**Cooking quality of commercial spaghetti: Effect of the water-
to-dried pasta ratio**

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Abstract

The consumption of two vital resources (e.g., water and energy) during home pasta cooking has so far received limited attention. The main focus of this work was to assess how the instrumental and sensory quality of cooked pasta is affected by the water-to-dried pasta ratio (WPR) using a model cooking system with three commercial brands of spaghetti. At WPR equal to 10 or 3 L/kg, the three sensory attributes of firmness, stickiness, and bulkiness, as well as the overall cooking quality, displayed no statistically significant sensitivity towards WPR. Cooked pasta water uptake, diameter, hardness at 90% deformation, and resilience were mainly influenced by the raw protein content of dried pasta than by WPR, while the cooking loss was regarded as approximately constant. By using the model cooking system that assured mild mixing of spaghetti to avoid their sticking during cooking, it would be possible to use 70% less cooking water and consume about 65% less electricity, the latter cutting significantly the climate change potential of home pasta cooking.

Key words: Cooking energy consumption; cooking water-to-dried pasta ratio; model cooking system; spaghetti cooking quality; sensory and texture analyses.

Introduction

The life cycle energy of most common foods is greatly conditioned by that necessary for their cooking [1-3]. By referring to one of the most popular Italian food, that is dried pasta, the overall life cycle energy consumption resulted to be equal to 17.1 or 22.9 MJ per kg of dried pasta on condition that four portions or just a single one were prepared using an electric cooker [1]. Even by resorting to the so-called eco-sustainable cooking practice in conjunction with an induction hob, the specific energy consumption was not less than 6.9 ± 0.4 MJ/kg [4]. Such a significant energy consumption is largely due to the numerous litres of water needed to cook dry pasta, these having to be not only heated up to the boiling temperature, but also partly evaporated during pasta cooking. Despite the great majority of pasta makers recommend using 10 litres of water per kg of dried pasta [5-7], such a water-to-dried pasta ratio (WPR) seems to be excessive. In fact, a smaller WPR of the order of 7 [5], 3.1-4.2 [8], or as little as 2 [9] L/kg was suggested. Such a problem has even arisen the attention of media and networking [10] with no scientific approach.

Once pasta has been added to boiling water, its enthalpy allows the pasta to be heated to a suitable temperature for being cooked. When both water and pasta temperatures have reached an equilibrium, the cooking process takes place [11]. Starch gelatinization and protein coagulation are the main reactions involved [12]. However, the structural transformations of pasta are influenced by all the changes occurred throughout the pasta making process, and especially by the more or less degree of protein aggregation resulting from the drying step at high or low temperatures, respectively [13]. As proteins coagulate and interact, a more or less continuous network forms. When it is insufficiently strong and elastic, starch granules undergoing swelling and gelatinization not only fill all

free interspaces, but also let the amylose-rich fragments leach in cooking water, while the amylopectin-rich ones move to the pasta surface and thus reduce pasta-cooking quality. When the protein network succeeds in entrapping the starch granules, which hydrates slowly, the resulting cooked pasta is firm with no stickiness and clumpiness [14]. Both these reactions are controlled by water uptake and occur in quite the same range of temperature and moisture conditions, even if proteins react faster and at slightly lower moisture levels than starch granules [15, 16]. As pasta cooking proceeds, water diffuses toward its central area, and acts as a plasticizer, thus increasing the mobility of protein and starch molecules. The lower the internal moisture content of pasta the greater the competition for water among such macromolecules becomes, this yielding quite an irregular distribution of water in the inner areas [13]. Generally, the structure of cooked spaghetti, as observed by scanning electron microscopy, can be subdivided into three different concentric regions. In the external one, starch granules are so broadly deformed and swollen to be indistinguishable from proteins. In the intermediate region, partly swollen granules appear to be embedded in a dense protein network, while in the central one starch granules exhibit a small swelling and a limited degree of gelatinization because of restricted water availability [16]. By accounting for just two cooked and uncooked regions, starch gelatinisation was assumed to occur only at their interface [12]. As cooking progressed, water concentration resulted to vary radially in the cooked region only, while it was approximately constant in the uncooked one. In the circumstances, whatever the WPR used, at the spaghetti surface the water concentration will approach its equilibrium value, while the concentration gradient will control the rehydration kinetics of pasta. As WPR was reduced by about 73% (i.e., from 30.8 to 8.3 L/kg), a

85 limited reduction of 5, 10, or 15 % in the cooked pasta mass, firmness, or cooking loss
86 was respectively observed [17].

87 By referring to a standard pasta format (i.e., Barilla Spaghetti No. 5) as cooked
88 using the so-called minimum energy consumption cooking method [4], the instrumental
89 quality of cooked spaghetti was found to be practically independent of WPR in the range
90 of 12 to 2 L/kg, while the specific electric energy consumption linearly decreased from
91 1.93 to 0.39 Wh g⁻¹, and carbon footprint and eutrophication potential of pasta cooking
92 lessened by about 80% and 50%, respectively [18].

