Reducing the cooking water-to-dried pasta ratio and environmental impact of pasta cooking

Alessio Cimini, Matteo Cibelli, Mauro Moresi*

Department for Innovation in the Biological, Agrofood and Forestry Systems,

University of Tuscia, Via S. C. de Lellis, 01100 Viterbo, Italy

***** To whom all correspondence should be addressed.

Tel. n°: +39-0761-357497;

fax n°: +39-0761-357498;

e-mail: mmoresi@unitus.it

Short version of title: **Environment-friendly pasta cooking**

Abstract

BACKGROUND: During daily pasta cooking, the general consumer pays little attention to water and energy issues. The aims of this work were to measure the cooking quality of a standard format of dry pasta by varying the water-to-dried pasta ratio (WPR) in the range of 12 to 2 L/kg, and assess the environmental impact of pasta cooking.

RESULTS: In the above range of WPR, the cooked pasta water uptake (1.3±0.1 g/g), cooking loss (3.7±0.9 %), and degree of starch gelatinization (11.2±0.8 %) resulted to be about constant. Also, the main *Texture Analysis* parameters (e.g., cooked pasta hardness at 30 and 90% deformation, and resilience) showed no statistically significant sensitivity to WPR. On the contrary, by reducing WPR from 12 to 2 L/kg, the specific electric energy consumption linearly decreased from 1.93 to 0.39 Wh/g, and carbon footprint and eutrophication potential of pasta cooking lessened by about 80% and 50%, respectively.

CONCLUSIONS: By using the environmentally sustainable pasta cooking procedure tested here, there would be no need to cook dry pasta in a large excess of water (i.e., 10 L/kg), as commonly suggested by the great majority of pasta manufacturers. However, such a great mitigation in the environmental impact of pasta cooking asks for novel more proper pasta cookers than those currently used.

KEY WORDS: Carbon footprint and eutrophication potential; cooking loss and starch gelatinization degree; cooking water-to-dried pasta ratio; energy consumption; Texture Analysis.

INTRODUCTION

The energy consumed to cook the great majority of food products generally represents the highest part of the overall energy consumed throughout their whole food life cycle. [1-3] In particular, the greenhouse gas (GHG) emissions associated with pasta cooking (CF_{PC}) were found to be equal to 0.6 or 1.7 kg of carbon dioxide equivalents (CO_{2e}) per kg of dry pasta, depending on the use of a gas or electric hob, respectively. [4] Thus, the cradle-to-grave carbon footprint (CF_{CG}) of dried pasta amounted to 1.93 or 3.03 kg CO_{2e}/kg. [4] Even in the case of deferred catering of cooked pasta, pasta cooking was found to be the major hotspot and its environmental impact might be reduced by using gas rather than electric appliances. [5]

In this specific process, water is not only the physical medium through which heat is transferred to the product undergoing rehydration, but also a key component for starch gelatinization and protein coagulation. [6] Such reactions are controlled by water uptake during pasta cooking and occur in almost the same range of temperature and moisture conditions, even if proteins react faster and at slightly lower moisture levels than starch granules. [7] Despite the amount of water generally used to cook one kg of dried pasta is 10-12 L, [4, 8-9] it was suggested to reduce the cooking water-to-dried pasta ratio (WPR) to 3.1-4.2 L/kg, [10] or even to as little as 2 L/kg.[11] By only reducing so significantly the amount of cooking water, it would be possible to cut drastically CF_{PC}, being inadequate to resort to specific eco-friendly cooking methods [12] or to high-performance cookers regulated properly.[13]

Currently, the consumption of water associated with food and drink production and consumption is a critical issue related not only to the scarcity of drinking water, but also to the resulting pollution. In particular, the fact that Italy had one of the largest water footprints of the world was related to the consumption of two typical Italian foods (e.g., pasta and pizza margherita). [14] The problem of cooking pasta with the right amount of water has often attracted the attention of mass-media and networking, [15] even if it has been generally solved with a series of empirical advice of discarded utility for their unscientific subjective approach. Actually, cooked pasta quality is rather difficult to assess. Stickiness is generally regarded as the main defect of cooked pasta. However, other quality attributes are also accounted for, namely the sauce-binding capability, yellow color, cooking loss, [16, 17] degree of starch gelatinization that affects pasta texture and digestibility after consumption, [18] and cooking time. [19, 20] The sensory attribute of cooked pasta consistency was found to be quite well related to the cutting force of a row of five spaghetti strands. [21] Other sensory attributes of cooked pasta resulted to be linked to a few structural parameters detected using the so-called *Texture Profile Analysis* test, which is carried out by submitting several cooked spaghetti strands to two successive compression cycles that mimic the jaw action. [22]

The first aim of this work was to assess the effect of WPR on the cooking quality of a standard format of durum wheat semolina dry pasta, while measuring not only the electric energy needs, but also the cooking water utilization. The second one was to minimize the environmental impact of the dried pasta cooking phase provided that there was no change in cooked pasta quality.

MATERIALS AND METHODS

Raw materials

A commercial durum wheat semolina dried pasta (Spaghetti no. 5, Barilla G. e R. F.lli SpA, Parma, Italy) was used. It was from the same production lot (n. 017096), packed in 1-kg paperboard boxes, and purchased in a local supermarket. It had diameter of 1.94±0.05 mm, length of 257±1 mm, composition reported in parentheses in g/100 g (moisture: <12.5; raw protein: 12.5; total carbohydrates: 70.2; fat: 2.0; total fiber: 3.0; ash: 0.013), specific energy content of 15.21 MJ/kg, and set time of 9 min.

Equipment and experimental procedure

Pasta cooking was carried out using:

- a 3-L magnetic stainless steel pan model Oumbärlig no. 502.864.20 (Inter IKEA Systems B.V. 1999-2014, Sweden) with a bottom diameter and height of 145 mm and 130 mm, respectively;
- a 2-kW 190-mm induction-plate stove (Melchioni INDU, Melchioni Spa, Milan, Italy);
- a mechanical stirrer EURO-ST P CV (IKA®-Werke GMBH, Staufen, D), that was kept rotating at the minimum stirring rate attainable (50 rev/min) either continuously or intermittently depending on the WPR used.

Any cooking test was started by setting the aforementioned pan over the cooking system, as shown in the electronic supplement (Fig. S1a). The latter was placed on a digital scale of the series PCE-BSH 10000 (CE Italy srl, Capannori, LU, Italy) with a load range of 0.6 g to 10 kg, and a reading accuracy of 0.2 g, this resulting in a percentage error of 0.2% on a 100-g mass reading. The lid was drilled twice, as shown in the electronic supplement (Fig. S1b). The 10-mm axial hole A allowed inserting a S-shaped non-magnetic stainless steel impeller to avoid spaghetti from sticking, while the 8-mm lateral one B allowed lodging a thermocouple so as to measure the cooking water temperature (T_{WM}) near the pan axis at mid-height of the water level.

