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Additional Information

1 **CONTROLLED DEFICIT IRRIGATION AS A WATER-SAVING STRATEGY FOR**
2 **PROCESSING TOMATO**

3
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17
18 **Abstract**

19 In a complex scenario characterized by climate change and increasing population demand, it is
20 necessary to adopt production strategies involving a lower use of water. For this purpose,
21 controlled deficit irrigation, CDI, strategies with an initial full irrigation covering 100% crop
22 evapotranspiration (ET_c) followed by mild (50% ET_c) and moderate (75% ET_c) irrigation
23 restrictions after the fruit set stage were evaluated. The study was performed during two years in
24 two growing areas of processing tomato in Spain, using conventional and high-lycopene cultivars.
25 With moderate levels of CDI an average saving of water of 26.1% was achieved, but productivity
26 was reduced on average by 10.7%. It should be considered though, that the effect was dependent
27 on the environment and genotype, and high-yield cultivars seemed to be more sensitive to the
28 negative effects of moderate CDI on productivity. In contrast, mild CDI levels did not affect
29 productivity and still entailed a water saving of 13%. Moderate CDI levels increased soluble
30 solids content, but this increase was not due to a higher accumulation of taste-related compounds,
31 such as sugars and acids. Indeed, irrigation dose had no significant effect on the levels of fructose,
32 glucose, citric and glutamic acid nor on derived variables related to tomato acceptability and CDI
33 decreased the levels of malic acid. Considering previous results, mild CDI strategies would be
34 preferred to continuous deficit irrigation strategies as the former contribute to reduce the use of
35 water, an increasingly scarce resource, avoiding negative impacts on productivity, a key
36 parameter to promote farmer adoption of CDI strategies.

37
38 **Keywords:** *Solanum lycopersicum* L.; commercial yield, sugar, acid, lycopene, irrigation
39

40 **Highlights**

41 Mild controlled deficit irrigation, CDI, (100-75%ET_c) does not affect yield

42 High yield cultivars are more sensitive to deficit irrigation strategies

43 Increased soluble solids with 100-50%ET_c CDI levels are not due to sugar accumulation

44 CDI entails a water saving of 13% with 100-75% ET_c and 26% with 100-50% ET_c

45

46 **1 Introduction**

47 Tomato (*Solanum lycopersicum* L.) is one of the most important horticultural crops worldwide,
48 with a global production that exceeded 177 million tons in 2016 (<http://www.fao.org/faostat>). Its
49 consumption is present in countries all around the world, with high levels of intake that exceed
50 35.8 kg per person per year in North America and 34.8 kg per person per year in southern Europe
51 (<http://www.fao.org/faostat>).

52 As an irrigated crop, tomato performance depends on the availability of water to obtain high
53 yields. Therefore, tomato production is jeopardized in warm areas already affected by water
54 shortages, such as the Mediterranean basin. Models predicting the effects of climate change
55 anticipate a 10-30% decrease in runoff in Southern Europe by 2050 with a clear drying of the area
56 (Milly et al. 2005). In this context, the main consequences expected in water resources for
57 agricultural production include i.a. an increased evapotranspiration in response to increased
58 temperatures and water shortages, particularly during spring and summer, and raised water
59 requirements for irrigation (Iglesias and Garrote 2015). But climate change is not the only factor
60 affecting water availability, as rising water demands due to population growth and industry
61 outweigh greenhouse warming in defining the state of global water systems in 2025 (Vörösmarty
62 et al. 2000).

63 In this scenario, it is necessary to develop alternatives to reduce water usage in tomato production
64 anticipating the negative effects of climate change. Several alternatives have been proposed,
65 including the removal of irrigation following plant establishment. However, an early water
66 shortage has a marked impact on marketable yield, due to fruit losses higher than 40% (Patanè et
67 al. 2011).