93 The main aim of this work was to check for the effect of a high (10 L/kg) or low (3
94 L/kg) WPR on the main chemico-physical and sensory characteristics of three
95 commercial spaghetti made of higher or lower quality durum wheat semolina using the
96 aforementioned model cooking system, as a preliminary step to develop novel less-energy
97 and -water consuming pasta cookers.

Materials and Methods

Raw materials

Three commercial brands of durum wheat semolina dried spaghetti were used, their main characteristics being summarized in Table 1. All chemicals and solvents used were of analytical grade and purchased from Carlo Erba (Milan, Italy) and from Sigma-Aldrich Srl (Milan, Italy).

Equipment and experimental procedure

The pasta cooking system used was previously described [4, 18]. It essentially consisted of a 3-L pan, a 2-kW 190-mm induction-plate stove, a digital scale with a load range of 0.6 g to 10 kg, a non-magnetic stainless steel S-shaped impeller mixer EURO-ST P CV (IKA®-Werke GMBH, Staufen, D), a piezo-buzzer, and a custom-made data logger based on an Arduino Nano 3.0 (ATmega328) board. Its picture is shown in the electronic supplement (Fig. S1). The pan lid was drilled twice to insert the above mixer, and a temperature sensor type DS18B20 to measure the cooking water temperature (T_{WM}) near the pan axis at mid-height of the water level used in each cooking test.

As the pan was filled with a given amount (m_{W0}) of cooking water at (20 ± 1) °C and closed with its lid, the induction hob was set at its maximum nominal power setting (2.0 kW) to bring rapidly the cooking water to the boiling point [4]. Then, a given amount of dried pasta (m_{PA}) was added to the boiling water. As the latter had restarted to boil, the hob control knob was adjusted to 0.4 kW to keep the cooking temperature around 98 °C and the lid closed [18]. In agreement with previous work [4, 18], all cooking tests were carried out by supplying a nominal power of about 0.246 W per g of the overall pasta-water mixture, this condition making the amounts of dried pasta (m_{PA}) and cooking water

(mw₀) to be related to WPR as reported in the electronic supplement (Table S1). The effective electricity consumption, expressed in kWh, was monitored via a digital power meter type RCE MP600 (RCE Srl, Salerno, Italy). To avoid spaghetti sticking together during cooking at WPR=3 L/kg, the aforementioned stirrer was kept rotating at 50 rev/min for 30 s and resting for the subsequent 30 s [18].

Dried pasta analyses

Spaghetti samples were milled using a refrigerated laboratory mill model IKA A10 (IKA-WERKE GmbH and CO KG, Staufen, Germany). Their chemical composition was assayed by the standard *International Association for Cereal Science and Technology* (ICC) procedures [19], namely moisture (ICC Standard method No. 110/1), total protein (ICC Standard method No.105/2), and ash (ICC Standard method No. 104/1). In particular, the raw protein content was calculated as total Kjeldahl nitrogen $\times$ 6.25 [20]. Fat was determined according to AACC method 30-20 [21]. Total starch was analysed by K-TSTA assay kit by Megazyme (Megazyme Bray, Co. Wicklow, Ireland).

Cooked spaghetti analyses

Each spaghetti sample was weighed, broken in half, and cooked in boiling deionized water [22-25]. The effects of cooking water pH and hardness on stickiness and cooking loss of spaghetti were deeply assessed [24, 26-27]. In particular, quite small differences in the above parameters were observed when considering deionized or tap water, especially for pasta samples made of durum wheat semolina [27].

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. After excess water had been removed by shaking the colander for 10 s, the samples were immediately used for the following analyses.

The AACC Method 66-50.01 [21] was used to monitor the central white core of spaghetti, cooked with different WPRs for as long as the aforementioned set time of 9 min, and up to the disappearance of the central white core, when a spaghetti strand was gently squeezed between two glass plates.

The amount of total organic matter (TOM) found in washing water after spaghetti cooking with a nominal WPR of 10 L/kg was determined following the ICC Standard method n. 153 [19].

Cooking loss (CL) was assessed by determining the amount of solid dispersed in the cooking water used [28]. After a cooking time of 9 min, cooked pasta was promptly drained with a colander. The resulting pasta water was transferred to a graduated cylinder, the empty pot accurately washed with deionized water to recover all adhering materials and finally the pasta water mass was levelled back to its initial mass (m_{w0}). Under very vigorous stirring, a few aliquots (~10 g) were collected and dried at 105 °C overnight. The residue was weighed, and the dry matter content of pasta water was referred to the initial mass of dried pasta used (m_{PA}). The increase in pasta mass was gravimetrically assessed as the difference between the masses of cooked pasta (m_{CPA}) and dried pasta (m_{PA}) and referred to the mass of raw pasta to yield the relative increase in cooked pasta mass (RICPM).

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, in compliance with the Barilla standard TA test, as detailed previously [18]. By placing 17 strands of cooked spaghetti over a stainless steel compression platen

and tested using a stainless steel cutting probe (see Fig. S2 in the electronic supplement), it was possible to determine the average cooked spaghetti diameter (d_{CP}), cooked pasta hardness on the first and second compression cycle at 30% (F_{30}) and 90% deformation (F_{90}), and its resilience (CPR), the latter being defined as the force-vs-time area during the 1st withdrawal of the compression divided by the force-vs-time area of the 1st compression. Each TA test was repeated five times.