In accordance with previous findings, [13] the induction hob was firstly regulated to its maximum setting (2.0 kW) to bring as quickly as possible the cooking de-ionized water (m_{W0}) from 20±1 °C to about 98 °C. Once the dried pasta (m_{PA}) had been added to the boiling water and the latter had restarted to boil, the hob control knob was adjusted to 0.4 kW to keep the cooking temperature around 98 °C for as long as the optimal cooking time. Such a power level was selected after a few preliminary tests carried out as reported previously, [13] but not shown for the sake of simplicity. Thus, by referring to the overall mass (m_{T0}) of the water-pasta suspension used previously, namely 1.625 kg, the nominal specific power was calculated ($e_{C,nom}$≈0.246 W/g) and kept constant for WPR ranging from 2 to 12 L/kg. Thus, once WPR had been set, the initial amounts of dried pasta (m_{PA}) and cooking water (m_{W0}) were estimated as follows:

$$m_{PA} = \frac{P_{C,nom}}{e_{C,nom}(1+WPR)} \qquad (1)$$

$$m_{W0} = m_{PA0}\, WPR \qquad (2)$$

All above data were acquired by a custom-made data logger based on an Arduino Nano 3.0 (ATmega328) previously described, 2017), [13] while the electric energy consumption, expressed in kWh, was monitored via a digital power meter type RCE MP600 (RCE Srl, Salerno, Italy), characterized by an accuracy of ±1.0% when measuring power in the range of 0.4-3,999 W.

Sample preparation

A given amount (m_{PA}) of spaghetti was weighted, broken in half, and cooked in boiling deionized water [21,23] by varying WPR from 2 to 12 L per kg of dried pasta. Cooking properties of pasta samples were assessed by collecting several strands of spaghetti with a colander. Such strands were cooled by rinsing under running tap water for 60 s. As excess water had been removed by shaking the colander for 10 s, the samples were immediately used for the chemico-physical analyses described below.

Visual analysis of cooked spaghetti central core.

The Method 66-50.01 [24] was used to monitor the central white core of any strand of spaghetti when gently squeezed between two glass plates.

Cooking loss and water absorption by cooked pasta

Whatever the WPR used, cooking loss (CL) was evaluated by determining the amount of solid dispersed in the cooking water used. [16] After recovering cooked pasta with a colander, residual cooking water was brought back to its initial volume (m_{W0}). Under constant mixing, a few aliquots (~10 g) were dried at 105 °C overnight. The cooking loss (CL) was referred to the initial mass of dried pasta used (m_{PA}) and expressed as grams of matter loss per g of dry pasta. Because of water absorption, the increase in cooked pasta mass was gravimetrically assessed as the difference between the masses of cooked pasta (m_{CPA}) and dried pasta (m_{PA}). The relative increase in cooked pasta mass (RICPM) was expressed as grams of water per g of dry pasta.

Starch gelatinization

Starch gelatinization was estimated via the colorimetric measurement of starch–iodine complex formed in an aqueous suspension of the cooked pasta sample as such and after complete starch gelatinization. [25, 26] The degree of starch gelatinization (SGD) was calculated as the ratio between the net absorbance of the iodine complexes prepared from the aqueous suspension before or after thermal starch gelatinization, as measured at 600 nm with a Thermofisher Scientific mod. Evolution 60S spectrophotometer.

Texture analysis (TA)

The textural characteristics of cooked pasta were determined using a Universal Testing Machine UTM mod. 3342 (Instron Int. Ltd., High Wycombe, UK) equipped with a 1000-N load cell and connected to a personal computer (PC) via a controller 3300 (version 01-v2,02/03-b6,58/EFI- v1.36) and operated via a specially designed software (Bluehill 2.33.893-hotfix). Seventeen strands of cooked spaghetti were aligned over a stainless steel compression platen (see Fig. S2a in the electronic supplement) to avoid spaghetti sticking to it, as well as to clean easily the platen itself, and tested using the cutting probe, shown in Fig. S2bc. For a time interval smaller than 10 min, the difference among TA parameters was found to be statistically insignificant at the probability level of 0.05. The average cooked spaghetti diameter (d_{CP}) was calculated as the difference between the total displacement of the probe at the contact points with the platen and pasta samples, both revealed by a trigger force of 0.05 N. Each TA test was carried out in accordance with the Barilla Group standard test. [27] By setting the probe speed at 1 mm/s, a first bite was performed by submitting the strands to a 30% compression. The probe was then moved upward to reach its initial position. After a pause of 5 s, it was newly moved downward to submit the specimens to a second 90% compression and then moved upward to return to its initial position. In the electronic supplement, Figure S3 shows a typical TPA curve generated by UTM. The height of the force peak on the first and second compression cycles was defined as the pasta hardness at 30% (F_{30}) and 90% deformation (F_{90}). The force-vs-time area (A_D) during the 1st withdrawal of the compression divided by the force-vs-time area (A_C) of the 1st compression (see Fig. S3) was defined as the cooked pasta resilience (CPR), this measuring how well the cooked pasta can regain its original form. [28] The upstroke actions during the first and second bites represented the work necessary to pull the compressing probe away from the spaghetti strands and the force-vs-time area was defined as adhesiveness (A_A). In almost all tests carried out, A_A was found to be negligible, as shown in Fig. S3.

Cooking water and energy balances

The pasta cooking process was subdivided into two distinct phases. The first one was aimed at heating the cooking water up to its boiling point, while the second one was the real pasta cooking phase. To check for the cooking water balance during such a process, the block diagram shown in the electronic supplement (Fig. S4) was used. To this end, the following data were collected:

i) The initial mass of cooking water (m_{W0}).

ii) The cooking water mass at the boiling point (m_{WBP}) to estimate the mass of water evaporated throughout the cooking water heating phase:

$$m_{We} = m_{W0} - m_{WBP} \quad (3)$$

iii) The cooking water mass as soon as the pan has been unlidded (m_{WLO}), just before dried pasta adding (m_{PA}). As the lid was removed, there was a sudden release of water vapor (adiabatic flash), its mass being equal to:

$$m_{WAF1} = m_{WBP} - m_{WLO} \quad (4)$$

iv) The masses of residual cooking water or *pasta water* (m_{Wf}), and cooked pasta (m_{CPA}), once water-pasta mixture has been fractionated with a colander. In this way, the mass of water absorbed by pasta (m_{WPA}), or adiabatically flashed (m_{WAF2}) at the end of the cooking process when the lid has been newly removed, was estimated as:

$$m_{WPA} = m_{CPA} - m_{PA} \quad (5)$$

$$m_{WAF2} = m_{W0} - m_{We} - m_{WAF1} - m_{WPA} - m_{Wf} \quad (6)$$

Such data allowed to trace which fraction of m_{W0} was evaporated (η_{WE}), adiabatically flashed as the pan had been unlidded (η_{WAFi}), absorbed by cooked pasta (η_{WPA}), and unused (η_{Wf}) at the end of the pasta cooking process.

The energy balance was performed as reported previously. [13] In particular, the energy efficiency (η_C) of the pasta cooking system examined here was estimated as the ratio between the instantaneous values of the energy theoretically (E_{th}) and effectively (E_{cons}) consumed. E_{th} was estimated by summing the sensible heat required to raise the cooking water, lidded pan, and dried pasta from the initial temperature (T_{i0}) to the instantaneous water temperature at mid-height (T_{WM}), and heat of wheat starch gelatinization, its enthalpy (ΔH_{gel}) being extracted from Ratnayake et al. [29] E_{cons} was supplied by the induction hob, monitored using the aforementioned multimeter and linearly related to the cooking time (t_C) as follows:

$$E_{cons}(t) = \alpha\, t_C + \beta \quad (7)$$

where α and β are empiric constants estimated using the least squares method.

All abbreviations and symbols used in this article along with their definitions are given in the Nomenclature section, while all parameters needed to calculate η_C are listed in Table 1.