68 Another approximation is to apply deficit irrigation (DI) which consists of applying lower water
69 volumes than the crop requirements. In this case, the use of water is also considerably reduced,
70 while the effects on yield are less dramatic. For example, a moderate deficit irrigation strategy
71 covering 75% of crop evapotranspiration (ET_c) under Spanish conditions entailed a mean
72 reduction in water use of 28.2% and a moderate impact on yield, with a mean decrease of 16.4%,
73 with a soluble solids increase of 8.4% (Lahoz et al. 2016). Under certain conditions and varieties,
74 the production of aroma volatiles related to flavor also increased. Despite the possible benefits in
75 quality, the truth is that the drop in commercial yield, being moderate, is still too high to represent
76 an alternative for farmers. Under other environmental conditions, the effect of DI on yield may
77 be milder. For example, in Italian conditions, a higher level of DI with 50% ET_c represented a
78 water saving of 46.2% and improved soluble solids content, titratable acidity, and vitamin C
79 content, while it did not significantly affect the marketable yield (Patanè et al. 2011).

80 Partial root-zone drying (PRD) can also lead to a substantial improvement in water use efficiency,
81 but it seems that similar results can be achieved by closely monitored deficit irrigation, without
82 the complexity and additional cost of PRD (Sadras 2009). Controlled deficit irrigation (CDI)
83 represents an interesting alternative for areas where DI evidenced a negative effect on yield, as it
84 seeks to optimize the use of water stress only in non-critical periods of the development of the
85 plant. Tomato requires a constant and sufficient water supply during the vegetative growth stage
86 (Nuruddin et al. 2003; Patanè and Cosentino 2010), but also during the reproductive stage
87 involving flowering and fruit set (Waister and Hudson 1970). For that reason, CDI (eg. 100-x%
88 ET_c) maintains a full supply of water to cover 100% ET_c and irrigation is only reduced after fruit
89 set, covering a variable proportion of crop evapotranspiration (x%).

90 CDI represents another advantage. Recent studies showed that CDI would also have a positive
91 effect on the functional quality of tomato, as it favored the accumulation of L-ascorbic acid
92 (vitamin C) and certain phenolic compounds such as chlorogenic and ferulic acids, and rutin while
93 it had a limit effect on carotenoids (Martí et al. 2018). Nevertheless, the development of products
94 with the highest functional value depended on the right combination of climatic conditions, mild
95 levels of CDI and certain genotypes (especially high-lycopene cultivars). Increasing the levels of
96 bioactive compounds in tomato would entail an added value, satisfying the demand of quality
97 markets. Indeed, the functional value of tomato has gained importance, as this species represents
98 a main dietary source of bioactive compounds including carotenoids, vitamin C and polyphenols
99 (Chun et al. 2005; Garcia-Closas et al. 2004). These compounds have been related not only with
100 the prevention of certain types of cancer (Martí et al. 2016; Rao and Rao 2007) but also
101 cardiovascular diseases and Alzheimer (Martí et al. 2019) and consumers are increasingly aware
102 of the role of food in the prevention of diseases (Siró et al. 2008).

103 In Italian conditions, as for Patanè et al. (2011), a CDI of 100-50% ET_c offered a similar
104 performance compared to DI covering 50% ET_c , with no significant impact on marketable yield
105 and an increase in TSS. It would be interesting to know if in other environmental conditions CDI
106 can also reduce the impact on yield. A more in depth study on the impact on the accumulation of
107 sugars and acids would also complete the analysis of the impact of DI strategies on quality. This
108 is, in fact, the objective of the present work, to analyze the effect of mild (100-75% ET_c) and
109 moderate (100-50% ET_c) CDI on the agronomic performance and the accumulation of taste-
110 related compounds in processing tomato of conventional high yield cultivars and high lycopene
111 varieties targeted to quality markets. In order to obtain reliable results, the study was performed
112 during two years, in two of the main processing tomato growing areas of Spain: Extremadura and
113 Navarra. The results obtained would enable comparison with previous work dealing with DI, and
114 identify effective strategies to reduce the use of an increasingly scarce input such as water while
115 offering the maximum functional and organoleptic quality to the consumer.