Finally, A panel of six trained judges evaluated the sensory properties of the cooked spaghetti samples using the following traits defined as follows [29]:

- i) *Firmness*, as the resistance of cooked pasta when chewed or flattened between the fingers or sheared between the teeth.
- ii) *Stickiness*, as the state of surface disintegration of cooked pasta following visual inspection.
- iii) *Bulkiness*, as the degree of adhesion of cooked spaghetti strands on the basis of visual and manual inspection.
- iv) *Overall cooking quality* (CQ), as estimated by averaging the scores obtained for the above three sensory attributes.

In Italy, such attributes were considered quite reliable to judge the pasta cooking quality [30-31]. Moreover, they are strictly related to those (namely, firmness, liveliness, and starch release) used by the international standard method ISO [32].

Sensory profiling was performed using a 100-point category scale [29]. A printed response sheet with written instructions for the test was given to each panelist at the start of each session (see Table S2 in the electronic supplement). More specifically, spaghetti was regarded of poor quality with $CQ \leq 40$, not completely satisfactory ($40 < CQ \leq 50$), fair ($50 < CQ \leq 70$), good ($70 < CQ \leq 80$), and excellent ($CQ > 80$). One of the samples was

presented to panelists at each session, and 18 sessions were held so that each of the three specimens cooked at both WPR levels was evaluated three times by each judge. The order of sample presentation was completely randomized, and the samples were identified with three random numbers.

Cooking water and energy balances

The cooking water and energy balances during pasta cooking were assessed by referring to the block diagrams shown in the electronic supplement (Fig. S3) [18]. The first balance involved measurement of the cooking water mass at four time points, that is (1) at the beginning of the process (m_{W0}), (2) at the water boiling point (m_{WBP}), (3) as the pan was unlidded (m_{WLO}) before dried pasta adding (m_{PA}), and (4) as the pan was newly unlidded to recover cooked pasta (m_{CPA}) from residual cooking water or *pasta water* (m_{Wf}) using a colander. In this way, it was possible to estimate the masses of water as evaporated throughout the heating phase ($m_{WE}=m_{W0}-m_{WBP}$), adiabatically flashed before dried pasta addition ($m_{WAF1}=m_{WBP}-m_{WLO}$), adsorbed by pasta ($m_{WPA}=m_{CPA}-m_{PA}$), remaining at the end of the cooking process (m_{Wf}), and adiabatically flashed when the lid was newly removed ($m_{WAF2}=m_{W0}-m_{WE}-m_{WAF1}-m_{WPA}-m_{Wf}$), as well as their relative fractions (η_{Wi}) with respect to m_{W0} .

The energy efficiency (η_C) of the pasta cooking system used here was estimated as the ratio between the instantaneous values of the theoretically (E_{th}) and effectively consumed (E_{cons}) energy [4]. The former 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 gelatinisation, its enthalpy being extracted from Ratnayake et al. [33]. The

energy supplied by the induction hob (E_{cons}) was continuously monitored using the aforementioned multimeter, and linearly related to the cooking time (t) as follows:

$$E_{\text{cons}}(t) = \alpha t + \beta \quad (1)$$

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

A full list of all abbreviations and symbols used in this article along with their definitions is reported in the Nomenclature section, while all parameters needed to calculate η_c were reported previously [18].

2.6 Statistical analysis of data

Each pasta cooking test was replicated four times to assess the average values and standard deviations of a series of variables, such as cooking water mass, electric energy consumption, cooking loss, specific water absorption, TA parameters, and sensory attributes. Any set of data was shown as average $\pm$ standard deviation and was analyzed by Tukey test at a significance level of 0.05. Analysis of variance was used to assess the statistical effects of raw spaghetti diameter (d_{RP}) and protein content (x_{RP}), and cooking-to-dried pasta ratio on CL, RICPM, and TA and sensory parameters using SYSTAT version 8.0 (SPSS Inc., 1998). 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 and discussion

Commercial spaghetti characteristics

The physico-chemical characteristics of the three commercial spaghetti brands are shown in Table 1. Moisture, starch, fat and ash contents were in line with those characteristics of typical durum wheat semolina spaghetti. The raw protein content (x_{RP}) and diameter (d_{RP}) for the spaghetti samples under study varied from 11.5 to 13.9 g/(100 g), and 1.9 to 2.0 mm, respectively. Total organic matter (TOM) test was used to measure *a priori* spaghetti stickiness by determining the amount of material leached by exhaustive rinsing of drained, cooked spaghetti. Samples 1, 2 and 3 resulted to be of fair, good, and excellent quality, respectively [19].

Electric power supplied to cook and stir pasta

For WPR=3 L/kg, the electric power supplied by the mechanical stirrer was found to be practically constant (6.1 ± 0.5 W). By accounting for the amount of raw pasta used (~406 g), the specific stirring energy consumed (0.0011 Wh/g) resulted to be totally negligible with respect to the specific cooking energy (e_{PA}), as listed in Table S1.