Environmental impact of pasta cooking

According to the Product Environmental Footprint category rules for dry pasta, [30] the environmental impact of pasta cooking was assessed by accounting for the only impact categories of climate change (CF) and eutrophication (NP). To assess the carbon footprint of pasta cooking (CF_{PC}) as a function of WPR, that is the total amount of GHGs produced directly and indirectly by such an activity, [31] the inventory analysis included the consumption of electric energy and tap water, as well the disposal of pasta water:

$$CF_{PC} = m_{PA} \, (e_{PC,eff} \, EF_{EE} + WPR \, EF_{TW} + \eta_{Wf} \, WPR \, EF_{WD}) \quad (8)$$

with

$$e_{PC,eff} = E_{cons}/(1-\eta_{IG}) \quad (9)$$

where $e_{PC,eff}$ is the specific electric energy effectively absorbed from the Italian grid, η_{IG} the average electric energy loss in 2015, [32] η_{Wf} the volume fraction of pasta water to be disposed of; while EF_{EE}, EF_{TW}, and EF_{WD} are the emission factors (referred to a time horizon of 100 years) associated with the average Italian thermo-electric production from non-renewable and renewable sources in 2015, tap water utilization, and pasta water disposal by aerobic treatment plants with an average capacity size of 233,000 per capita equivalents. Such emission factors are listed in Table 1. In particular, EF_{EE} was extracted from ISPRA, [32] while EF_{TW} and EF_{WD} from the Ecoinvent database of the Life Cycle Analysis (LCA) software Simapro 7.2 v.2 (Prè Consultants, Amersfoort, NL).

Pasta water is generally discarded into sinks or toilets and this is hazardous for the environment, since it is rich in starchy materials and causes excessive biomass growth. The corresponding *nutrification* or *eutrophication* effect score (NP_{PC}) was estimated by multiplying the Chemical Oxygen Demand load of pasta water (Q_{COD}) and eutrophication potential (NP_{WD}) relative to phosphate (PO_4^{3-}):

$$NP_{PC} = Q_{COD}\ NP_{WD} \quad (10)$$

with

$$Q_{COD} = COD_S\ c_S\ \eta_{Wf}\ WPR\ m_{PA} \quad (11)$$

where COD_S is the theoretical Chemical Oxygen Demand of starch (1.185 g O_2/g starch), c_S the pasta water starch content, and NP_{WD} was extracted from Heijungs et al. [33] and listed in Table 1.

Statistical analysis of data

All pasta cooking tests were replicated four times to assess a series of dependent variables, such as the mass of cooking water (m_W); temperature of the cooking water at mid-height (T_{WM}), electric energy consumption (E_{cons}), cooking loss (CL), specific water absorption (RICPM), starch gelatinization degree (SGD), and TA parameters (F_{30}, F_{90}, CPR). Any set of data was shown as average ± standard deviation and was analyzed by Tukey test at a significance level of 0.05. Any linear regression was estimated using the least squares method and the goodness of fit was evaluated by means of its coefficient of determination (r^2).

RESULTS

Whatever the water-to-dried pasta ratio used, each pasta cooking test was carried out by setting $P_{C,nom}$ at 0.4 kW and estimating m_{PA} and m_{W0} via Eq.s (1) and (2), as shown in Table 2. Moreover, a mechanical stirrer was used to avoid spaghetti sticking together during cooking at WPR≤6 L/kg. After a series of preliminary trials, it was kept working continuously throughout all the cooking process for WPR=2 L/kg, but for 30 s followed by a resting period of 30 or 90 s for WPR equal to 3 or 6 L/kg, respectively. In all conditions, the corresponding electric power supplied was practically constant (5.8±0.3 W). By accounting for the different rest intervals used, the overall mixing energy consumed was calculated as equal to 0.870, 0.435, or 0.218 Wh for WPR=2, 3, or 6 L/kg, respectively. The resulting specific energy requirement was thus negligible with respect to that (E_{cons}) needed to cook pasta (Table 2). As shown in the electronic supplement (Fig. S5), the time needed to heat the different initial masses of cooking water used up to the boiling point decreased from about 350 to 253 s as WPR was reduced from 12 to 2 L/kg dry pasta. This time interval was proportional to the amount of cooking water used (m_{W0}), the energy efficiency of the induction hob used being approximately constant.

The main results of the cooking and TA tests, the former being quadricated and the latter repeated from 10 to 22 times, were summarized in Table 2.

Effect of WPR on the energy-related parameters

Fig. 1a shows the effect of WPR on the parameters related to the energy aspects of the process. Firstly, it was checked for the effective electric power supplied by the induction hob during either the cooking water heating phase (P_H) or pasta cooking one (P_C). Thus, E_{cons} was linearly related to t_C using Eq. (7). All regressions were characterized by coefficients of determination (r^2) greater than 0.995, while the estimated slopes (α) by coefficients of variation ranging from 0.3 to 3%. Thus, the effective power supplied per unit mass of the water-pasta suspension undergoing cooking ($e_{C,eff}$) was found to be practically constant (153±5 W/kg) whatever WPR (Table 2). Same situation for the overall cooking energy efficiency (η_C=66±2 %). On the contrary, the specific energy consumed per unit mass of dried pasta (e_{PA}) reduced almost linearly from about 1.93 to 0.39 Wh/g as WPR was reduced from 12 to 2 L/kg of dry pasta:

$$e_{PA} = (0.160 \pm 0.004)\ WPR \qquad (r^2=0.997) \qquad (12)$$

Effect of WPR on the cooking water utilization

Fig 1b shows the effect of WPR on the percentage utilization of the water used to cook spaghetti. The fraction of water evaporated during the cooking process (η_{WE}) slightly increased from 2.1 to 2.5% for WPR halving from 12 to 6 L/kg, but enhanced to 3.4 and 6.5% as WPR was further reduced to 3 and 2 L/kg, respectively. The cooking water adiabatically flashed (η_{WAF12}), anytime the pot was unlidded during the pasta cooking process, was practically independent of WPR (r^2=0.180) and of the order of 3±1 %. On the contrary, the cooking water absorbed by cooked pasta (η_{WPA}) was about the 11% of the water initially added into the pot (m_{W0}) when dry pasta was cooked in a great excess of water (WPR=12 L/kg), but doubled to 21% of m_{W0} when WPR was halved to 6 L/kg. As WPR was reduced to 3 or 2 L/kg, such a water uptake jumped to 42 or 70% of m_{W0}, respectively. Consequently, by diminishing WPR from 12 to 2 L/kg, the so-called *pasta water*, that is the cooking water leftover after recovering cooked pasta with a colander, lessened from 84 to 21% of m_{W0}.

Effect of WPR on cooked spaghetti quality

Fig 1c shows the effect of WPR on cooked spaghetti quality. In particular, the relative increase in cooked pasta mass as due to water absorption (RICPM) was not related to WPR (r^2=0.090), but about constant (1.3±0.1 g/g) as WPR was decreased from 12 to 2 L/kg. The starch gelatinization degree (SGD) lessened from 12 to 9.8%, while the cooking loss (CL) tended to decrease as WPR was decreased (r^2=0.69). Actually, the loss of solid matter dissolved in the cooking water was about 4.2 g per 100 g of dried pasta for WPR ranging from 12 to 6 L/kg. For WPR=3 or 2 L/kg, such amount dropped to 3.5 or 2.2%, respectively.

Effect of WPR on cooked pasta TA parameters

Fig. 1d clearly shows the negligible effect of WPR on the three TA parameters accounted for. More specifically, throughout all TA tests the spaghetti strand diameter, and cooked pasta hardness upon either 30% or 90% deformation were practically constant, and equal to 2.6±0.1 mm, 5.8±0.5N, or 13.2±0.6 N, respectively. Finally, cooked pasta resilience (CPR) was about linearly related to WPR (r^2=0.890), even if its derivate with respect to WPR was so small (0.0022±0.0004) that it might be for the sake of simplicity regarded as constant (0.63±0.01).

