Commercial short-cut extruded pasta:

Cooking quality and carbon footprint vs. water-to-pasta ratio

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Abstract

Pasta cooking is an energy-intensive process. Its energy requirements might be significantly cut by reducing simultaneously the cooking water-to-dry pasta ratio (WPR) and effective power supplied during the so-called pasta cooking phase. In the case of cooked short-cut extruded pasta of the *Penne rigate* type, the textural (i.e., hardness at 40 % and 98 % compression, and resilience) and chemical (i.e., relative water uptake, degree of starch gelatinisation, and cooking loss) parameters were almost constant for WPR ranging from 3 to 10 L kg⁻¹. When cooking one kg of short pasta with just 3 L of water under mild mixing the energy needs reduced by about two-thirds with respect to the conventional WPR value of 10 L kg⁻¹. In this way, it would be possible to reduce the greenhouse gases emitted to sustain the current consumption of dry pasta by about 50 %. An empirical equation was also developed to predict a minimum WPR value assuring no agglomeration of any commercial type of long or short pasta by accounting for the external surface and empty volume of each pasta piece, and most probable water uptake by cooked pasta.

Key words: Carbon footprint; cooking energy consumption; minimum and effective cooking water-to-dried pasta ratio; *Penne rigate*; cooking quality; Texture Analysis.

1. Introduction

Dry pasta is a staple food largely produced and consumed worldwide. Its overall production is of approximately 14.3 million metric tons, the 22.7% and 14.0% of which being produced in Italy and USA, respectively (UNAFPA, 2015a). The cradle-to-grave carbon footprint (CF_{CG}) of dried pasta was found to range from 1.93 to 3.03 kg carbon dioxide equivalents (CO_{2e}) per kg of dry pasta, depending on the use of a gas or electric stove, respectively (Barilla, 2017). Thus, the contribution of pasta cooking (CF_{PC}), equalling to 0.6 or 1.7 kg CO_{2e} kg^{-1} , respectively, might represent from the 31 to 56 % of CF_{CG} . Since the per capita consumption of pasta in Italy is about 23.5 kg yr^{-1} (UNAFPA, 2015b) and current Italian population is 59,245,662 (Worldometers, 2019), the greenhouse gas (GHG) emissions associated with the Italian consumption of dry pasta would range from 2.69 to 4.22 Tg CO_2 yr^{-1} . Such emissions would represent as much as the 0.7 or 1.1 % of the overall Italian GHG emissions in 2016 (e.g., circa 398 Tg CO_{2e} when including those adsorbed by land use, land use change and forestry: ISPRA, 2018). Thus, any attempt to improve the sustainability of dry pasta should be firstly aimed at cutting the GHG emissions associated with its cooking.

Dry pasta is generally cooked in boiling water, such a temperature being required to enhance convective motions within the water-pasta suspension and thus increase heat and mass transfer from the bulk to the pasta surface throughout the cooking phase (Piazza et al., 1994; Sicignano et al., 2015). Such motions, as well as pasta mixing, are essential to cook homogeneously pasta with no agglomerates and/or partly cooked areas.

The pasta cooking energy needs are not only dependent on the home appliance (i.e., gas-fired or electric stoves), but also on the cooking water-to-pasta ratio (WPR) used. The overall energy efficiency (η_c) of dried pasta cooking using gas-fired and induction hobs

was found to vary from 30 to 46 %, respectively (Cimini and Moresi, 2017). The induction hob resulted to be the most efficient cooking system and thus is regarded as an option for clean cooking in developing countries (Banerjee et al., 2016). Moreover, its usage, as coupled to an environmentally sustainable pasta cooking practice previously set up, allowed useless water evaporation to be limited and consequently pasta cooking carbon footprint to be reduced to 0.67 ± 0.04 kg CO_{2e} per kg of dry pasta (Cimini and Moresi, 2017). Greater energy saving was achieved by reducing WPR from the typical values of 10-12 L kg⁻¹ to as low as 2 L kg⁻¹, the chemico-physical quality of cooked spaghetti being not practically affected (Cimini et al., 2019). Moreover, no difference in the sensory attributes of firmness, stickiness, bulkiness, and overall cooking quality of a few commercial cooked spaghetti was also detected at WPR equal to 10 or 3 L kg⁻¹ (Cimini et al., 2018).

In principle, the minimum WPR value should vary with the pasta shape. In particular, the shapes (i.e., spaghetti with an average diameter of 2 mm) exhibiting a greater external surface-to-volume ratio than others (i.e., rigatoni or helicoidal having an outer diameter of 15-19 mm) are generally more liable to come across and adhere to each other. Obviously, the importance of such a problem is low at the high cooking water-to-dry pasta ratios generally recommended by pasta makers (i.e., 10-12 L kg⁻¹), but it enhances as WPR is reduced.

The primary aim of this work was to assess the effect of WPR in the range of 3-10 L kg⁻¹ on the chemico-physical cooking quality of three commercial durum wheat semolina dried pastas of the *Penne rigate* type (i.e., medium-length grooved tubes with ridges, cut diagonally at both ends), all being extruded through the same bronze die and dried under almost the same thermo-hygrometric conditions. The secondary aim was to

estimate the minimum WPR ratio sufficient to avoid short and long pasta strands sticking to each other and, consequently, the GHG emissions that might be avoided by adopting a more proper cooking procedure.

2. Materials and Methods

2.1. Raw materials

Three commercial brands of durum wheat semolina dried pasta of the *Penne rigate* type were kindly provided by De Matteis Agroalimentare Spa (Flumeri, AV, Italy). Their main characteristics are summarized in Table 1. These products were extruded using the same bronze die (external diameter 600 mm; thickness 140 mm; insert no. 330; hole diameter 10.1 mm) under the operating conditions listed in Table 1. Analytical grade chemicals were provided by Carlo Erba (Milan, Italy) or Sigma-Aldrich Srl (Milan, Italy).