As shown in the electronic supplement (Fig. S4), the time course of the cooking process was substantially similar in all the cases examined, except for the time needed to heat the different initial masses of cooking water used up to the boiling point. As WPR was reduced from 10 to 3 L/kg, such a time interval decreased from about 340 to 275 s. This reduction was, of course, proportional to the reduction in the mass of cooking water used, the energy efficiency of the induction hob being practically constant in both cases tested. The main results of all cooking tests were summarised in the electronic supplement (Table S1).

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 cooking process. Firstly, the effective electric energy supplied by the induction hob (E_{cons}) during both the cooking water heating and pasta cooking phases was linearly related to t using Eq. (1). All regressions were characterized by coefficients of determination (r^2) greater than 0.995. Moreover, the estimated slopes (α) represented the effective power supplied (P_H and P_C) during the above phases and their dispersion was measured 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 ($e_{C,\text{eff}}$) was about constant (149 ± 3 W/kg), as shown in Table S1. The overall cooking energy efficiency (η_C) was about constant (69 ± 3 %) for both WPRs examined. On the contrary, the specific energy consumed per unit mass of dried pasta (e_{PA}) reduced from about 1.49 ± 0.02 to 0.53 ± 0.01 Wh/g as WPR was reduced from 10 to 3 L/kg of dried pasta.

Effect of WPR on cooking water utilization

Fig 1b shows the percentage utilization of the water used to cook spaghetti at the two WPRs assayed. By reducing WPR from 10 to 3 L/kg, the fraction of water evaporated during the cooking process (η_{WE}) or adiabatically flashed (η_{WAF12}) anytime the pot was unlidded slightly increased from 2.3 ± 0.1 to $3.8 \pm 0.9\%$, or from 2 ± 1 to $3.5 \pm 0.8\%$, respectively. On the contrary, the fraction of cooking water absorbed by cooked pasta (η_{WPA}) was the $13 \pm 2\%$ of that initially added into the pot (m_{W0}) when dry pasta was cooked in a great excess of water (WPR=10 L/kg), but it approximately tripled to $41 \pm 4\%$ of m_{W0} for WPR=3 L/kg. Thus, even at such a low WPR the pasta cooking process appeared to have been performed with no shortage of water. In fact, after having

recovered the cooked pasta with a colander, drained water, generally named as *pasta water*, declined from 83 ± 1 to 51 ± 3 % of m_{W0} , but not tended to zero.

Effect of WPR on cooked spaghetti quality

Fig 1c shows the effect of WPR on cooked spaghetti quality. As WPR was reduced from 10 to 3 L/kg, the relative increase in cooked pasta mass as due to water absorption (RICPM) tended to reduce by about one third, except for spaghetti brand 2, its RICPM reducing by circa 17% (Table S1). Altogether, such a brand exhibited the lowest increase in cooked pasta mass. Since it was the most widespread pasta brand in the Italian supermarkets in 2017, its high production output was in all probability associated with a very high temperature drying process. Even the solid matter dissolved in the cooking water tended to decrease slightly with WPR.

Effect of WPR on the cooked pasta TA parameters

The main results of the TA tests are shown in Fig. 1d. Whatever the spaghetti brand tested, the three TPA parameters, as well as the diameter of cooked spaghetti (d_{CP}), tended to increase slightly with WPR, this increase being statistically significant at the probability level of 0.05 (Table S1). However, Fig. 1d clearly shows that for each spaghetti type examined the variability of TA parameters with WPR was of little entity.

Effect of WPR on the sensory properties of cooked pasta

The difference in the three sensory attributes of the samples studied at the two WPRs tested was found to be statistically negligible at the 95% confidence level (Table 2). In particular, for spaghetti brand 1, 2, or 3, the resistance of cooked pasta to be chewed

(Firmness) was regarded as quite sufficient, good, or excellent, whereas both the state of surface disintegration (Stickiness) and degree of adhesion (Bulkiness) of cooked spaghetti strands were considered as high, rare, or almost absent, respectively. Finally, their overall cooking quality was respectively retained as not completely satisfactory, fair, and excellent, being the average CQ score smaller than 50, and 70, but greater than 80 [29]. Thus, the cooking quality of such spaghetti paralleled their corresponding TOM values (Table 1).

Analysis of variance for the instrumental and sensory properties of cooked pasta

To account for the different diameter (d_{RP}) and raw protein content (x_{PR}) of the spaghetti used (Table 1), all instrumental and sensory properties determined so far were submitted to analysis of variance, as shown in Table 3.

RICPM resulted to be firstly affected by x_{PR} ($p=0.003$), then by WPR ($p=0.038$), and finally by d_{RP} ($p=0.091$). On the contrary, the solid matter dissolved in the cooking water was significantly influenced by all the aforementioned variables, even if the main effect of d_{RP} was greater than that of WPR, which was on turn about three times greater than that of x_{PR} (Table 3). The observed reduction in CL was already detected as WPR was lessened from 30.8 to 8.3 L/kg [17]. The greater the amount of pasta in water, the greater the probability of spaghetti strands to attach longitudinally to each other becomes. As agglomerates of two-to-four spaghetti strands forms, the surface of pasta exposed to the water reduces, this limiting the rehydration kinetics, as well as the cooking losses into the cooking water. Nevertheless, for the sake of simplicity, an average cooking loss of 4.1 ± 0.4 g per 100 g of dried pasta was accounted for.