Effect of WPR on the environmental impact of pasta cooking

Fig. 2 shows the effect of WPR on the carbon footprint (CF_{PC}), and eutrophication effect score (NP_{PC}) of home pasta cooking according to the eco-sustainable cooking procedure used here. Firstly, the contribution of the tap water consumption and pasta water disposal to the overall carbon footprint of pasta cooking was found to be insignificant with respect to that resulting from the energy consumption. Thus, their contributions can be disregarded, this validating the assumptions by the Product Environmental Footprint category rules for dry pasta. [30] Secondly, CF_{PC} was linearly related to WPR (r^2=0.995) and any reduction in WPR would positively reduce the climate change potential of pasta cooking.

As concerning the eutrophication potential, NP_{PC} reduced from 1.16±0.02 to 0.57±0.05 g PO_4^{3-} per kg of dried pasta as WPR was decreased from 12 to 2 L/kg.

DISCUSSION AND CONCLUSIONS

By observing the structure of cooked spaghetti via scanning electron microscopy, three different concentric regions were generally identified. [7] In the external region, starch granules appeared to be very deformed and swollen, and practically indistinguishable from proteins. In the intermediate one, a dense protein network embedding partly swollen granules was distinguished. Then, in the inner region, starch granules displayed quite a slight degree of swelling and gelatinization for the limited water availability. [7] By accounting for just two cooked and uncooked regions and assuming that starch gelatinization occurred only at their interface, water concentration in the cooked region tended to decrease radially from the spaghetti surface to a value, that increased as cooking progressed, but remained approximately constant all over the uncooked one. [6] In the circumstances, the amount of water used to cook spaghetti should not affect the water concentration at the pasta surface. The lower the WPR used, the higher the probability of spaghetti strands to attach longitudinally to each other will be. As spaghetti agglomerate, the surface of pasta exposed to the water reduces, this limiting the pasta rehydration kinetics and cooking loss into the cooking water.

In this work, specific water uptake (RICPM) by raw spaghetti was found to be about constant (1.3±0.1 g/g), this confirming that there was no shortage of water during the cooking trials under study, even at the lowest WPR value tested. On the contrary, the decrease in the starch gelatinization degree (SGD) from 12 to 9.8% was probably due to the lower concentration of water in the internal region of any spaghetti strand at WPR=2 L/kg. However, whatever the WPR value used the unsoaked whitish central core of each strand was still visible at the end of the recommended cooking time (9 min), as shown in the electronic supplement (Fig. S6). This confirmed that spaghetti “al dente” were still far from being fully gelatinized. [34] Then, the drop in CL for WPR decreasing from 12 to 2 L/kg was attributed to the smaller the amount of water used and thus to its smaller solid dissolution capacity.

Finally, all the TA parameters resulted to be practically independent of WPR.

Such results might be regarded as approximately congruent with the restricted (i.e., 5, 15, or 10%) reduction in the cooked pasta mass, cooking loss, and cooked firmness observed as WPR was reduced from 30.8 to 8.3 L/kg. [35]

The eco-sustainable cooking procedure used here resulted in an overall energy efficiency (η_C) of the cooking system used of 66±2 %, almost independent of WPR. Such efficiency was in line with previous results obtained when cooking short-cut extruded pasta using the same eco-sustainable procedure, but higher than that (30-46%) achievable in typical domestic appliances and cookware sets. [13]

On the contrary, as WPR was reduced from 12 to 2 L/kg of dry pasta, the cooking energy consumed reduced from about 1.93 to 0.39 Wh/g, this greatly affecting the GHG emissions associated with pasta cooking. By referring to the cradle-to-grave carbon footprint (CF_{CG}) of 3.03 kg CO_{2e}/kg of dried pasta when using an electric cooker, [4] the replacement of the original contribution of the pasta cooking phase (~1.7 kg CO_{2e}/kg) with that (0.14 kg CO_{2e}/kg) estimated here for WPR=2 L/kg would reduce CF_{CG} to ~1.47 kg CO_{2e}/kg. In the circumstances, the contribution of the pasta cooking phase would decrease from about 56 to 10% of CF_{CG}.

By applying the eco-sustainable cooking procedure used here with WPR=2 L/kg, it would be possible to serve cooked spaghetti with almost the same quality of those cooked at WPR=10 L/kg with the remarkable effect of reducing the GHGs emissions associated with the current Italian consumption of dry pasta (~1.61×10^6 Mg/yr) [36] from 4.9 to 2.4 Tg

CO_{2e}/yr, that is from the 1.2 to 0.6% of the total Italian GHG emissions, including land use, land use change and forestry (~397 Tg CO_{2e} in 2015). [37]

The cradle-to-distribution center eutrophication effect score was found to be of the order of 10.43 g PO_4^{3-}/kg. [4] In particular, the contribution of durum wheat production (9.22 g PO_4^{3-}/kg) was by far greater than that (1.21 g PO_4^{3-}/kg) associated with all the other LCA phases (i.e., milling, manufacture of packaging materials, pasta production and distribution). Thus, when dry pasta was cooked in a great excess of water (e.g., 12 L/kg), the estimated NP_{PC} score (1.16 g PO_4^{3-}/kg) resulted to be near to that associated to pasta manufacture and distribution, but it might be about halved (~0.57 g PO_4^{3-}/kg) by using as little as 2 L of water per each kg of dry pasta.

In conclusion, it was scientifically established that there is no need to cook dried pasta in a large excess of water (i.e., 10 L/kg) as commonly suggested by the great majority of pasta manufacturers. In fact, the cooked pasta TA parameters, that usually well correlate with the main sensory attributes, and relative increase in cooked pasta mass exhibited no statistically significant sensitivity to the cooking water-to-dried pasta ratio used. These results were attributed to a mechanical stirrer that avoided spaghetti strand agglomeration during cooking, this being responsible for inhomogeneously cooked spaghetti.

When cooking one kg of dried pasta with 10 or 2 L of water, cooked spaghetti quality was not statistically different, but the pasta cooking carbon footprint, and eutrophication potential scores reduced from 0.69 to 0.14 kg CO_{2e}/kg, and from 1.16 to 0.57 g PO_4^{3-}/kg, respectively. Such a great mitigation in the environmental impact of pasta cooking asks for the development of more proper pasta cookers than the current domestic appliances and cookware sets used, as in the case of the present energy-saving kettles for tea or coffee.