2.2 Equipment and experimental procedure

The pasta cooking system used essentially consisted of a 3-L pan, an induction hob and a stirrer, as previously described (Cimini and Moresi, 2017; Cimini et al., 2019). All cooking tests were performed using an amount (m_{w0}) of bottled still mineral water with a fixed residue at 180 °C of about 300 mg L⁻¹, as suggested by ISO (2016).

After having filled the pan with the aforementioned water at about 20 °C and covered the pan with a lid, the induction stove was regulated at its maximum power rating (2.0 kW) to make water boil rapidly (Cimini and Moresi, 2017; Cimini et al., 2018, 2019). The amount of dried pasta (m_{PA}) added to the boiling water was calculated as reported before (Cimini et al., 2019) to supply the same effective cooking power per unit mass of

water-pasta mixture (e_{CE}). As water had newly reached the boiling point, the stove control knob was set at 0.4 kW to maintain the cooking water temperature around 98 °C. Such a pasta-cooking phase was performed with the lid closed for as long as the cooking time recommended by the pasta maker (Table 1). The electric energy supplied by the induction hob (E_s) was measured using a digital power meter type RCE MP600 (RCE Srl, Salerno, Italy). The stirrer mentioned above was kept rotating at its minimum level (i.e., 50 rev min^{-1}) for 30 s and resting for the subsequent 90, 60 or 30 s to limit pasta adhesion during cooking at WPR equal to 6, 4, or 3 L kg^{-1} , respectively.

2.3 Raw and cooked pasta analyses

The moisture, total protein ($\text{N} \times 6.25$), and ash contents of raw pasta samples were determined via ICC Standard methods No. 110/1, 105/2, and 104/1, respectively (ICC, 1995). The fat and total starch contents were assayed using the AACC method 30-20 (AACC International, 2000) and K-TSTA assay kit (Megazyme Bray, Co. Wicklow, Ireland), respectively.

A few short pasta strands were collected at different cooking times up to and beyond the set time suggested by the pasta maker, and immediately cut at right angles with a cutter to detect the presence of the central white annular portion. The time required for such a continuous white line to disappear represented the so-called optimum cooking time (ISO, 2016). Actually, when a broken white line was visible, the cooking process was regarded as completed, the resulting pasta being described as cooked “al dente”. All three commercial brands examined were cooked al dente after a cooking time of 11 min. Cooked pasta pieces were recovered from the *pasta water* by means of a colander, and

cooled by running tap water for 60 s. Excess water was then drained by shaking the colander for 10 s.

The water uptake by cooked pasta (WU) was expressed as the difference between the mass of cooked pasta (m_{CP}) and that of raw pasta (m_{PA}) divided by m_{PA} . The starch gelatinization degree (SGD) was colorimetrically measured as described by Cocci et al. (2008).

After having brought the mass of the pasta water recovered to its initial value (m_{W0}), some aliquots (~10 g) were collected under mixing, and dried to constant weight at 105 °C overnight. The ratio between the masses of residue and raw dried pasta used (m_{PA}) represented the *cooking loss* (CL), that is the amount of solid dispersed in the cooking water (D'Egidio et al., 1990).

The ICC Standard method n. 153 (ICC, 1995) was used to measure the amount of total organic matter (TOM) found in washing water after pasta cooking with a nominal water-to-dried pasta ratio of 10 L kg⁻¹.

The textural properties 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. Three pieces of cooked pasta were inserted into three stainless steel bars (see Fig. S1a in the electronic supplement), and tested using the cutting probe, shown in Fig. S1bc. Each Texture Analysis (TA) test was performed as described by Ballestrieri et al. (2015). The difference between the total displacement of the probe at the contact points with the three aligned bars and pasta samples, both revealed by a trigger force of 0.05 N, allowed the average thickness (s_{CP}) of cooked *Penne rigate* to be estimated. After setting the probe speed at 1 mm s⁻¹, a first compression cycle was carried out to submit the pasta pieces to a 40% compression with respect to s_{CP} (first bite). The probe was then lifted up

to its initial position. After a pause of 5 s, it was moved downward to submit the pasta pieces to a second 98% compression (second bite). Finally, the cutting probe was raised to reach again its initial position. The force peak on the 1st or 2nd compression cycle represented the pasta hardness at 40% (F_{40}) or 98% (F_{98}) deformation. The cooked pasta resilience (R_{CP}) was estimated as the ratio between the force-vs-time areas during the withdrawal (A_D) and compression (A_C) of the probe in the first bite. Each TA test was repeated five times. No statistically significant difference among the above TA parameters ($p=0.05$) was noticed if the time delay between cooked pasta draining and testing was no longer than 10 min.

2.4 Water and energy balances during the pasta cooking process

Differently from previous work (Cimini et al., 2018, 2019), the cooking water mass was only measured at the beginning (m_{W0}) and end of the cooking process, once cooked pasta (m_{CP}) had been strained from pasta water (m_{WF}). The water adsorbed by cooked pasta (m_{WPA}) and that evaporated (m_{WE}), as well as their relative fractions (η_{Wi}) with respect to m_{W0} , were estimated as:

$$m_{WPA} = m_{CP} - m_{PA} \quad (1)$$

and

$$m_{WE} = m_{W0} - m_{WF} - m_{WPA} \quad (2)$$

As reported by Cimini et al. (2019), the energy efficiency (η_C) of the induction hob was calculated by dividing the theoretical energy needed to cook pasta by that effectively supplied (E_s) by the induction hob.