116

117 **2 Materials and methods**

118 *2.1 Experimental design and plant material*

119 The experiment was conducted during two consecutive years and in two Spanish growing areas
120 (Extremadura and Navarra) to evaluate CDI on four processing tomato cultivars: two cultivars
121 with good agronomical performance ‘H-9036’ and ‘H-9661’ (Heinz Seeds) widely used by local
122 farmers, and two mid to high lycopene cultivars ‘H-9997’ (Heinz Seeds) and ‘ISI-24424’
123 (Diamond seeds S.L.; Isi Sementi S.P.A.). Three irrigation regimes were evaluated. A control
124 treatment satisfying the crop evapotranspiration (ET_c) of the plant during the entire growth cycle
125 (100-100% ET_c), and two CDI strategies. Both of them comprised irrigation covering 100% ET_c
126 (phase 1) until fruit set and the start of the growing phase. Then a mild (25%) or moderate (50%)
127 reduction of irrigation (phase 2) was applied in order to cover a 75% and 50% of ET_c respectively
128 (Table 1). For each treatment, three field sections of 100 plants each for cultivation (4 cv. x 25
129 plants) were employed. The statistical design was a split plot with three replications where the
130 main factor was the irrigation rate (100-50%, 100-75% and 100-100% ET_c) and the second factor
131 was cultivar.

132 **Table 1.** Irrigation doses applied to the plants (L m⁻²) at different development stages.

133

	Navarra						Extremadura					
	2012			2013			2012			2013		
Irrigation (%ETc)	100-100	100-75	100-50	100-100	100-75	100-50	100-100	100-75	100-50	100-100	100-75	100-50
Planting	50.6	50.7	51.8	45.8	45.2	44.9	5.3	5.3	5.3	4.2	4.4	5.1
Planting to fruit set	180.0	178.2	175.6	168.3	169.9	168.9	201.1	202.2	200.8	468.8	468.6	467.9
Fruit set to harvest	266.6	196.1	123.9	261.3	194.7	129.7	457.2	355.7	256.6	255.0	192.2	129.5
Total	497.2	425.0	351.3	475.3	409.8	343.5	663.6	563.2	462.7	728.0	665.2	602.5
Water savings		14.5%	29.3%		13.8%	27.7%		15.1%	30.3%		8.6%	17.2%

134

135

136

137 *2.2 Growing conditions*

138 The trials were conducted in the two Spanish main production areas of processing tomato:
139 Extremadura (research center Finca ‘La Orden-Valdesquera’, Badajoz, lat. 38° 53’ 26’’ N, long.
140 6° 40’ 00’’ W, 186 m. a. s. l.) and Navarra (INTIA Experimental Farm, Cadreita, lat. 42° 12’ 34’’
141 N, long. 1° 43’ 1’’ W, 267 m. a. s. l.). Integrated pest management with the typical fertilization
142 doses and phytosanitary treatments of each cultivation site was applied.

143 Planting was carried out when adequate climatic conditions for a spring-summer cycle were
144 present (Fig. 1). For Extremadura, it was performed on April 24th in 2012 and May 2nd in 2013.
145 In Navarra, planting was performed on May 10th in 2012 and May 23rd in 2013. A spacing of 1.50
146 m x 0.2 m (3.33 plants m⁻²) was used in Extremadura and a spacing of 1.60 m x 0.35 m (3.57
147 plants m⁻²) in Navarra. Plants were grown in the open air under 15 µm black polyethylene plastic.

148 *2.3 Irrigation scheduling*

149 The scheduling of the irrigation was carried out considering the water requirements of the plant.
150 The Penman-Monteith (Allen et al. 1998) method was used to calculate the ET_c. Evaporative
151 coefficient was not considered because the soil was cover with plastic. A flow meter was installed
152 in the field sections destined for each of the different treatments to measure the real volume of
153 water applied (Table 1). Weekly monitoring of the phenology of each variety, starting with the
154 first fruit set, was made in order to establish the end of the period of fruit set. Irrigation should
155 ensure the survival of plants. In both growing areas, maximum temperature and relative humidity
156 were registered using an HMP45C probe (Vaisala, Helsinki, Finland). In Extremadura, solar
157 irradiance was recorded using a CMP3 pyranometer (Kipp&Zonen, Delft, the Netherlands). A
158 110/S pyranometer (Skye, Powys, United Kingdom) was used for this purpose in Navarra. A
159 detailed description of the climatic conditions was reported by Martí et al. (2018).