NOMENCLATURE

A_A	Energy to pull the compressing probe away from the spaghetti strands after a 30% compression [J]
A_C	Downstroke energy to compress the spaghetti strands by 30% of their initial diameter [J]
A_D	Upstroke energy to decompress the 30%-compressed spaghetti strands [J]
CF_{CG}	Cradle-to-grave carbon footprint of dry pasta [g CO_{2e} kg^{-1}]
CF_{PC}	Carbon footprint of the pasta cooking phase [g CO_{2e} kg^{-1}]
CL	Cooking loss [g/100 g]
COD_S	Chemical Oxygen Demand of starch (=1.185 g O_2/g) [g O_2/g]
c_{pi}	Specific heat of the i-th component [kJ/(kg K)]
CPR	Cooked pasta resilience (=A_D/A_C) [dimensionless]
c_S	Starch content in pasta water [g/L]
d_{CP}	Spaghetti diameter [mm]
E_{cons}	Energy consumed to cook pasta [W h]
EF_{EE}	Emission factor for the electric energy distributed at the Italian grid, inclusive of non-renewable and renewable sources [g CO_{2e} kWh^{-1}]
EF_{TW}	Emission factor for tap water utilization [g CO_{2e} L^{-1}]
EF_{WD}	Emission factor for wastewater disposal [g CO_{2e} L^{-1}]
E_{th}	Energy theoretically consumed to cook pasta [kJ]

$e_{C,nom}$	Nominal power supplied per unit mass of the water-pasta suspension undergoing cooking [W/kg]
$e_{C,eff}$	Effective power supplied per unit mass of the water-pasta suspension undergoing cooking [W/kg]
e_{PA}	Specific energy consumed per unit mass of dry pasta [Wh/g]
$e_{PA,\ eff}$	Specific energy effectively consumed per unit mass of dry pasta [Wh/g]
F_{30}	Cooked pasta hardness at 30% deformation (first bite) [N]
F_{90}	Cooked pasta hardness at 90% deformation (second bite) [N]
GHG	Greenhouse gas
m_i	Amount of the i-th component used to cook pasta [kg]
m_{WLO}	Cooking water mass as soon as the pan has been unlidded [kg]
n	Number of cooking tests performed [dimensionless]
NP_{PC}	Nutrification effect score of pasta cooking [g PO_4^{3-}/kg]
NP_{WD}	Nutrification potential associated to the disposal of wastewaters having a given COD [g PO_4^{3-}/kg O_2]
P	Power supplied by the induction hob [kW]
p	Probability level
Q_{COD}	Specific COD load of pasta water [g O_2/kg]
r^2	Coefficient of determination
RICPM	Relative increase in cooked pasta mass [g/g]
SGD	Degree of starch gelatinization [%]
t_C	Cooking time [s]
T_{WM}	Temperature of cooking water at mid-height [°C]
TA	Texture analysis

WPR	Water-to-dried pasta ratio [L/kg]
x_S	Mass fraction of starch in raw pasta [g/g]

Greek Symbols

α	Empiric coefficient of Eq. (7) [kJ]
β	Empiric constant of of Eq. (7) [kW]
ΔH_{gel}	Gelatinization enthalpy of wheat starch [kJ kg^{-1}]
η_C	Energy efficiency of the cooking system [%]
η_{IG}	Electric energy loss of the Italian grid [%]
η_{WE}	Fraction of water evaporated (=m_{WE}/m_{W0}) [dimensionless]
η_{WAF1}	Fraction of water adiabatically flashed as the lid is firstly removed to add dried pasta (=m_{WAF1}/m_{W0}) [dimensionless]
η_{WAF12}	Fraction of water adiabatically flashed when the pan is unlidded (=$\eta_{WAF1}+\eta_{WAF2}$) [dimensionless]
η_{WAF2}	Fraction of water adiabatically flashed as the lid is newly removed to recover cooked pasta (=m_{WAF2}/m_{W0}) [dimensionless]
η_{WPA}	Fraction of water absorbed by cooked pasta (=m_{WPA}/m_{W0}) [dimensionless]
η_{Wf}	Fraction of pasta water (=m_{Wf}/m_{W0}) [dimensionless]

Subscripts

C	Referred to the pasta cooking phase
E	Referred to water evaporated
H	Referred to the heating phase of the cooking water
L	Referred to lid

P	Referred to pan
PA	Referred to dried pasta
W	Referred to cooking water
0	Initial

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REFERENCES

1 Carlsson-Kanyama, A, Boström-Carlsson K, 2001. Energy use for cooking and other stages in the life cycle of food. Forskningsgruppen för Miljöstrategiska Studier (FMS) Report no. 160, Stockholm, Sweden.

2 Garnett T, 2008. Cooking up a storm. Food, greenhouse gas emissions and our changing climate. Food Climate Research Network. Centre for Environmental Strategy, University of Surrey. Retrieved on 7 July 2018 from https://fcrn.org.uk/sites/default/files/CuaS_web.pdf

3 Xu Z, Sun D-W, Zhang Z, and Zhu Z, 2015. Research developments in methods to reduce carbon footprint of cooking operations: A review. Trends in Food Science and Technology 44, 49-57.

4 Barilla, 2017. EPD217 Barilla durum wheat semolina pasta in paperboard box. Retrieved on 7 July 2018 from https://edgeenvironment.com/wp-content/uploads/2016/11/epd217-Durum-wheat-semoline-dried-pasta.pdf

5 Fusi A, Guidetti R, and Azapagic A, 2016. Evaluation of environmental impacts in the catering sector: the case of pasta. Journal of Cleaner Production 132, 146-160.

6 Piazza L, Riva M, and Masi P, 1994. Modelling pasta cooking processes. In Y. Yano, R. Matsuno, K. Nakamura (Ed.s), Developments in food engineering. Blackie Academic & Professional, London, UK, pp 304-306.

7 Sicignano A, Di Monaco R, Masi P, and Cavella S, 2015. From raw material to dish: pasta quality step by step. Journal of the Science of Food and Agriculture 95(13), 2579-87.

8 Consorzio Agrario del NordEst, 2017. *Environmental Product Declaration. Applied to dried durum wheat semolina pasta- Patrimoni d'Italia*. Retrieved on 7 July 2018 from https://www.environdec.com/Detail/?Epd=10700

9 De Cecco, 2011. De Cecco durum wheat semolina pasta. Retrieved on 7 July 2019 from http://www.environdec.com/en/Detail/epd282

10 Ahn K, 2014. One-minute pasta! Plus more revolutionary pasta-cooking hacks you need to know. Retrieved from https://food-hacks.wonderhowto.com/how-to/one-minute-pasta-plus-more-revolutionary-pasta-cooking-hacks-you-need-know-0156659/

11 Molino and Pastificio Sgambaro, n.d. Cooking pasta with a minimal amount of water Retrieved on 7 July 2018 from http://www.sgambaro.com/ecotips/cooking-pasta-with-a-minimal-amount-of-water/

12 Heyhoe K, 2009. Cooking green: Reducing your carbon footprint in the kitchen. Da Capo Press Edn - LifeLong Books, Boston, MA, USA.

13 Cimini A, and Moresi M, 2017. Energy efficiency and carbon footprint of home pasta cooking appliances. Journal of Food Engineering 204, 8-17.

14 Martinez-Aldaya M, and Hoekstra AY, 2009. The water needed to have Italians eat pasta and pizza. (Value of water research report 36; No. 3). UNESCO-IHE Institute for Water Education, Delft, the Netherlands.

15 McGee H, 2009. How much water does pasta really need? The New York Times, Feb. 24, 2009. Retrieved on 7 July 2018 from http://www.nytimes.com/2009/02/25/dining/25curi.html

16 D'Egidio MG, Mariani BM, Nardi S, Novaro P, and Cubadda R, 1990. Chemical and technological variables and their relationships: a predictive equation for pasta cooking quality. Cereal Chemistry 67, 275–281.

17 Di Monaco R, Cavella S, Di Marzo S, and Masi P, 2004. The effect of expectations generated by brand name on the acceptability of dried semolina pasta. Food Quality and Preference 15, 429-437.

18 Wootton M, and Chaudhry MA, 1980. Gelatinization and in vitro digestibility of starch in baked products. Journal of Food Science, 45, 1783–1784.