2.5 *Carbon footprint of pasta cooking*

According to the Product Environmental Footprint category rules for dry pasta (UNAFPA, 2018), the carbon footprint of pasta cooking (CF_{PC}) is mainly dependent on the electric energy requirements to cook pasta. Thus, it was estimated by multiplying the overall electric energy consumed (E_{PC}) by its 100-year time horizon Global Warming Potential factor (GWP_{EE}):

$$CF_{PC} = E_{PC} GWP_{EE} \quad (3)$$

with

$$E_{PC} = e_{PA}/(1-\eta_{IG}) \quad (4)$$

where e_{PA} is the specific energy consumed to cook 1 kg of raw pasta, while GWP_{EE} ($=0.3213 \text{ kg CO}_{2e} \text{ kWh}^{-1}$) and η_{IG} ($\approx 5.8 \%$) were referred to the average thermo-electric production from non-renewable and renewable sources and electric energy loss of the Italian grid in 2016, as extracted from ISPRA (2018). In compliance with the PAS 2050 standard method (BSI, 2008), the production of capital goods (machinery, equipment and energy wares) was excluded from the system boundary.

2.6 *Statistical analysis of data*

Each cooking test was repeated three times. Each parameter was shown as average $\pm$ standard deviation and was analyzed by Tukey test at a probability level (p) of 0.05.

3. Results and discussion

3.1 Main short pasta characteristics

Table 1 lists the main physico-chemical characteristics and production conditions for the three commercial brands under study.

All pasta samples were dried at temperatures falling within the typical range (85-96 °C) used in the very-high-temperature pasta drying processes (Milatovich and Mondelli, 1990; Zweifel et al., 2003). They were extruded through the same bronze die, and thus exhibited almost the same internal and external diameters, and length, these being approximately equal to 5.0, 8.9, and 36 mm, respectively. Their 100-piece weight was about 150 g for samples 1 and 3, and 158 g for sample 2 (Table 1).

The raw protein content was expressed as total nitrogen x 6.25, as reported in pasta labels (EU Regulation No. 1169/2011), and was found to vary from 108 to 131 g kg⁻¹. The average moisture, raw protein, starch, fat and ash contents did not differ from those of typical durum wheat semolina dry pasta.

The amount of total organic matter (TOM) leached after thorough rinsing of drained, cooked pasta was determined as an indirect measure of the sensory attributes of stickiness and overall cooking quality (Cubadda et al., 2007, 2009). Since all TOM values shown in Table 1 were by far smaller than 14 g kg⁻¹ (ICC Standard no. 153, 1995), all samples appeared to be of good quality.

As the raw protein content increased from 108 to 131 g kg⁻¹, the time at which the central white core of a short strand of cooked pasta fully disappeared tended to increase from 11.0 to 14.5 min (Table 1). Moreover, the short strands of pasta type 3 exhibited almost the same broken central white line after about 11 min whatever the cooking water-to-dried pasta ratio used (i.e., 10, 6 or 3 L kg⁻¹), as shown in Fig. S2 in the electronic

supplement. The same optimal cooking time was assessed even for the short strands of the other pasta types examined (data not shown for the sake of simplicity). Thus, all pasta cooking tests were protracted for 11 min whatever the short pasta type and WPR used.

3.2 *Electric energy requirements*

All the energy-related parameters collected during the cooking tests are listed in the electronic supplement (Table S1).

The electric power supplied by the induction hob (E_S) was found to be a linear function of the cooking time (t), such a relationship being characterized by a coefficient of determination (r^2) greater than 0.99. The proportionality coefficient coincided with the power supplied during the water heating phase (P_H) or pasta cooking one (P_C). As shown in Fig. 1, P_H and P_C were approximately constant and equal to 1.85 ± 0.02 or 0.24 ± 0.01 kW, respectively. Moreover, the effective power supplied per unit mass of the water-pasta suspension undergoing cooking (e_{CE}) was nearly constant (149 ± 3 W kg⁻¹) independently of WPR (Table S1). Antithetically, the specific energy consumed per unit mass of raw pasta (e_{PA}) linearly increased from about 0.52 to 1.6 Wh g⁻¹ as WPR was increased from 3 to 10 L kg⁻¹. The broken line plotted in Fig. 1 represented the least squares regression:

$$e_{PA} = (0.153 \pm 0.004) \text{ WPR} \quad (r^2=0.992) \quad (5)$$

To prevent short pasta strands from sticking one another, the aforementioned stirrer was kept rotating at 50 rev min⁻¹ for 30 s and resting for different times at WPR < 10 L kg⁻¹. In all cases, the electric power supplied was of the order of 6.1 ± 0.5 W, as measured via the digital power meter. Thus, the overall mixing energy consumed throughout a cooking time of 11 min was estimated as equal to 0.28, 0.37 or 0.56 Wh for WPR = 6, 4, or 3 L kg⁻¹, respectively. The specific stirring energy consumed to cook the different

amounts of raw pasta increased from 1.2 to 1.4 Wh kg⁻¹. Thus, the energy needed to stir pasta during its cooking was insignificant with respect to that (e_{PA}) needed to cook it (Table S1).

Finally, the overall cooking energy efficiency (η_C) was about constant (67 ± 2 %) whatever the WPR used and agreed with that previously observed when cooking another type of short pasta (i.e., helicoidal) with the same eco-sustainable procedure at WPR=12 L kg⁻¹ (Cimini and Moresi, 2017).