160 *2.4 Sampling*

161 A single collection of fruits was conducted for each cv. and irrigation treatment at the optimum
162 moment for harvest following commercial practices in the area (i.e. a minimum of 85% fruits in
163 the red-ripe stage and no more than 5% of over-ripened fruits). Harvest was performed by hand.
164 The specific dates of harvest were August 21st in 2012 and August 20th in 2013 for Extremadura,
165 and August 29th in 2012 and September 26th in 2013 for Navarra.

166 *2.5 Agronomic and basic quality indicators*

167 Commercial yield, total yield and mean fruit weight were determined for each of the 25 plants of
168 the replicate. Two commercial red ripe fruits of each of the 25 plants were blended to obtain a
169 homogenized sample to determine TSS, pH, dry matter and color. TSS were evaluated using a
170 digital refractometer (ATAGO PR-1, Tokyo, Japan), with a precision of 0.1⁰Brix (results
171 expressed as ⁰Brix at 20⁰C). The Hunter ‘a’ and ‘b’ color parameters were obtained using a digital
172 colorimeter (CR 300, Minolta, Japan) and the Hunter a/b ratio was calculated. The soluble solids
173 yield (t ha⁻¹) was estimated from the product of soluble solid content by commercial yield in
174 accordance with Patanè et al. (2011). Aliquots of the sample were frozen at -80°C until further
175 analysis.

176

177 *2.6 Chemicals and reagents*

178 Analytical grade standards of malic, citric and glutamic acids, sucrose, fructose, and glucose were
179 purchased from Sigma-Aldrich (Steinheim, Germany). 2,6-pyridine dicarboxylic acid (PDC)
180 hexadimethrine bromide (HDM) and sodium dodecyl sulfate (SDS) were also supplied by Sigma-
181 Aldrich. Sodium hydroxide (NaOH) was purchased from Panreac (Castellar del Vallés, Spain). A
182 Milli-Q water system (Millipore, Molsheim, France) was used to obtain ultrapure water.

183 *2.7 Analysis of organic acids and sugars*

184 Defrosted samples were centrifuged at 12,000 rpm (10,483g) for 5 min at 4°C to separate the
185 upper phase, which was diluted 1:20 with ultrapure water. The resulting solution was filtered
186 using a 0.22 µm-Nylon centrifuge tube filter (Costar Spin-X, Corning, NY, USA) before its
187 analysis by capillary electrophoresis (CE).

188 Quantification of organic acids and sugars was performed following the procedure described by
189 Cebolla-Cornejo et al. (2012) using a 7100 CE system (Agilent Technologies, Waldbronn,
190 Germany) with diode array detection and temperature control of sample compartment. Prior to its
191 first utilization, uncoated fused silica capillaries (67 cm total length, 60 cm effective length, 375
192 µm od, 50 µm id) from Polymicro Technologies (Phoenix, AZ, USA) were rinsed with NaOH
193 1M at 50°C (5 min), NaOH 0.1M (5 min), water (10 min) and running buffer at 25°C (30 min).
194 Between runs, the capillary was flushed with SDS 58 mM (2 min) and running buffer (5 min).
195 Running buffer consisted of a solution 20 mM 2,6-pyridinedicarboxylic acid (PDC) with 0.1%
196 (w:v) hexadimethrine bromide (HDM) adjusted to pH 12.1. A hydrodynamic injection at 3400 Pa
197 for 10 s was used. Separation was performed using a voltage of -25 kV at 20°C. Indirect detection
198 of target compounds was recorded at 214 nm.