19 Edwards NM, Izydorczyk JE, Dexter JE, and Biliaderis CG, 1993. Cooked pasta texture: comparison of dynamic viscoelastic properties to instrumental assessment of firmness. Cereal Chemistry 70, 122–126.

20 Sgrulletta E, and De Stefanis D, 1995. Valore nutrizionale e culinario delle paste alimentari di produzione nazionale. Tecnica Molitoria 46, 1297–1303, 1315.

21 Cubadda R, Iafelice G, and Marconi E, 2009. Pasta cooking quality and its evaluation. Tecnica Molitoria International 60 (10/A), 174-180.

22 Sozer N, Dalgıc AC, and Kaya A, 2007. Thermal, textural and cooking properties of spaghetti enriched with resistant starch. Journal of Food Engineering 81, 476–484.

23 Bourne MC, 2002. Food texture and viscosity: Concept and measurement (2nd edn). Academic Press, London, UK. pp 182-186.

24 AACC International, 1999. Method 66-50.01. Pasta and noodle cooking quality - Firmness. In Approved methods of analysis (11th ed). St. Paul, MN: AACC International. Retrieved on 8 July 2008 from http://dx.doi.org/10.1094/AACCIntMethod-66-50.01

25 Cocci E, Sacchetti G, Vallicelli M, Angioloni A, and Dalla Rosa M, 2008. Spaghetti

cooking by microwave oven: Cooking kinetics and product quality. Journal of Food Engineering 85, 537–546.

26 Dalla Rosa M, Lerici CR, Cencic L, and Pinnavaia G, 1989. Sul grado di gelatinizzazione dell'amido in alimenti diversi. Tecnica Molitoria 40, 692–699.

27 Ballestrieri D, D'Alessandro A, and Carnevali P, 2015. Texture profile analysis of cooked long pasta. MP-000515 Barilla Tests.

28 Haraldsson J, 2010. Development of a method for measuring pasta quality parameters. Degree project work, School of Natural Sciences, Linnaeus University, Kalmar, Sweden. Retrieved on 7 July 2018 from https://www.diva-portal.org/smash/get/diva2:322522/FULLTEXT01.pdf

29 Ratnayake WS, Otani C, and Jackson DS, 2009. DSC enthalpic transitions during starch gelatinization in excess water, dilute sodium chloride, and dilute sucrose solutions. Journal of the Science of Food and Agriculture 89, 2156-2164.

30 Sessa F, 2016. Product Environmental Footprint Category Rules (PEFCR). Dry pasta 160718. Draft for public consultation. Rev. 18/07/2016. Retrieved on 6 January 2018 from https://webgate.ec.europa.eu/fpfis/wikis/display/EUENVFP/PEFCR+Pilot%3A+Pasta

31 BSI, 2008. Publicly Available Specification (PAS 2050) for the assessment of the life cycle greenhouse gas emission of goods and services. British Standards Institution, London, UK.

32 ISPRA, 2017. Fattori di emissione atmosferica di CO2 ed altri gas a effetto serra del settore elettrico. Report n. 257/2017. Istituto Superiore per la Protezione e la

Ricerca Ambientale, Rome, Italy. Retrieved on 7 July 2018 from http://www.isprambiente.gov.it/files2017/pubblicazioni/rapporto/R_257_17.pdf

33 Heijungs R, Guinée JB, Huppes G, Lankreijer RM, Udo de Haes HA, Wegener Sleeswijk A, Ansems AMM, Eggels PG, van Duin R, and de Goede HP, 1992. Environmental Life Cycle Assessment of Products: Guide. Ed. CML (Center of Environmental Science), Leiden, NL, p 87.

34 Fasano A, Premilerio M, and Tesi A, 2011. A mathematical model for spaghetti cooking with free boundaries. Networks and Heterogeneous Media 6, 37-60.

35 de la Peña E, Wiesenborn DP, and Manthey FA, 2014. Pasta-to-water ratio, hotplate surface temperature, and beaker material affect pasta cooking time and cooked quality. Cereal Chemistry 91(5), 489–495.

36 Consumo nel mondo, n.d. Retrieved on 7 July 2018 from http://www.pasta.it/consumo.htm

37 ISPRA, 2017. Italian Greenhouse Gas Inventory 1990-2015. National Inventory Report 2017. Report n. 261/2017 (p. 492). Istituto Superiore per la Protezione e la Ricerca Ambientale, Rome, Italy. Retrieved on 7 July 2018 from http://www.isprambiente.gov.it/files2017/pubblicazioni/rapporto/R_261_17.pdf

TABLES AND TABLE HEADINGS

Table 1 Parameters used to estimate the cooking water and energy balances, as well as the carbon footprint and eutrophication potential of pasta cooking as a function of the water-to-dried pasta ratio (WPR).

Table 2 Spaghetti cooking tests carried out under constant power supplied by the induction hob during water boiling (P_H) and spaghetti cooking (P_C) when using different amounts of dried pasta (m_{PA}) and cooking water (m_{W0}): effect of WPR on the overall energy consumed (E_{cons}); cooking energy efficiency (η_C); effective power supplied per unit mass of cooking water and dried pasta ($e_{C,eff}$); energy consumed per unit mass of dried pasta (e_{PA}); percentage fractions of water evaporated (η_{WE}), adiabatically flashed before pasta addition (η_{WAF1}) and drainage (η_{WAF2}), absorbed by cooked pasta (η_{WPA}), and remaining after cooking (η_{Wf}); relative increase in cooked pasta mass (RICPM); starch gelatinization degree (SGD); cooking loss (CL); main TA parameters (F_{30}, F_{90}, CPR); and diameter of cooked spaghetti (d_{CP}). All cooking tests were replicated 4 times, while TA ones from 10 to 22 times.

Table 1

Parameters used to estimate the cooking water and energy balances, as well as the carbon footprint and nitrification potential of pasta cooking as a function of the water-to-dried pasta ratio (WPR).

Parameters	**Value**	**Unit**
c_{pW}	4.186	kJ/(kg K)
c_{pP}	0.837	kJ/(kg K)
c_{pPA}	1.840	kJ/(kg K)
ΔH_{gel}	11.9	J/g
m_{W0}	1.08-1.50	kg
m_{PA}	125-542	g
m_{P}	783.5	g
m_{L}	158.2	g
x_{S}	0.702	g/g
η_{IG}	6.2	%
FE_{EE}	333.24	g CO_{2e}/kWh
FE_{TW}	0.154	g CO_{2e}/L
FE_{WD}	0.317	g CO_{2e}/L
NP_{WD}	0.022	kg PO_4^{3-}/(kg O_2)

Table 2

Spaghetti cooking tests carried out under constant power supplied by the induction hob during water boiling (P_H) and spaghetti cooking (P_C) when using different amounts of dried pasta (m_{PA}) and cooking water (m_{W0}): effect of WPR on the overall energy consumed (E_{cons}); cooking energy efficiency (η_C); effective power supplied per unit mass of cooking water and dried pasta ($e_{C,eff}$); energy consumed per unit mass of dried pasta (e_{PA}); percentage fractions of water evaporated (η_{WE}), adiabatically flashed before pasta addition (η_{WAF1}) and drainage (η_{WAF2}), absorbed by cooked pasta (η_{WPA}), and remaining after cooking (η_{Wf}); relative increase in cooked pasta mass (RICPM); starch gelatinization degree (SGD); cooking loss (CL); main TA parameters (F_{30}, F_{90}, CPR); and diameter of cooked spaghetti (d_{CP}). All cooking tests were replicated 4 times, while TA ones from 10 to 22 times.