3.3 *Cooking water use*

As WPR was reduced from 10 to 3 L kg⁻¹, the percentage of water evaporated during the cooking process (η_{WE}) tended to increase from 4.4 ± 0.1 to 6.5 ± 0.7 % of that initially added into the pot (m_{W0}), while that absorbed by cooked pasta (η_{WPA}) increase from 10.2 ± 0.1 to 33 ± 2 % (Fig. 2). Conversely, the fraction of *pasta water* (η_{WF}) reduced from 85.4 ± 0.1 to 60.2 ± 0.9 % of m_{W0} . Thus, even at WPR=3 L kg⁻¹, there was no shortage of water at the end of pasta cooking. By referring to previous work on commercial spaghetti cooking (Cimini et al., 2018), at WPR=3 L kg⁻¹ the fraction of water absorbed by cooked spaghetti amounted to 41 ± 4 % of m_{W0} , probably because spaghetti exhibited a higher surface-to-volume ratio than the short pastas used here.

3.4 *Cooked pasta quality*

As concerning cooked pasta quality, Table S1 shows the mean values and standard deviations of all parameters determined. As shown in Fig. 3, the relative water uptake (WU), degree of starch gelatinisation (SGD), and cooking loss (CL) as referred to cooked

pasta appeared to be independent of WPR and pasta type, being equal to $1.03 \pm 0.01 \text{ g g}^{-1}$, $8.2 \pm 0.7 \%$, and $3.5 \pm 0.4 \text{ g kg}^{-1}$, respectively.

3.5 Textural properties of cooked pasta

Table S2 shows the main results of the TA tests. Within the range of WPR values examined, all TA parameters, as well as the thickness (s_{CP}) of cooked pasta, exhibited a statistically insignificant variation at the probability level of 0.05 (Table S2). However, the cooked pasta hardness at 40 % (F_{40}) and 98 % (F_{98}) compression resulted to increase almost linearly with the protein content of raw pasta (x_{PR}), as shown by the broken lines plotted in Fig. 4:

$$F_{40} = (-1.5 \pm 0.9) + (0.040 \pm 0.075) x_{PR} \quad (r^2 = 0.76) \quad (6)$$

$$F_{98} = (-8.1 \pm 0.9) + (0.151 \pm 0.019) x_{PR} \quad (r^2 = 0.86) \quad (7)$$

This paralleled the relationship between the protein content of raw pasta and cooked pasta firmness, previously established by Cubadda et al. (2007), as well as that relating the sensory attributes of Firmness, Stickiness, Bulkiness, and Overall Cooking Quality of cooked pasta to x_{PR} (Cimini et al., 2018).

On the contrary, as shown by the continuous lines plotted in Fig. 4, the cooked pasta resilience (R_{CP}) and thickness (s_{CP}) appeared to be independent of x_{PR} , and equal to 0.55 ± 0.02 and $2.14 \pm 0.09 \text{ mm}$, respectively.

3.6 Carbon footprint of pasta cooking

Since the carbon footprint of pasta cooking (CF_{PC}) is a linear function of e_{PA} and, in turn, e_{PA} relies on WPR only, as shown by Eq.s (3)-(5), CF_{PC} was easily predicted as

$$CF_{PC} = (0.052 \pm 0.001) WPR \quad (8)$$

By resorting to the eco-sustainable cooking procedure used here, it was possible to reduce CF_{PC} from 0.49 ± 0.04 to 0.18 ± 0.01 kg CO_2e kg^{-1} of raw pasta as WPR was lowered from 10 to 3 L kg^{-1} , respectively. The estimated CF_{PC} scores were definitively smaller than those associated to home pasta cooking using a conventional gas- or electric-fired stove (UNAFPA, 2018). More specifically, for $WPR=3$ L kg^{-1} the cradle-to grave carbon footprint of raw pasta might be practically halved from 3.03 (Barilla, 2017) to 1.51 kg CO_2e kg^{-1} and the overall GHG emissions associated with the current Italian consumption of dry pasta ($\sim 1.4 \times 10^6$ Mg/year) might be cut by as much as 2.1 Tg CO_2e yr^{-1} , thus approximately halving the climate change potential of dried pasta.

3.7 Empirical prediction of the minimum WPR

Theoretically, the minimum volume of water (V_w) to pour into a pan to cook as homogeneously as possible a given type of long or short pasta should at least fill all the internal cavities (if present) of each pasta strand;
 assure the water uptake (WU) by cooked pasta:

$$V_w = n_p V_c + m_{PA} WU / \rho_w \quad (9)$$

with

$$m_{PA} = n_p m_p \quad (10)$$

where, n_p is the overall number of pasta pieces present in a given amount of raw pasta (m_{PA}), m_p the mass of a single pasta piece, V_c the overall volume of all internal cavities, and ρ_w the density of water. Thus, the minimum cooking water-to-dry pasta ratio (WPR_{min}) might be estimated as:

$$WPR_{min} = V_w / m_{PA} = \frac{V_c}{m_p} + \frac{WU}{\rho_w} \quad (11)$$

By referring to the internal diameter (d_i) and length (L_p) of each pasta piece of the three brands used here (Table 1), as well as the average specific water uptake (WU) (see Table S1), the estimated WPR_{min} ranged from 1.45 to 1.49 L kg⁻¹. By applying Eq. (11) to the commercial spaghetti previously used, their diameter and WU varying in the ranges of 1.9-2.0 mm, and 1.25-2.96 g g⁻¹, respectively (Cimini et al., 2018, 2019), WPR_{min} fluctuated from 1.3 to 3.0 L kg⁻¹.