199 *2.8 Statistical analysis*

200 All statistical analyses were performed using the SPSS 22.0 software (NYSE: IBM, Armonk, NY,
201 USA). The Pillai trace test was employed to calculate the *p*-value in MANOVA analysis.
202 Individual ANOVAs and Tukey B multiple range tests (*p* < 0.05) were calculated for the
203 individual variables. Graphical MANOVA Biplot representations were performed using the
204 freeware licensed by Prof. Vicente-Villardón (2015). The confidence intervals ($\alpha = 0.05$) were
205 represented by the projection of Bonferroni circles on each variable for the identification of
206 differences statistically significant between groups. In the MANOVA Biplot, dashed lines
207 represent non-significant effects.

208 **3 Results and discussion**

209 *3.1. Environmental conditions*

210 Extremadura, with a lower latitude, usually records higher temperature and radiation than
211 Navarra. This general trend was observed during both years. In 2012, though, the differences
212 between both locations were limited, but still, Extremadura had higher maximum temperatures
213 and accumulated radiation (Fig. 1), while in 2013 the accumulated radiation was higher in
214 Navarra. In this latter year, the climatic conditions were not optimal for tomato production. In
215 Extremadura, a considerably lower accumulated radiation was registered compared to 2012, while
216 the differences in maximum temperature were not so pronounced. In Navarra during this second
217 year, the bad weather during May forced to delay transplant. Lower maximum temperatures and
218 accumulated radiation during the whole cycle resulted in a delayed growth of plants and lower
219 water requirements. As a result, the growth cycle was extended (Fig. 1). Bad weather was also

220 registered at the end of the cycle, accordingly, the gradient of accumulated radiation decreased
221 and maximum temperatures dropped. These conditions favored an outbreak of *Alternaria solani*
222 that affected especially the cultivar 'ISI-24424'.

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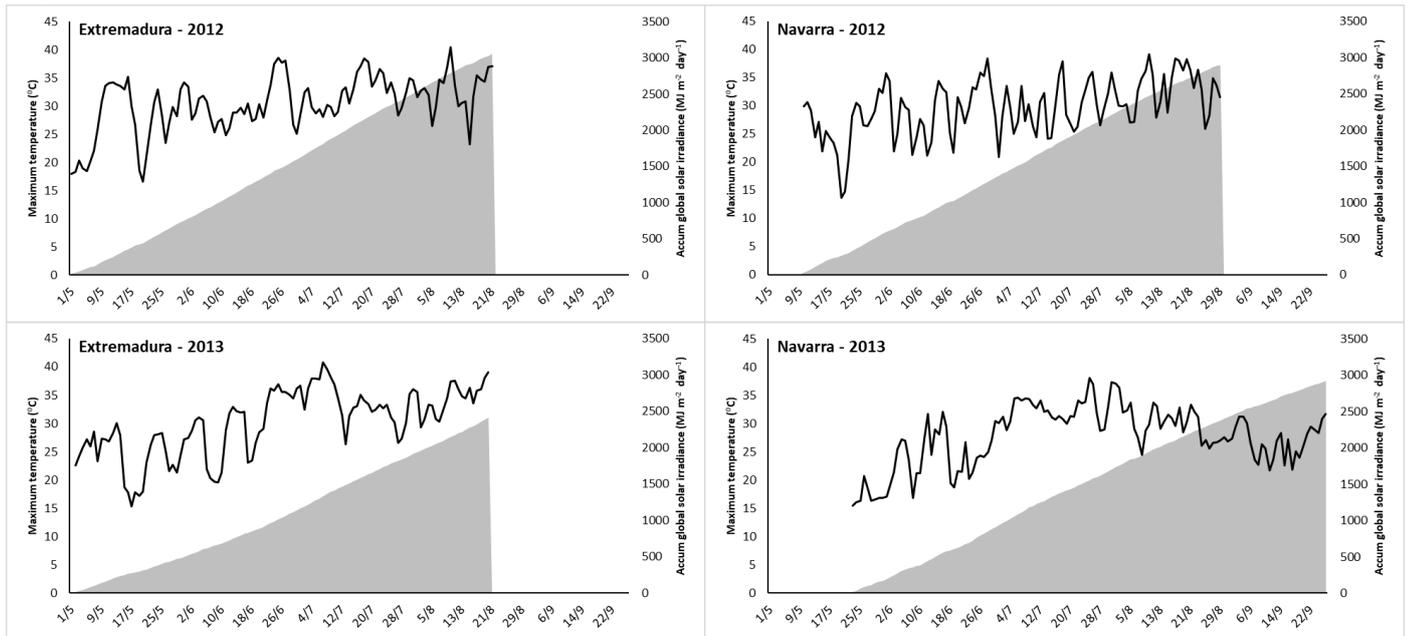