As concerning the TA parameters, the analysis of variance showed that cooked pasta hardness at 90% deformation (F_{90}), resilience (CPR), and diameter (d_{CP}) were affected firstly by the protein content (x_{PR}) and then by the original diameter (d_{RP}) of the spaghetti brands examined, the effect of WPR being found statistically negligible (Table 3). Only in the case of F_{30} , the effect of WPR was found be more important than that of d_{RP} (Table 3). Such results confirmed that at both WPR levels tested there was no shortage of water at the spaghetti surface and thus no relevant effect on TA parameters. Moreover, as the protein content of raw pasta increased from 11.5 to 13.9 g/(100 g), the cooked pasta hardness at 90% deformation increased from about 11.5 to 16 N (Fig. 1d and Table S1).

As regarding the sensory attributes, the analysis of variance showed that all the attributes of Firmness, Stickiness, Bulkiness, and Overall Cooking Quality were mainly affected by the protein content (x_{PR}) of the spaghetti brands examined. The raw spaghetti diameter and WPR exerted the secondary and tertiary effects on Firmness and Stickiness, while they exhibited a reverted importance on Bulkiness and CQ.

Finally, as shown in Fig. 2, cooked pasta hardness at 90% deformation (F_{90}) was linearly related to the corresponding overall cooking quality (CQ):

$$CQ = (-47 \pm 12) + (8.4 \pm 0.9) F_{90} \quad (r^2 = 0.96) \quad (2)$$

In conclusion, these investigations not only endorsed further the good agreement between the main parameters derived from instrumental and sensory methods, but also allowed the TA parameter F_{90} to be regarded as a suitable and useful tool for measuring commercial spaghetti quality, especially in the case of assessing the effect of the cooking water-to-dried pasta ratio.

Conclusions

In this work, it was established that cooking dried pasta in a large excess of water (i.e., 10 L/kg) as commonly suggested by the great majority of pasta manufacturers might be avoided to save energy and water. By using a properly equipped induction cooker and the eco-sustainable model cooking procedure used here, it would be possible to cook pasta with almost the same sensory attributes with as little as 0.53 kWh and 3 L per kg of dried pasta. This reduction in electricity and water usage asks for the replacement of the domestic appliances and cookware sets generally used today with novel energy-saving pasta cookers similar to the current energy-saving kettles for tea or coffee, equipped with a mild mixer to avoid spaghetti sticking during pasta cooking in low water volumes. Further work is still needed to extend such a finding to other durum wheat semolina pasta formats of different quality.

Nomenclature

CL	Cooking loss [g/100 g]
CPR	Cooked pasta resilience [dimensionless]
CQ	Overall cooking quality [dimensionless]
d_{CP}	Cooked spaghetti diameter [mm]
d_{RP}	Raw spaghetti diameter [mm]
$e_{C,eff}$	Effective power supplied per unit mass of the water-pasta suspension undergoing cooking [W/g]
e_{PA}	Specific energy consumed per unit mass of dry pasta [Wh/g]
E_{cons}	Energy effectively consumed to cook pasta [kJ]

382	EPD	Environmental Product Declaration
383	E_{th}	Energy theoretically consumed to cook pasta [kJ]
384	F_{30}	Cooked pasta hardness at 30% deformation (first bite) [N]
385	F_{90}	Cooked pasta hardness at 90% deformation (second bite) [N]
386	m_{CPA}	Mass of cooked pasta [kg]
387	m_{PA}	Mass of dried pasta [kg]
388	m_{T0}	Overall mass of the pasta-water mixture ($= m_{PA} + m_{W0}$) [kg]
389	m_{W0}	Initial mass of cooking water [kg]
390	m_{WAF1}	Mass of cooking water adiabatically flashed before dried pasta addition [kg]
391	m_{WAF12}	Mass of cooking water adiabatically flashed anytime the pan was unlidded
392		[kg]
393	m_{WAF2}	Mass of cooking water adiabatically flashed as the lid was removed at the
394		end of pasta cooking [kg]
395	m_{WBP}	Mass of cooking water at its boiling point [kg]
396	m_{WE}	Mass of water evaporated throughout the water heating phase [kg]
397	m_{Wf}	Mass of pasta water [kg]
398	m_{WLO}	Cooking water mass as soon as the pan has been unlidded [kg]
399	m_{WPA}	Mass of water adsorbed by dry pasta [kg]
400	p	Probability level
401	P_C	Power supplied by the induction hob during pasta cooking [kW]
402	P_H	Power supplied by the induction hob during cooking water heating [kW]
403	r^2	Coefficient of determination
404	RICPM	Relative increase in cooked pasta mass [g/g]
405	t	Cooking time [s]

406 T_{WM} Temperature of cooking water at its mid-height [$^{\circ}\text{C}$]

407 TA Texture analysis

408 WPR Water-to-dried pasta ratio [L/kg]

409 x_{PR} Raw spaghetti protein content [$\text{g}/100\text{ g}$]