In the circumstances, such a theoretical minimum amount of cooking water might be insufficient to wet the external surface of all pasta pieces and, thus, to avoid pasta sticking during cooking. To assure a good distribution of heat and water over the pasta surface, it was assumed to cover the external surface (S_p) of each pasta piece with a suitable layer (S_F) of water. Therefore, the above minimum water volume should be equal to:

$$V_W = n_p S_p S_F + n_p V_c + m_{PA} WU / \rho_W \quad (12)$$

Thus, the effective minimum cooking water-to-dry pasta ratio (WPR^*) should become

$$WPR^* = \frac{S_p S_F}{m_p} + \frac{V_c}{m_p} + \frac{WU}{\rho_W} \quad (13)$$

Table 2 shows a schematic diagram of the cross section of the pasta type examined in this work, as well as the relationships needed to estimate all the above geometric parameters. By accounting for the geometric characteristics of the three commercial short pastas used (Table 1), each pasta piece would have been uniformly covered with 1.52- or 1.58-mm thick layer of water if one kg of raw pasta was cooked with just 3 L of cooking water. In the case of raw spaghetti 1.94 mm in diameter with $WU=1.3\pm0.1$ g g⁻¹, as those

previously used (Cimini et al., 2019), s_F would reduce to 1.15 or 0.47 mm if WPR was equal to 3 or 2 L kg⁻¹, respectively.

Whatever the raw short or long pasta type chosen of known geometric characteristics, Eq. (13) might, as a rule of thumb, be used to predict the minimum WPR value by assuming that a layer of water 1.5 mm in thickness was sufficient to avoid pasta adhesion during cooking in the presence of a proper agitation degree.

4. Conclusions

Pasta cooking is an energy-intensive process. Its energy requirements might be significantly reduced by lowering concurrently the cooking water-to-dry pasta ratio (WPR) and effective power supplied during the so-called pasta cooking phase. In the case of shot-cut extruded pasta of the *Penne rigate* type, the instrumental and chemical quality parameters of cooked pasta were almost constant when WPR was varied from 3 to 10 L kg⁻¹. Obviously, the higher the protein content of raw pasta the higher the hardness of cooked pasta at the first (F₄₀) and second (F₉₈) bites became.

Owing to the great number of commercial pasta types available, it was established an empirical equation to predict which WPR value is needed to avoid pasta adhesion during cooking by resorting to the external surface and empty volume of each pasta piece, and most probable water uptake by cooked pasta.

In the circumstances, it was possible to cook one kg of short pasta with just 3 L of water under mild mixing with a minimum energy need of 0.54±0.02 Wh g⁻¹, this cutting the GHGs emitted to sustain the current consumption of dry pasta by about 50 %.

Further work is thus required to develop a specialized appliance to cook pasta.

369 **Nomenclature**

370	A_C	Downstroke energy to compress the pasta pieces by 40% of their initial
371		thickness [J]
372	A_D	Upstroke energy to decompress the 40%-compressed cooked pasta pieces [J]
373	b_R	Rib base [mm]
374	CF_{CG}	Cradle-to-grave carbon footprint of dry pasta [$\text{kg CO}_2\text{e kg}^{-1}$]
375	CF_{PC}	Carbon footprint of pasta cooking [$\text{kg CO}_2\text{e kg}^{-1}$]
376	CL	Cooking loss [g kg^{-1}]
377	d_i	Internal diameter of each pasta piece [mm]
378	d_{Rb}	Tube diameter at the base of each rib [mm]
379	d_{Ru}	External diameter of each pasta piece [mm]
380	E_{PC}	Effective energy consumed to cook pasta, as defined by Eq. (4) [kWh]
381	E_S	Energy effectively consumed to cook pasta [kJ]
382	e_{CE}	Effective power supplied per unit mass of the water-pasta mixture undergoing
383		cooking [W kg^{-1}]
384	e_{PA}	Specific energy consumed per unit mass of dry pasta [Wh g^{-1}]
385	F_{40}	Cooked pasta hardness at 40% compression (first bite) [N]
386	F_{98}	Cooked pasta hardness at 98% compression (second bite) [N]
387	GHG	Greenhouse gas
388	GWP_{EE}	Emission factor referred to the average Italian thermo-electric production
389		from non-renewable and renewable sources [$\text{kg CO}_2\text{e kWh}^{-1}$]
390	h_R	Rib height [mm]
391	i_R	Rib hypotenuse [mm]
392	L_p	Length of each pasta piece [mm]

393	m_{CP}	Mass of cooked pasta [kg]
394	m_{PA}	Mass of dried pasta [kg]
395	m_p	Mass of each pasta piece [kg]
396	m_{WE}	Mass of water evaporated, as defined by Eq. (2) [kg]
397	m_{WF}	Mass of pasta water [kg]
398	m_{WPA}	Mass of water adsorbed by dry pasta, as defined by Eq. (1) [kg]
399	m_{W0}	Initial mass of cooking water [kg]
400	n_p	Overall number of pasta pieces in a given amount of raw pasta
401		[dimensionless]
402	n_R	Number of ribs per each pasta piece [dimensionless]
403	P_C	Effective power supplied during pasta cooking [kW]
404	P_H	Power supplied during water heating [kW]
405	p	Probability level
406	R_{CP}	Cooked pasta resilience ($=A_D/A_C$) [dimensionless]
407	r^2	coefficient of determination
408	SGD	Degree of starch gelatinisation [%]
409	S_p	External surface of each pasta piece [dm ²]
410	s_{CP}	Cooked pasta thickness [mm]
411	s_F	Water layer thickness [dm]
412	TA	Texture analysis
413	TOM	Total organic matter [g kg ⁻¹]
414	t	Cooking time [s]
415	t_{Ru}	Above rib thickness [mm]
416	t_{Rb}	Below rib thickness [mm]

417	V_c	Overall volume of all the internal cavities of each pasta piece [L]
418	V_W	Minimum volume of water needed to cook homogeneously cooked pasta [L]
419	WPR	Water-to-dried pasta ratio [L kg ⁻¹]
420	WPR_{min}	Minimum cooking water-to-pasta ratio, as defined by Eq. (11) [L kg ⁻¹]
421	WPR^*	Effective minimum cooking water-to-pasta ratio, as defined by Eq. (13) [L
422		kg ⁻¹]
423	WU	Relative increase in cooked pasta mass [g g ⁻¹]
424	x_{PR}	Raw protein content [g kg ⁻¹]