Fig. 1. Maximum temperatures (black continuous line) and accumulated global solar irradiance (grey area) for Extremadura and Navarra during the growth cycle (day/month) in 2012 and 2013.

230 3.2. Agronomic performance and basic quality indicators

231 Water is one of the key factors affecting tomato fruit growth and production (Wang et al. 2011).
232 Usually, an increase in the water supply results in increased yield but reduced fruit quality, due
233 to the higher water content of the fruit (Dorais et al. 2001). This is true up to certain limits, as
234 increasing irrigation doses over the recommended 100% ET_c would have no significant effect on
235 the agronomical performance, while it would bring about a dilution effect reducing soluble solids
236 and lycopene content (Lahoz et al. 2016). Therefore, a smart irrigation schedule and strategy
237 obtains a good equilibrium between yield and quality, being more beneficial for farmers and more
238 sustainable for the environment.

239 However, water is an increasingly scarce resource. In a complex scenario characterized by climate
240 change and increasing populations, the optimistic future depends on whether agriculture is able
241 to manage and consume water in a sustainable way (Iglesias and Garrote 2015). In this context,
242 the development of technological advances and their transference to farmers via educational
243 programs will be crucial. Among existing alternatives, deficit irrigation strategies acquire an
244 important role, as they limit the use of water providing an adaptation to scenarios with lower
245 water availability. However, the success of these strategies relies on their adoption by farmers.
246 Currently, strategies that significantly affect yield, even at low rates, have a negative prognostic
247 in terms of farmer adoption.

248 In our work, the year, site of cultivation, irrigation dose, and genotype significantly affected the
249 performance of tomato crop, as revealed by the MANOVA analysis (Pillai trace, $p < 0.01$). The
250 uncontrolled environment (year and site of cultivation) had a marked effect on the agronomical
251 behavior of the crop. Individual ANOVAs revealed that climatic differences for the two
252 cultivation years significantly affected commercial yield, the percentage of commercial fruits,
253 soluble solids yield, pH, dry matter, and color (Table 2). In general, higher values corresponded
254 to the year 2012, except for the pH which was higher in 2013. In addition, the site of cultivation
255 had a significant effect on all agronomical and basic quality parameters except for dry matter and
256 color (Table 2). The conditions of Navarra were more favorable for all significant variables with
257 the only exception of soluble solids, as a higher value for the latter was obtained in Extremadura.

258 The irrigation dose had a lesser effect on the agronomical performance compared to the
259 uncontrolled environmental conditions (Table 2). Nevertheless, there was a significant reduction
260 in commercial yield (10.9%) and average fruit weight (9.2%) when CDI 100-50%ET_c was
261 applied, compared to the control dose (100-100%ET_c). A milder CDI level (100-75% ET_c) had
262 no significant impact on commercial yield. The percentage of commercial fruits showed the
263 opposite behavior, with a higher proportion of commercial fruits with a CDI of 100-50%ET_c
264 compared with CDI 100-75%ET_c and the control 100-100%ET_c.

265 The most restrictive CDI level (100-50%ET_c) significantly increased the soluble solids content
266 and dry matter %, while no significant differences were obtained between 100-75%ET_c and the
267 control (Table 2). The pH followed the opposite trend, being slightly higher in the control (100-
268 100%ET_c), while the no differences were observed between the two CDI regimes (Table 2). On
269 the other hand, neither soluble solid yield nor the color of the fruit were affected by irrigation
270 dose, but a significant genotype x irrigation dose interaction was observed for both parameters
271 (Table 2).