410

411 ***Greek Symbols***

412 α Empiric coefficient of Eq. (1) [kW]

413 β Empiric constant of Eq. (1) [kJ]

414 η_C Energy efficiency of the cooking system [%]

415 η_{WE} Fraction of water evaporated ($=m_{WE}/m_{W0}$) [dimensionless]

416 η_{WAF1} Fraction of water adiabatically flashed as the lid is firstly removed to add
417 dried pasta ($=m_{WAF1}/m_{W0}$) [dimensionless]

418 η_{WAF12} Fraction of water adiabatically flashed when the pan is unlidded
419 ($=\eta_{WAF1}+\eta_{WAF2}$) [dimensionless]

420 η_{WAF2} Fraction of water adiabatically flashed as the lid is newly removed to
421 recover cooked pasta ($=m_{WAF2}/m_{W0}$) [dimensionless]

422 η_{WPA} Fraction of water adsorbed by cooked pasta ($=m_{WPA}/m_{W0}$) [dimensionless]

423 η_{WF} Fraction of pasta water ($=m_{WF}/m_{W0}$) [dimensionless]

424

425 **Acknowledgements** This research was supported by the Italian Ministry of Instruction,
426 University and Research, special grant PRIN 2015 - prot. 2015MFP4RC_002. The authors would
427 like to thank the BS student, Maurizio Mottola and Andrea Bandiera, for their skillfull assistance
428 during the experimental work.

429

Compliance with ethical standards

Conflict of interest

The authors declare that there are no conflicts of interest.

Compliance with ethics requirements

This article does not contain any studies with human or animal subjects.

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TABLES AND TABLE HEADINGS

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Table 2 Effect of water-to-dried pasta ratio (WPR) on the mean values and standard deviations of the three sensory attributes of Firmness, Stickiness, Bulkiness, and Overall Cooking Quality, as evaluated by 6 trained judges, of three cooked commercial spaghetti brands labelled 1, 2, or 3. All sensory tests were repeated 18 times.

Table 3 Analysis of variance for the relative increase in cooked pasta mass (RICPM), cooking loss (CL), main TA parameters (F_{30} , F_{90} , CPR, d_{CP}) and sensory attributes (Firmness, Stickiness, Bulkiness, Overall Cooking Quality).

Table 1

Main characteristics and chemical composition of the three commercial spaghetti brands used in this work.

Spaghetti Brand	1	2	3
<i>Main Characteristics</i>			
Raw spaghetti length [mm]	263±3	257±1	257±1
Raw spaghetti diameter [mm]	1.90±0.05	1.94±0.05	2.00±0.05
Factory suggested cooking time [min]	9	9	9
White core disappearance time [min]	11.00	11.50	14.50
Total organic matter (TOM)	1.41 ± 0.04	1.29 ± 0.05	0.95 ± 0.03
<i>Chemical Composition (g/100 g)</i>			
Moisture	11.3± 0.07	10.5 ± 0.07	10.6 ± 0.07
Raw protein (N x 6.25)	11.5 ± 0.19	13.5 ± 0.06	13.9 ± 0.04
Starch	64.9 ± 1.98	65.1 ± 3.74	62.4 ± 3.04
Fat	2.30 ± 0.03	1.60 ± 0.04	1.80 ± 0.08
Ash	0.76 ± 0.01	0.85 ± 0.01	0.77 ± 0.03

Table 2

Effect of water-to-dried pasta ratio (WPR) on the mean values and standard deviations of the sensory attributes of Firmness, Stickiness, Bulkiness, and Overall Cooking Quality, as evaluated by 6 trained judges, of the three cooked commercial spaghetti brands labelled 1, 2, or 3. All sensory tests were repeated 18 times.

Spaghetti label	1		2		3	
Parameter						
WPR [L/kg]	10	3	10	3	10	3
Firmness [-]	56± 9 ^a	59±14 ^a	78± 6 ^b	78± 6 ^b	100± 0 ^c	94± 8 ^c
Stickiness [-]	57±11 ^a	54±12 ^a	61± 5 ^b	71±10 ^b	88± 4 ^c	84± 9 ^c
Bulkiness [-]	32±10 ^a	33±12 ^a	48± 9 ^b	52± 6 ^b	85± 3 ^c	66± 12 ^c
Overall Cooking Quality[-]	48±8 ^a	49±11 ^a	63±4 ^b	67±5 ^b	91±2 ^c	83±5 ^c

- Different lowercase letters indicate statistically significant difference among the parameter means of the spaghetti brands cooked at different WPRs at the probability level of 0.05.

Table 3

Analysis of variance for the relative increase in cooked pasta mass (RICPM), cooking loss (CL), main TA parameters (F_{30} , F_{90} , CPR, d_{CP}) and sensory attributes (Firmness, Stickiness, Bulkiness, Overall Cooking Quality).