425

426 ***Greek Symbols***

427	η_C	Energy efficiency of the cooking system [dimensionless]
428	η_{IG}	Electric energy loss of the Italian grid [dimensionless]
429	η_{WE}	Fraction of water evaporated ($=m_{WE}/m_{W0}$) [dimensionless]
430	η_{WPA}	Fraction of water adsorbed by cooked pasta ($=m_{WPA}/m_{W0}$) [dimensionless]
431	η_{WF}	Fraction of pasta water ($=m_{WF}/m_{W0}$) [dimensionless]
432	ρ_W	Water density [kg L ⁻¹]

433

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438

439 **Declarations of interest**

440 None

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508 **TABLES AND TABLE HEADINGS**

509

510 **Table 1** Main production conditions, characteristics and chemical composition of the
511 three commercial *penne rigate* brands used in this work.

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514 **Table 2** Schematic scheme of the cross section of a pasta piece of the *penne rigate*
515 type and its main geometric characteristics to be directly measured or
516 calculated.

517

Table 1

Main production conditions, characteristics and chemical composition of the three commercial *penne rigate* brands used in this work.

	Donna Vera	Borges	Baronia
Pasta Brand	A	B	C
<i>Pasta Production Conditions</i>			
Production Lot	L7265H	L7287H	L7282L
Kneading water fraction [%]	32	28	28
Extrusion flow rate [Mg h ⁻¹]	5.56	6.05	6.05
Temperature at the pasta shaker [° C]	100	92	92
Pre-drying temperature [° C]	87	87	87
Pre-drying relative humidity variation [%]	16	17.5	17.5
Drying temperature [° C]	86	89	89
Drying relative humidity variation [%]	8.5	8.3	8.3
<i>Main Characteristics</i>			
Penne length, L _p [mm]	36±2	36±2	34±2
Penne internal diameter, d _i [mm]	5.08±0.07	5.07±0.08	5.02±0.06
Penne external diameter, d _{Ru} [mm]	8.88±0.04	8.94±0.05	8.93±0.06
Above rib thickness, t _{Ru} [mm]	1.90±0.04	1.94±0.05	1.96±0.04
Below rib thickness, t _{Rb} [mm]	1.50±0.14	1.42±0.18	1.43±0.20
100-piece weight [g]	150±8	158±13	149±9
Cooking time suggested by pasta maker [min]	10-12	10-12	10-12
White core disappearance time [min]	11.00	11.50	14.50
Total organic matter, TOM [g kg ⁻¹]	6.9 ± 0.8	6.5 ± 0.5	6.2 ± 0.5
<i>Chemical Composition [g kg⁻¹]</i>			
Moisture	124 ± 0.4	114 ± 0.4	116 ± 2
Raw protein (Nx6.25)	108 ± 2	119.0 ± 0.1	131 ± 1
Starch	621 ± 6	682 ± 7	639 ± 2
Fat	21 ± 4	13.0 ± 0.3	17.0 ± 0.9
Ash	5.2 ± 0.4	5.1 ± 0.4	5.3 ± 0.2

Table 2
Schematic scheme of the cross section of a pasta piece of the *penne rigate* type and its main geometric characteristics to be directly measured or calculated.

Cross section scheme
Rib height	$h_R = t_{Ru} - t_{Rb} = d_{Ru} - d_{Rb}$
Number of ribs per piece	$n_R = \left\lfloor \frac{\pi d_{Rb}}{h_R} \right\rfloor$
Rib base	$b_R = \frac{\pi d_{Rb}}{n_R}$
Rib hypotenuse	$i_R = \sqrt{\left(\frac{b_R}{2}\right)^2 + h_R^2}$
External surface of each piece	$S_p = 2 n_R i_R L_p + 2 \left[\frac{\pi}{4} (d_{Rb}^2 - d_i^2) + n_R \frac{b_R h_R}{2} \right]$
Volume of cylinder cavity	$V_c = \frac{\pi}{4} d_i^2 L_p$

FIGURES AND FIGURE HEADINGS

Figure 1 Cooking tests using the induction hob set at different power levels during the cooking water heating (P_H : yellow-filled symbols) and pasta cooking (P_C : red-filled symbols) phases using three short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Specific energy consumed to cook dry pasta (e_{PA} : open symbols) and cooking energy efficiency (η_C : closed symbols) *versus* the cooking water-to-pasta ratio (WPR). The inclined broken line was plotted using Eq. (5), while the horizontal broken ones represent the average values of P_C and P_H , respectively.

Figure 2 Cooking tests carried out with three short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Percentages of water evaporated (η_{WE} : red-filled symbols), adsorbed by cooked pasta (η_{WPA} : open symbols), and recovered as pasta water (η_{WF} : closed symbols) *vs.* WPR.

Figure 3 Cooking tests carried out with three short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Relative water uptake (WU: red-filled symbols), cooking loss (CL: open symbols), and degree of starch gelatinization (SGD: closed symbols) *vs.* WPR. The continuous lines refer to the mean values of WU, CL, and SGD, while the broken ones to the ± 5 or 10% deviation bands.

Figure 4 Texture Analysis tests carried out with three cooked short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Cooked pasta hardness at 40 % (F_{40} : closed symbols) and 98 % (F_{98} : open symbols) compression, resilience ($R_{CP} \times 10$: yellow-filled symbols), and thickness (s_{CP} : red-filled symbols) vs. protein content of raw pasta (x_{PR}). The broken lines were plotted using Eq. (6) and (7), while the continuous ones show the mean values of R_{CP} , and s_{CP} .