272 **Table 2.** Effect of the year, site of cultivation, irrigation dose and genotype on agronomic performance and quality parameters. The statistical relevance is
 273 provided (ns, not significant; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$). ¹Different letters indicate significant differences at $p < 0.05$ (Tukey B test).

		Commercial yield (t ha ⁻¹)	Commercial fruits (%)	Average fruit weight (g)	Soluble solids (°Brix)	Soluble solids yield (t ha ⁻¹)	pH	Dry matter (%)	Hunter colour a/b	Malic acid (g kg ⁻¹)	Citric acid (g kg ⁻¹)	Glutamic acid (g kg ⁻¹)	Fructose (g kg ⁻¹)	Glucose (g kg ⁻¹)
Year (Y)	<i>p value</i>	***	***	ns	ns	***	***	*	***	***	ns	**	***	***
	2012	157.88	89.07	80.23	4.61	7.25	4.16	4.88	2.50	0.80	3.87	1.55	11.80	11.86
	2013	118.18	86.25	79.60	4.52	5.29	4.31	4.79	2.05	1.13	3.80	1.37	14.76	13.70
Site of cultivation (S)	<i>p value</i>	***	***	***	*	***	***	ns	ns	***	***	***	ns	ns
	Extremadura	123.07	85.60	77.29	4.62	5.65	4.14	4.84	2.26	1.02	3.44	1.10	13.16	13.04
	Navarra	153.00	89.72	82.54	4.51	6.90	4.33	4.83	2.28	0.92	4.23	1.81	13.40	12.51
Irrigation dose ¹ (I)	<i>p value</i>	***	***	***	***	ns	**	***	ns	*	ns	ns	ns	ns
	100- 100%ET _c	145.41b	86.35a	83.49c	4.41a	6.37	4.25b	4.77a	2.28	1.01b	3.74	1.41	13.29	12.53
	100-75%ET _c	139.14b	86.31a	80.40b	4.47a	6.23	4.23a	4.79a	2.28	0.93a	3.78	1.49	13.22	12.54
	100-50%ET _c	129.54a	90.31b	75.85a	4.80b	6.22	4.22a	4.95b	2.26	0.96ab	3.98	1.47	13.32	12.27
Genotype (G)	<i>p value</i>	***	***	***	ns	***	***	***	***	***	***	**	**	**
	'H-9661'	134.83b	89.62b	74.98a	4.51	6.06b	4.22ab	4.84b	2.20b	0.92a	4.11bc	1.57b	12.27a	12.22a
	'H-9997'	134.30b	89.48b	73.52a	4.61	6.20b	4.24b	4.97c	2.35c	0.96a	4.22c	1.31a	13.00ab	12.53a
	'H-9036'	166.40c	88.44b	73.42a	4.57	7.55c	4.21a	4.83b	2.14a	0.89a	3.78b	1.54b	14.22b	13.87b
	'ISI-24424'	116.59a	83.10a	97.72b	4.56	5.27a	4.28c	4.70a	2.40c	1.11b	3.23a	1.40ab	13.62b	12.49a
YxS	<i>p value</i>	*	ns	***	***	ns	***	**	***	ns	ns	**	**	**
YxG	<i>p value</i>	ns	***	***	ns	**	***	*	***	*	ns	**	ns	ns
Yxl	<i>p value</i>	ns	ns	**	*	ns	ns	***	*	ns	ns	ns	ns	ns
SxG	<i>p value</i>	**	ns	**	**	***	***	**	***	ns	ns	ns	*	ns
Sxl	<i>p value</i>	ns	ns	**	ns	ns	***	*	ns	ns	ns	ns	ns	ns
Gxl	<i>p value</i>	**	ns	ns	*	*	ns	***	***	ns	ns	ns	ns	ns