Parameter	Source	df	Mean-Square	F-ratio	p value
RICPM	d _{RP}	2	3.309	2.749	0.091
	x _{PR}	1	13.834	11.493	0.003
	WPR	1	6.009	4.993	0.038
	Error	18	1.204		
Cooking Loss	d _{RP}	1	4.731	221.172	0.000
	x _{PR}	2	1.388	64.872	0.000
	WPR	1	4.284	200.253	0.000
	Error	61	0.021		
F_{30}	d _{RP}	18	0.480	1.247	0.244
	x _{PR}	7	1.972	5.124	0.000
	WPR	1	1.574	4.088	0.046
	Error	85	0.385		
F_{90}	d _{RP}	18	144.466	5.764	0.000
	x _{PR}	7	1640.067	65.438	0.000
	WPR	1	0.030	0.001	0.972
	Error	86	25.063		
CPR	d _{RP}	18	0.375	5.987	0.000
	x _{PR}	7	3.319	52.963	0.000
	WPR	1	0.023	0.366	0.547
	Error	86	0.063		
d_{CP}	d _{RP}	18	6.206	5.880	0.000
	x _{PR}	7	61.803	58.554	0.000
	WPR	1	0.141	0.134	0.716
	Error	86	1.055		
Firmness	d _{RP}	18	2724.936	1.649	0.066
	x _{PR}	7	41307.809	24.996	0.000
	WPR	1	4335.473	2.624	0.109
	Error	86	1652.552		
Stickiness	d _{RP}	18	2114.381	1.655	0.064
	x _{PR}	7	33260.024	26.036	0.000
	WPR	1	1219.766	0.955	0.331

	Error	86	1277.468		
Bulkiness	d _{RP}	18	1044.653	0.982	0.488
	x _{PR}	7	18339.866	17.232	0.000
	WPR	1	4270.425	4.012	0.048
	Error	86	1064.303		
Overall Cooking	d _{RP}	18	1837.951	1.321	0.195
Quality	x _{PR}	7	29404.382	21.139	0.000
	WPR	1	3512.761	2.525	0.116
	Error	86	1391.033		

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FIGURES AND FIGURE HEADINGS

Figure 1 Effect of the cooking water-to-dried pasta ratio (WPR) on some energy-related and quality parameters characterizing the pasta cooking process of the three spaghetti brands labelled **1** (blue color), **2** (red color), or **3** (green color) under study:

- a) Specific energy consumed to cook dried pasta (e_{PA} :) , and dimensionless cooking energy efficiency (η_C :) *versus* WPR.
- b) Percentages of water evaporated (η_{WE} :) , released as vapor when the pot is unlidded firstly to add dried pasta and then to drain cooked pasta (η_{WAF12} :) , adsorbed by cooked pasta (η_{WPA} :) , and leftover upon pasta drainage (η_{WF} :) against WPR.
- c) Relative increase in cooked pasta mass (RPMI:) , and cooking loss (CL:) against WPR.
- d) Cooked pasta hardness at 30% (F_{30} :) and 90% (F_{90} :) deformation, resilience (CPR x10:) , and diameter (d_{CP} :) *versus* WPR.

Figure 2 Overall cooking quality (CQ) of cooked commercial spaghetti *versus* the corresponding hardness at 90% deformation (F_{90}). The broken line was plotted using Eq. (2). The horizontal and vertical bars refer to the average coefficients of variation of both data.

Figure 1

1a)

Effect of the cooking water-to-dried pasta ratio (WPR) on some energy-related and quality parameters characterizing the pasta cooking process of the three spaghetti brands labelled **1** (blue color), **2** (red color), or **3** (green color) under study:

1a) Specific energy consumed to cook dry pasta (e_{PA} :) and dimensionless cooking energy efficiency (η_C :) versus WPR.

600 1b)

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603 1b) Percentages of water evaporated (η_{we} :) , released as vapor when the pot is
604 unlidded firstly to add dried pasta and then to drain cooked pasta (η_{waf12} :) ,
605 adsorbed by cooked pasta (η_{wpa} :) , and leftover upon pasta drainage (η_{wfr} :)
606 against WPR.
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608 1c)

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611 1c) Relative increase in cooked pasta mass (RCPMI:) and cooking loss (CL:)

612 against WPR.

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616 1d)

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619 1d) Cooked pasta hardness at 30% (F₃₀:) and 90% (F₉₀:) deformation, resilience
620 (CPR x10:) , and diameter (d_{CP}:) versus WPR.

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Figure 2

Overall cooking quality (CQ) of cooked commercial spaghetti *versus* the corresponding hardness at 90% deformation (F_{90}). The broken line was plotted using Eq. (1). The horizontal and vertical bars refer to the average coefficients of variation of both data.

Appendix A. Supplementary data

Table S1

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 (m_{PA}) of three different amounts of spaghetti brands labelled 1, 2, or 3 and cooking water (m_{W0}): effect of the water-to-dried pasta ratio (WPR) on the mean value and standard deviation of several parameters characterizing the cooking pasta process, that is the overall energy consumed (E_{consT}), 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); cooking loss (CL); and main TPA parameters (F_{30} , F_{90} , CPR, d_{CP}). All cooking tests were quadruplicated, while TA tests were repeated 20 times.