566 **Figure 1**

567
568
569 Cooking tests using the induction hob set at different power levels during the cooking
570 water heating (P_H : yellow-filled symbols) and pasta cooking (P_C : red-filled symbols)
571 phases with three short pasta brands labelled A (open or closed squares), B (open or
572 closed triangles), and C (open or closed circles): Specific energy consumed to cook dry
573 pasta (e_{PA} : open symbols) and cooking energy efficiency (η_C : closed symbols) *versus* the
574 cooking water-to-dried pasta ratio (WPR). The inclined broken line was plotted using Eq.
575 (5), while the horizontal broken ones represent the average values of P_C and P_H ,
576 respectively.

Figure 2

Cooking tests carried out with three short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Percentages of water evaporated (η_{WE} : red-filled symbols), adsorbed by cooked pasta (η_{WPA} : open symbols), and recovered as pasta water (η_{WF} : closed symbols) vs. WPR.

Figure 3

Cooking tests carried out with three short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Relative water uptake (WU: red-filled symbols), cooking loss (CL: open symbols), and degree of starch gelatinization (SGD: closed symbols) vs. WPR. The continuous lines refer to the mean values of WU, CL, and SGD, while the broken ones to the ± 5 or 10% deviation bands.

Figure 4

Texture Analysis tests carried out with three cooked short pasta brands labelled A (open or closed squares), B (open or closed triangles), and C (open or closed circles): Cooked pasta hardness at 40 % (F_{40} : closed symbols) and 98 % (F_{98} : open symbols) compression, resilience ($R_{CP} \times 10$: yellow-filled symbols), and thickness (s_{CP} : red-filled symbols) vs. protein content of raw pasta (x_{PR}). The broken lines were plotted using Eq. (6) and (7), while the continuous ones show the mean values of R_{CP} , and s_{CP} .

Appendix A. Supplementary data

Table S1

Pasta cooking tests carried out with the induction hob set at the high or low power rating during water heating (P_H) or pasta cooking (P_C), respectively, and different amounts of three commercial short pasta brands (m_{PA}), labelled A, B, or C, and cooking water (m_{W0}): effect of the water-to-dried pasta ratio (WPR) on the mean value and standard deviation of the overall energy supplied (E_S), cooking energy efficiency (η_C); effective power supplied per unit mass of cooking water and dried pasta (e_{CE}); energy consumed per unit mass of dried pasta (e_{PA}); percentage fractions of water evaporated (η_{WE}), absorbed by cooked pasta (η_{WPA}), and remaining after cooking (η_{WF}); relative water uptake (WU); cooking loss (CL); and starch gelatinization degree (SGD). All cooking tests were triplicated.

Pasta label	WPR	m_{W0}	m_{PA}	P_H	P_C	E_S	η_C	e_{CE}	e_{PA}	η_{WE}	η_{WPA}	η_{WF}	WU	CL	SGD
-	[L kg ⁻¹]	[g]	[g]	[kW]	[kW]	[Wh]	[%]	[W kg ⁻¹]	[Wh g ⁻¹]	[%]	[%]	[%]	[g g ⁻¹]	[g kg ⁻¹]	[%]
A	3.00 ±0.01	1218.5 ±0.2	406.4 ±0.7	1.85 ±0.02 ^a	0.25 ±0.01 ^a	211 ±16	62 ±5 ^a	152 ±8 ^a	0.52 ±0.04 ^a	6.2 ±0.9 ^a	34.5 ±0.4 ^a	59.3 ±0.8 ^a	1.03 ±0.01 ^a	39 ±1 ^a	8.3 ±0.4 ^a
	4.00 ±0.01	1299.7 ±0.1	324.1 ±0.1	1.86 ±0.01 ^a	0.23 ±0.01 ^a	207 ±3	64 ±3 ^a	143 ±1 ^a	0.64 ±0.01 ^b	5.5 ±0.3 ^b	25.6 ±0.1 ^b	69.0 ±0.2 ^b	1.03 ±0.01 ^a	38.7 ±0.9 ^a	9.2 ±2.1 ^a
	5.99 ±0.01	1393.3 ±0.1	232.8 ±0.4	1.85 ±0.02 ^a	0.25 ±0.01 ^a	229 ±1	68 ±2 ^b	151 ±2 ^a	0.99 ±0.01 ^c	4.6 ±0.5 ^c	17.5 ±0.2 ^c	77.9 ±0.4 ^c	1.05 ±0.01 ^a	40.5 ±0.4 ^a	8.3 ±0.1 ^a
	10.02 ±0.04	1477.2 ±0.2	147.4 ±0.5	1.85 ±0.01 ^a	0.25 ±0.01 ^a	231 ±11	67 ±2 ^b	151 ±2 ^a	1.57 ±0.07 ^d	4.4 ±0.3 ^c	10.5 ±0.1 ^d	85.1 ±0.1 ^d	1.05 ±0.01 ^a	40.9 ±0.4 ^a	7.3 ±0.2 ^b
B	3.0 ±0.0	1218.5 ±0.3	406.1 ±0.2	1.88 ±0.02 ^b	0.24 ±0.01 ^a	226 ±4	66 ±2 ^a	150 ±1 ^a	0.56 ±0.01 ^a	6.0 ±0.8 ^a	33.8 ±0.7 ^a	60.2 ±0.6 ^a	1.01 ±0.02 ^a	33.8 ±0.6 ^a	7.7 ±0.4 ^a
	4.00 ±0.01	1299.3 ±0.2	324.6 ±0.1	1.86 ±0.02 ^a	0.23 ±0.01 ^a	206 ±2	67 ±1 ^a	144 ±1 ^a	0.63 ±0.01 ^b	5.6 ±0.6 ^a	24.7 ±0.2 ^b	69.7 ±0.3 ^b	0.99 ±0.01 ^a	35.8 ±0.4 ^b	7.8 ±0.7 ^a
	5.99 ±0.01	1391.9 ±0.8 ^b	232.5 ±0.2 ^b	1.85 ±0.01 ^a	0.25 ±0.01 ^a	230 ±1	67 ±1 ^a	152 ±2 ^a	0.99 ±0.01 ^c	4.8 ±0.5 ^b	17.0 ±0.1 ^c	78.2 ±0.2 ^c	1.02 ±0.01 ^a	36.2 ±0.5 ^b	7.9 ±0.1 ^a
	9.97 ±0.02	1477.1 ±0.1	148.2 ±0.3 ^a	1.82 ±0.11 ^a	0.24 ±0.01 ^a	204 ±28	68 ±1 ^b	151 ±2 ^a	1.37 ±0.19 ^d	4.3 ±0.03 ^b	10.3 ±0.1 ^d	85.4 ±0.4 ^d	1.02 ±0.01 ^a	37.0 ±1 ^b	7.6 ±0.4 ^a
C	3.0	1218.6	405.9	1.85	0.24	224	65	147	0.55	7.3	32	61	0.95	27	8.9