WPR	**m_{W0}**	**m_{PA}**	**P_H**	**P_C**	**E_{cons}**	**η_C**	**$e_{C,eff}$**	**e_{PA}**	**η_{WE}**	**η_{WAF1}**	**η_{WPA}**	**η_{WAF2}**	**η_{Wf}**	**RICPM**	**SGD**	**CL**	**F_{30}**	**F_{90}**	**CPR**	**d_{CP}**
[L/kg]	[g]	[g]	[kW]	[kW]	[Wh]	[%]	[W/kg]	[Wh/g]	[%]	[%]	[%]	[%]	[%]	[g/g]	[%]	[g/100 g]	[N]	[N]	[-]	[mm]
11.98 ±0.01^{a}	1500.2 ± 0.0^{a}	125.2 ±0.1^{a}	1.99 ±0.01^{a}	0.24 ±0.01^{a}	242 ±5^{a}	65 ±1^{a}	151 ±3^{a}	1.93 ±0.04^{a}	2.1 ±0.3^{a}	0.63 ±0.01^{a}	10.8 ±0.1^{a}	2.4 ±0.1^{a}	84.0 ±0.5^{a}	1.30 ±0.01^{a}	12.0 ± 0.2^{a}	4.5 ±0.1^{a}	5.6 ±0.4^{a}	13.8 ±0.5^{a}	0.64 ±0.02^{a}	2.6 ±0.1^{a}
10.02 ±0.03^{b}	1477 ±5^{b}	147.6 ±0.3^{b}	1.83 ±0.01^{b}	0.24 ±0.01^{a}	225 ±3^{b}	70 ±2^{b}	145 ±4^{a}	1.52 ±0.02^{b}	2.3 ±0.2^{a}	0.7 ±0.2^{a}	15.2 ±0.3^{b}	-0.1 ±0.3^{b}	81.8 ±0.5^{b}	1.53 ±0.03^{b}	11 ±2^{a}	4.2 ±0.1^{b}	5.1 ±0.3^{a}	13.2 ±0.6^{a}	0.64 ±0.01^{a}	2.65 ±0.03^{a}
6.0 ±0.0^{c}	1392.9 ±0.1^{c}	232 ±0^{c}	1.95 ±0.01^{c}	0.25 ±0.01 ^{a}	238 ±2^{a}	64 ±1^{a}	156 ±4^{ab}	1.02 ±0.01^{c}	2.5 ±0.2^{a}	1.1 ±0.2^{b}	20.8 ±0.2^{c}	2.9 ±0.3^{c}	72.7 ±0.1^{c}	1.25 ±0.01^{c}	11.2 ±0.3^{a}	4.1 ±0.^{2b}	6.3 ±0.5^{b}	13.9 ±0.6^{a}	0.62 ±0.01^{a}	2.66 ±0.03^{a}
3.0 ±0.0^{d}	1218.5 ±0.1^{d}	406 ±0^{d}	1.96 ±0.01^{c}	0.25 ±0.01 ^{a}	222 ±2^{b}	65 ±1^{a}	153 ±7^{ab}	0.54 ±0.01^{d}	3.4 ±0.2^{b}	0.20 ±0.1^{c}	42.2 ±0.1^{d}	3.0 ±0.7^{c}	51.1 ±0.5^{d}	1.27 ±0.01^{d}	11.5 ±0.4^{a}	3.5 ±0.1^{c}	6.1 ±0.3^{b}	13.0 ±0.4^{b}	0.62 ±0.01^{a}	2.70 ±0.03^{a}
2.0 ±0.00^{e}	1083.1 ±0.1^{e}	542 ±0^{e}	1.90 ±0.02^{d}	0.26 ±0.01 ^{a}	213 ±6^{c}	65 ±1^{a}	159 ±5^{ab}	0.39 ±0.01^{e}	6.5 ±0.6^{a}	0.0 ±0.0^{d}	70.2 ±0.9^{e}	3 ±1^{c}	20 ±2^{e}	1.37 ±0.06^{a}	9.8 ±0.6^{b}	2.2 ±0.2^{d}	6.0 ±0.4^{b}	12.3 ±0.8^{b}	0.62 ±0.01^{a}	2.59 ±0.06^{b}

- Different lowercase letters indicate statistically significant difference among the column means at the probability level of 0.05.

FIGURES AND FIGURE HEADINGS

Figure 1 Effect of the cooking water-to-dried pasta ratio (WPR) on several parameters characterizing the pasta cooking process under study:

a) Specific energy consumed to cook dry pasta (e_{PA}); dimensionless cooking energy efficiency (η_C); power supplied to heat the cooking water (P_H) or cook pasta (P_C) against WPR.

b) Percentages of water evaporated during the cooking process (η_{WE}), released as vapor when the pot is unlidded firstly to add dried pasta and then to drain cooked pasta (η_{WAF12}), absorbed by cooked pasta (η_{WPA}), and leftover upon pasta drainage (η_{Wf}) *versus* WPR.

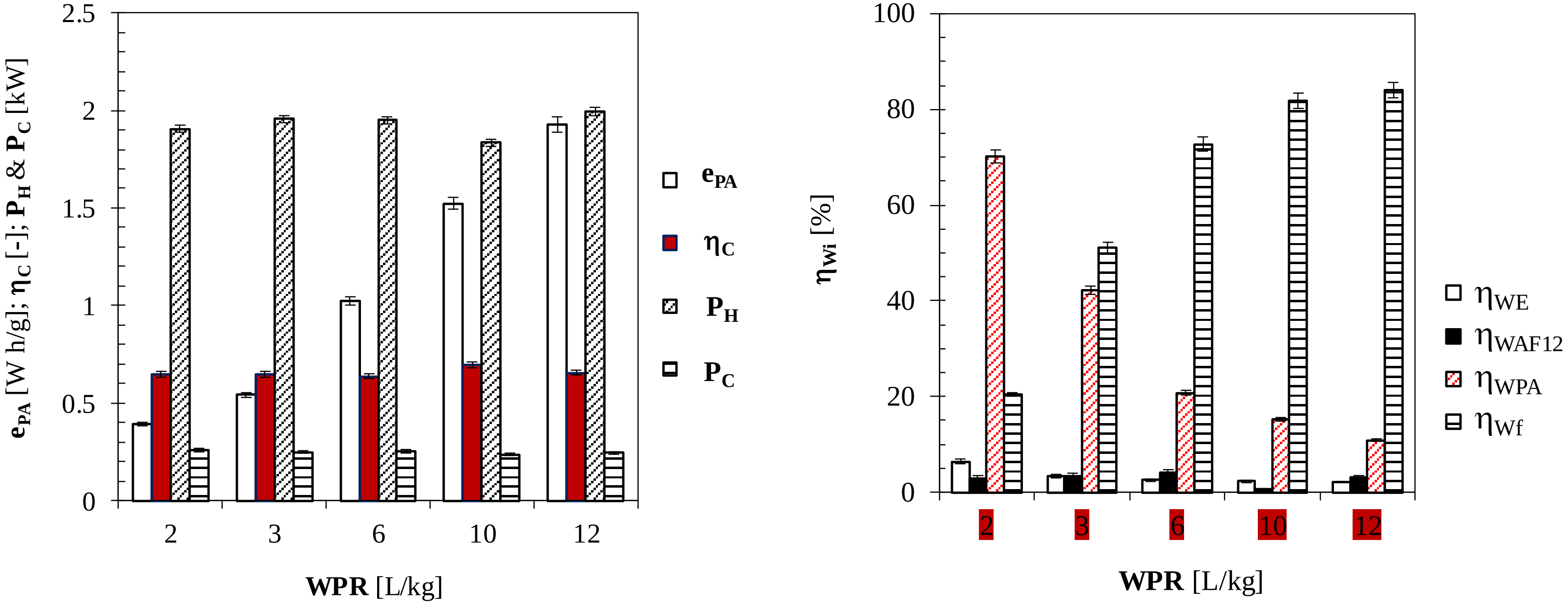
c) Relative increase in cooked pasta mass (RICPM), starch gelatinization degree (SGD), and cooking loss (CL) against WPR.

d) Cooked pasta hardness at 30% (F_{30}) and 90% (F_{90}) deformation; cooked pasta resilience (CPR); and cooked spaghetti diameter (d_{CP}) *versus* WPR.

