above results expressing the heat and mass transfer dynamics during pizza baking in a wood-fired oven helped to improve the understanding of this process and are preliminary to develop an accurate modelling and control strategy to reduce the variability and maximize the quality attributes of Neapolitan pizza.

In **Chapter 8** the cradle-to-grave carbon footprint of the different versions of the True Neapolitan Pizza was estimated in accordance with the PAS 2050 standard method. An average CF was estimated of ~4.69 kg CO_{2e}/diner, of which approximately 74% due to the production of the ingredients used (the sole buffalo mozzarella represents as much as 52% of the CF). The contribution of beverages, packaging materials, transport and energy sources ranged between 6.8 and 4.6% of CFBy as-suming the same specific greenhouse gas emissions associated to some life cycle phases in the case of a typical Neapolitan pizzeria (i.e., energy consumption, refrigerant gas leakage, detergent production and wastewater treatment), the Marinara and Margherita pizza carbon footprint was about 4 and 5 kg and CO_{2e}/kg, respectively. By garnishing the latter with buffalo mozzarella cheese, its footprint would increase up to ~8.4 kg CO_{2e}/kg. Such difference in their environmental impacts mainly derives from the use of condiments of only vegetable or even animal origin, these varying the protein and lipid contents and consequently the energy value of each pizza type. 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.

The quality of pizza decreasing as it cool, therefore it would be eaten freshly baked. The cardboard pizza box used for home delivery or take-away slows down the cooling rate of the pizza but reduces its texture quality as the residence time increases. **Chapter 9** proposed a new layout for take-away pizza, i.e., such dough balls unsold at the end of each working day were converted into pizzas, baked in the wood-fired oven, quick frozen, packed, preserved in a freezer till its selling, transported or delivered to home and finally reheated in a domestic oven. Firstly, some chemico-physical parameters, namely the pizza thermal mapping, weight loss due to water vaporization and instrumental texture profile, and the sensory acceptability of quick-frozen and reheated pizza with that of freshly baked pizza samples, as served at the table immediately or after 5 minutes of queuing at the pizza counter, or packed in cardboard boxes for 10, 20 or 30 minutes. The frozen pizza reheated exhibited a few textural properties, such as gumminess and springiness, similar or near to the values of a just freshly baked pizza. As expected, consumers preferred freshly baked pizza, but the frozen pizza sample was not significantly different from that. Secondly, the cradle-to-grave carbon footprint and cost of the frozen pizza were also assessed. An LCA study allowed to assess that frozen product affected quite irrelevantly the overall amount of GHG emitted by a typical pizzeria on a year basis. Thus, this novel product might offer a better-quality pizza to consumers of home-delivery or take-away pizza, reduce interference in crowded restaurants and well as avoid the wastage of unsold dough balls with a net profit increase.

List of Pubblications

Scientific Journals

- Falciano, A., Romano, A., Almendárez, B. E. G., Regalado-Gónzalez, C., Di Pierro, P., & Masi, P. (2022). Effect of the refreshment on the liquid sourdough preparation. Italian Journal of Food Science, 34(3), 99-104.
- Falciano, A., Sorrentino, A., Masi, P., & Di Pierro, P. (2022). Development of Functional Pizza Base Enriched with Jujube (Ziziphus jujuba) Powder. Foods, 11(10), 1458.
- Falciano, A., Masi, P., & Moresi, M. (2022). Performance characterization of a traditional wood-fired pizza oven. Journal of Food Science, 87(9), 4107-4118.
- Falciano, A., Masi, P., & Moresi, M. (2023). Semi-empirical modelling of a traditional wood-fired pizza oven in quasi steady-state operating conditions. Journal of Food Science, in press.
- Falciano, A., Moresi, M., & Masi, P. (2023). Phenomenology of Neapolitan Pizza Baking in a Traditional Wood-Fired Oven. Foods, 12(4), 890.
- Falciano, A., Cimini, A., Masi, P., & Moresi, M. (2022). Carbon Footprint of a Typical Neapolitan Pizzeria. Sustainability, 14(5), 3125.

Paper submitted under review

- Falciano, A., Di Pierro, P., Romano, A., Sorrentino, A., Cavella, S., & Masi, P. (2023). Study of a medium-high shelf life ready-to-use dough balls for making “Pizza Napoletana’’.
- Falciano, A., Puleo S., Colonna F., Moresi, M. Di Monaco R., and Masi, P. (2023). Novel high-quality take-away or home-delivery Neapolitan pizza product from unused dough balls: sensory and textural properties and carbon footprinting assessment.

Poster & oral presentations

- Falciano, A., Di Pierro, P., Romano, A., Sorrentino, A., Cavella, S., Masi, P. (2021). Development of a long shelf life ready-to-use dough rolls for making "Pizza Napoletana" (TSG). EFF2021 Int. Conference, 23-26 May 2021, Naples, Italy.
- Falciano, A. (2021). Processing and Innovation in the Neapolitan Pizza Manufacturing. First Virtual (XXV) WORKSHOP on THE DEVELOPMENTS IN THE ITALIAN PhD RESEARCH ON FOOD SCIENCE TECHNOLOGY AND BIOTECHNOLOGY 14-15 Settembre 2021 – Università di Palermo, Italy.
- Falciano, A., Di Pierro, P., Sorrentino, A., Romano, A., Masi, P., (2021). Developing of functional Neapolitan pizza base enriched with Jujube (Ziziphus jujuba) powder. EFFoST 2021, International Conference 1-4 Nov 2021, Lausanne, Switzerland.
- Falciano, A. (2022). Processing and Innovation in the Neapolitan Pizza Manufacturing. 26th Workshop on the Developments in the Italian PhD Research on Food Science, Technology and Biotechnology held between 19th-21st September 2022 at the UniASTISS venue in Asti, Italy.
- Falciano, A., Di Pierro, P., Romano, A., Sorrentino, A., Cavella, S., Masi, P. (2022). Study of a medium-high shelf life ready-to-use dough balls for making "Pizza Napoletana''. 10° Shelf Life International Meeting, SLIM 28 Nov-1 Dec 2022, Bogotà, Colombia
- Falciano, A., (2022). Pizza d'asporto: nuove procedure per il mantenimento della qualità sensoriale. La Pizza Napoletana e l'Arte del pizzaiolo napoletano a 5 anni dalla proclamazione di Jeju (Sud Corea). Convegno finale progetto PRIN Prot. 2017SFTX3Y: The Neapolitan pizza: processing, distribution, innovation and enviromental aspects. 7 dicembre 2022 - Sala Cinese – Reggia di Portici, Portici, Italia.