Spaghetti label Parameter	1		2		3	
WPR [L/kg]	10.0±0.0	3.0±0.0	10.02±0.03	3.0±0.0	10.0±0.0	3.0±0.0
m_{W0} [g]	1477.5±0.3	1218.3±0.1	1477±5	1218.5±0.1	1477.4±0.2	1218.2±0.1
m_{PA} [g]	147.7±0.0	406.1±0.1	147.6±0.3	406±0	147.7±0.0	406.3±0.0
P_H [kW]	1.88±0.04 ^a	1.89±0.05 ^a	1.83±0.01 ^a	1.96±0.01 ^b	1.88±0.02 ^a	1.93±0.03 ^{a,b}
P_C [kW]	0.25±0.01 ^a	0.25±0.01 ^a	0.24±0.01 ^a	0.25±0.01 ^a	0.24±0.01 ^a	0.24±0.01 ^a
$E_{cons,T}$ [Wh]	218±9 ^a	214±2 ^{a,b}	225±3 ^a	222±2 ^a	220±3 ^a	212±3 ^b
η_C [%]	71±0 ^a	68±2 ^b	70±2 ^{a,b}	65±1 ^c	72±1 ^d	68±0 ^b
$e_{C,eff}$ [W/kg]	151±3 ^a	152±1 ^a	145±4 ^a	153±7 ^a	146±7 ^a	147±3 ^a
e_{PA} [Wh/g]	1.47±0.06 ^a	0.53±0.01 ^b	1.52±0.02 ^a	0.54±0.01 ^b	1.49±0.02 ^a	0.52±0.01 ^b
η_{WE} [%]	2.3±0.1 ^a	3.2±0.7 ^b	2.3±0.2 ^a	3.4±0.2 ^b	2.2±0.1 ^a	4.8±2.2 ^{a,b}
η_{WAF1} [%]	0.3±0.1 ^a	0.6±0.1 ^b	0.7±0.2 ^b	0.2±0.1 ^a	0.5±0.4 ^{a,b}	0.6±0.7 ^{a,b}
η_{WAF2} [%]	2.5±0.6 ^a	3.9±0.9 ^b	-0.1±0.3 ^c	3.0±0.7 ^{a,b}	2.2±0.9 ^a	2.3±1.4 ^{a,b}
η_{WPA} [%]	12.8±0.3 ^a	44.4±1.3 ^d	15.2±0.3 ^b	42.2±0.1 ^c	11.1±0.8 ^c	37.5±0.6 ^f
η_{WF} [%]	82.2±0.6 ^a	47.9±1.6 ^c	81.8±0.5 ^a	51.1±0.5 ^d	84.0±0.2 ^b	54.8±1.2 ^c

RICPM [g/g]	2.96±0.03 ^a	1.95±0.04 ^b	1.53±0.03 ^c	1.27±0.00 ^d	2.80±0.08 ^e	1.74±0.02 ^f
CL [g/100 g]	4.2±0.3 ^a	3.6±0.1 ^b	4.2±0.1 ^a	3.5±0.1 ^b	4.5±0.1 ^a	4.4±0.1 ^a
F ₃₀ [N]	5.1±0.3 ^a	4.2±0.4 ^b	5.1±0.3 ^a	6.1±0.3 ^b	8.4±0.3 ^a	6.9±0.4 ^b
F ₉₀ [N]	12.0±0.5 ^a	11.0±0.6 ^b	13.2±0.6 ^a	13.0±0.4 ^a	16.4±0.6 ^a	15.4±0.5 ^b
CPR [-]	0.64±0.01 ^a	0.65±0.01 ^b	0.64±0.01 ^a	0.62±0.01 ^b	0.58±0.01 ^a	0.60±0.01 ^b
d _{CP} [mm]	2.56±0.02 ^a	2.44±0.03 ^b	2.65±0.03 ^a	2.70±0.03 ^b	2.86±0.02 ^a	2.79±0.02 ^b

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

Table S2

Evaluation of cooked pasta quality using three sensory attributes as extracted from Cubadda (1988).

Score	Attribute	Firmness	Stickiness	Bulkiness
0		absent	totally	totally
20		rare	very high	very high
40		insufficient	high	high
60		sufficient	rare	rare
80		good	almost absent	almost absent
100		excellent	absent	absent

Figure S1

Pictures of the cooking system used in this work, consisting of a pan closed with its lid, mixer, thermocouple, and induction hob, both being placed over a technical balance.

Figure S2

Picture view of the cutting probe used to perform the Texture Analysis of 17 strands of cooked spaghetti aligned over a stainless steel compression platen.

Figure S3

Block diagrams of the pasta cooking system used in this work to establish the cooking water (A) and energy (B) balances. All symbols were listed in the Nomenclature section.

Figure S4
1A)

1B)

2A)

2B)

3A)

3B)

Effect of cooking time (t) on the cooking water temperature at mid-height (T_{WM} : - - -), energy theoretically (E_{th} : — . —) and effectively (E_{cons} : —) consumed, and cooking energy efficiency (η_c : — · · —, — · · —) during cooking of the three spaghetti brands labelled **1**, **2**, or **3** with 3 (**A**) or 10 (**B**) L of water per kg of dried pasta, and the hob control knob set at the nominal power of 2 kW during the cooking water heating phase and at 0.4 kW during the pasta cooking one.