Figure 2 Effect of the cooking water-to-dried pasta ratio (WPR) on the carbon footprint (CF_{PC}), and eutrophication potential (NP_{PC}) of pasta cooking as referred to the eco-sustainable cooking procedure used here.

Figure 1

a) **b)**

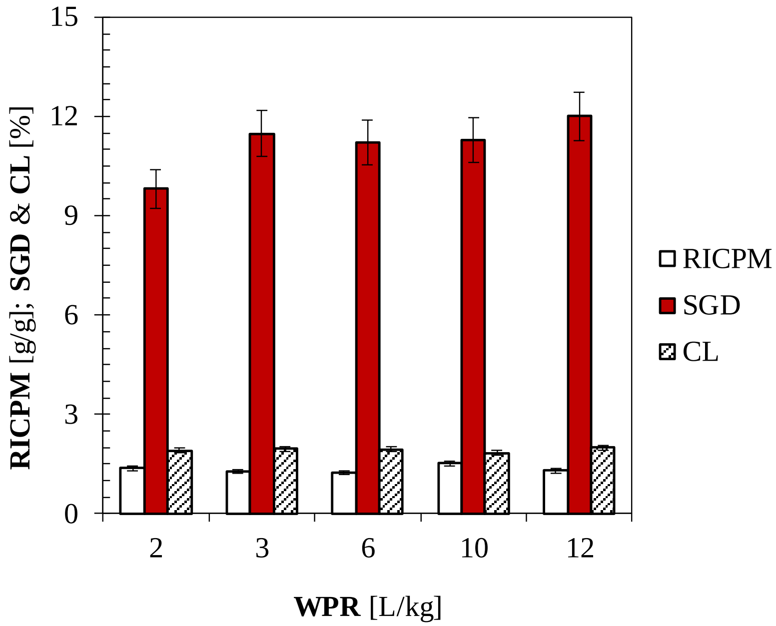


Effect of the cooking water-to-dry pasta ratio (WPR) on several parameters characterizing the pasta cooking process under study:

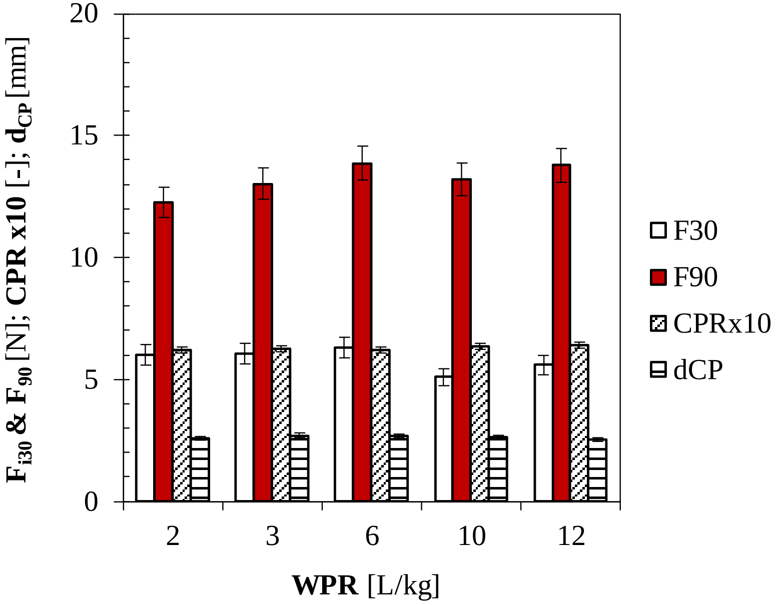
a) Specific energy consumed to cook dry pasta (e_{PA}); dimensionless cooking energy efficiency (η_C); power supplied to heat the cooking water (P_H) or cook pasta (P_C) against WPR.

b) Percentages of water evaporated during the cooking process (η_{WE}), released as vapor when the pot is unlidded firstly to add dried pasta and then to drain cooked pasta (η_{WAF12}), absorbed by cooked pasta (η_{WPA}), and leftover upon pasta drainage (η_{Wf}) *versus* WPR.

c)



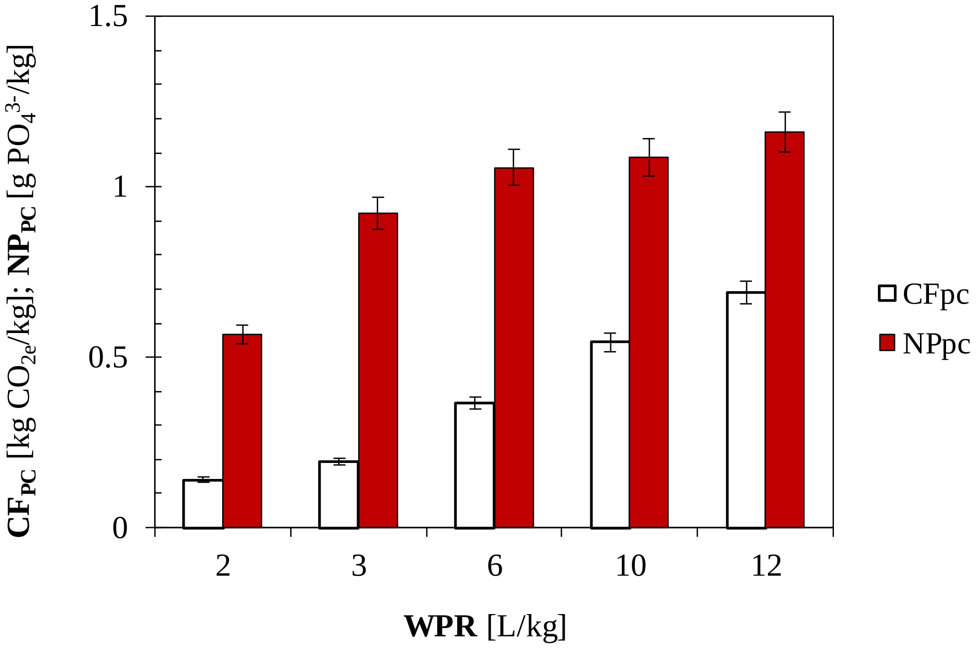
d)



c) Relative increase in cooked pasta mass (RICPM), starch gelatinization degree (SGD), and cooking loss (CL) against WPR.

d) Cooked pasta hardness at 30% (F_{30}) and 90% (F_{90}) deformation; cooked pasta resilience (CPR); and cooked spaghetti diameter (d_{CP}) *versus* WPR.

Figure 2



Effect of the cooking water-to-dry pasta ratio (WPR) on the carbon footprint (CF_{PC}), and eutrophication potential (NP_{PC}) of pasta cooking as referred to the eco-sustainable cooking procedure used here.