	±0.0	±0.4	±0.6	±0.01 ^{a,b}	±0.01 ^a	±3	±1 ^a	±5 ^a	±0.01 ^a	±2.5 ^a	±2 ^a	±1 ^a	±0.05 ^a	±2 ^a	±0.5 ^a
	4.00 ±0.01	1299.7 ±0.3	324.5 ±0.7	1.85 ±0.02 ^a	0.24 ±0.01 ^a	208 ±1	65 ±2 ^a	144 ±1 ^a	0.64 ±0.01 ^b	5.3 ±1.1 ^b	24.5 ±0.4 ^b	70.1 ±0.2 ^b	0.98 ±0.02 ^a	33 ±1 ^b	9.3 ±1 ^b
	6.00 ±0.01	1392.9 ±0.2	232.3 ±0.1	1.85 ±0.03 ^a	0.25 ±0.01 ^a	232 ±4	69 ±1 ^b	151 ±1 ^a	1.00 ±0.02 ^c	4.7 ±0.5 ^b	16.4 ±0.1 ^c	78.8 ±0.5 ^c	0.99 ±0.01 ^a	33.4 ±0.8 ^b	7.4 ±0.5 ^b
	10.0 ±0.1	1477.1 ±0.1	147.7 ±0.7	1.85 ±0.01 ^a	0.24 ±0.01 ^a	233 ±6	69 ±1 ^b	148 ±5 ^a	1.58 ±0.05 ^d	4.6 ±0.9 ^b	10.0 ±0.1 ^d	85.4 ±1.0 ^d	1.01 ±0.01 ^a	30.9 ±0.9 ^b	8.3 ±0.5 ^a

11

12 - Different lowercase Latin letters indicate statistically significant difference among the parameter means of the short pasta brands cooked at different WPRs at the
13 probability level of 0.05.

Table S2

Effect of water-to-dried pasta ratio (WPR) on the mean values and standard deviations of the main TA parameters (F_{40} , F_{98} , R_{CP} , s_{CP}) of three cooked commercial short pasta brands labelled A, B, or C. Each TA test was repeated n times.

Pasta label	WPR	n	F_{40}	F_{98}	R_{CP}	s_{CP}
	[L/kg]		[N]	[N]	[-]	[mm]
A	3	15	2.8±0.2 ^a	7.9±0.6 ^a	0.57±0.02 ^a	2.08±0.06 ^a
	4	15	2.9±0.2 ^a	7.9±0.6 ^a	0.56±0.03 ^a	2.16±0.02 ^b
	6	15	2.9±0.2 ^a	8.8±0.4 ^b	0.58±0.03 ^{a,b}	2.09±0.05 ^a
	10	15	2.8±0.2 ^a	7.8±0.4 ^a	0.59±0.02 ^b	2.06±0.05 ^a
B	3	15	3.4±0.5 ^a	10.2±0.9 ^a	0.54±0.03 ^a	2.12±0.08 ^a
	4	15	3.0±0.8 ^a	9.2±0.7 ^b	0.56±0.04 ^a	2.29±0.05 ^b
	6	15	3.6±0.2 ^a	11.1±0.6 ^c	0.55±0.02 ^a	2.15±0.05 ^a
	10	15	2.8±0.6 ^{a,b}	8.9±1.6 ^b	0.56±0.04 ^a	2.14±0.04 ^b
C	3	15	4.0±0.3 ^a	12±1 ^a	0.51±0.02 ^a	2.12±0.03 ^a
	4	13	3.7±0.2 ^b	11.3±1.3 ^a	0.53±0.03 ^a	2.32±0.04 ^b
	6	14	3.5±0.4 ^b	11.7±0.7 ^a	0.55±0.03 ^b	2.00±0.24 ^a
	10	28	3.8±0.5 ^{a,b}	11.3±1.4 ^a	0.51±0.03 ^a	2.19±0.06 ^c

- Different lowercase Latin letters indicate statistically significant difference among the parameter means of the same pasta label cooked at different WPRs at the probability level of 0.05.

Figure S1

a)

b)

b)

c)

Picture (a) of the Texture Analysis system used to measure the instrumental quality of three short strands of cooked pasta with details of the three stainless steel bars (b) and front (b) and side (c) views of the cutting probe used. All dimensions are in mm.

Figure S2

Pictures of a short strand of pasta type 3 as cooked using 1 kg of dried pasta in 10, 6 or 3 L of water for as long as 8, 9, 10, 11, 12 and 13 min, removed from the pan, cooled and cut at right angles with the cutter according to ISO (2016).