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275

276 CDI treatments led to an important decrease in the amount of water used for irrigation during
277 phase 2, i.e. following the first fruit set (Table 1). In Navarra water savings for the whole cycle
278 were similar both years. With the 100-75% ET_c regime, 14.5% and 13.8% of water were saved in
279 2012 and 2013 respectively. With the 100-50% ET_c regime, water savings doubled, reaching
280 levels of 29.3% and 27.7% respectively. On the other hand, in Extremadura water savings were
281 much lower in 2013 due to the poor climatic conditions. In 2012 savings reached 15.1% and
282 30.3% for the 100-75% and 100-50% regimes respectively, while in 2013 these values almost
283 halved (8.6% and 17.2% respectively).

284 The genotype had a significant effect on all the agronomic and basic quality parameters, with the
285 exception of soluble solids content (Table 2). The highest commercial yield corresponded to the
286 cultivar ‘H-9036’. Its high productivity (23.4% higher than the next cultivar) lead to the highest
287 soluble solids yield. But, this cultivar showed the lowest Hunter a/b ratio and thus, a less intense
288 red pigmentation. The lowest commercial yield, the percentage of commercial fruits, and soluble
289 solids yield were found in the high lycopene cultivar ‘ISI-24424’. However, ‘ISI-24424’ was
290 characterized by the highest average weight per fruit and water content. Both high lycopene
291 cultivars ‘ISI-24424’ and ‘H-9997’ registered the highest Hunter a/b ratio related to an intense
292 red pigmentation. ‘H-9997’ also had the highest percentage of dry matter. The differences in pH
293 among cultivars, being significant, were limited. ‘ISI-24424’ reached the highest pH values and
294 ‘H-9036’ the lowest.

295 Most of the studied traits showed important environmental interactions (Table 2). Therefore, a
296 detailed analysis was performed for each location and year using MANOVA biplots. In
297 Extremadura, the effects of CDI were much limited than in Navarra, as fewer variables were
298 significantly affected by DI (solid lines) and confidence circles were larger in the MANOVA
299 biplot (Fig. 2). Indeed, in Extremadura, in 2012, the differences between the control and 100-
300 75% ET_c were limited for most parameters while 100-50% ET_c clearly increased soluble solids
301 content (Fig. 2). On the other hand, in 2013 the differences between CDI strategies and the control
302 were negligible. In fact, as stated above, the differences in water savings were limited. For
303 Navarra, differences were already found in the agronomical performance between the control and
304 the milder CDI treatment (100-75% ET_c). Nevertheless, in 2013, with the worst climatic
305 conditions, the differences between CDI 100-75% ET_c and the control were much lower. In both
306 years, CDI 100-50% had clear negative effects on agronomical performance.

307 In order to provide an idea of the genotypic interactions with irrigation treatments and years,
308 relative commercial yields were calculated comparing the values obtained with CDI treatments
309 and the control (Fig. 3). This analysis revealed that the effect of CDI on yield was highly
310 dependent on the genotype and environmental conditions. In fact, in Extremadura, CDI treatments
311 only had a significant effect on yield for cultivar “H-9036”, while in Navarra the effects of CDI
312 were detected at some point for most of the cultivars. In general, the conventional cultivar ‘H-
313 9036’, with maximum productivity (Table 2), was highly sensitive to CDI treatments. It was also
314 the cultivar that experienced a higher reduction in yield when a high (100-50% ET_c) and mild
315 (100-75% ET_c) CDI treatments were compared. In contrast, the high lycopene cultivar ‘ISI-
316 24424’, characterized by its low productivity, registered no impact of CDI on yield, even with the
317 most restrictive dose in most environmental conditions. Considering the loss of production for
318 each year and cultivar, at the higher CDI level (Fig. 3) a mean reduction of 10.3% was obtained
319 in Navarra, and 7.3% in Extremadura.

320 Previous studies regarding DI during two years in Navarra showed that continuous restricted
321 irrigation from transplant to harvest using 75% ET_c requirements, despite saving 28.2% of water,

322 led to a general loss of 16.4% of commercial production. Nevertheless, significant interactions
 323 were detected and the impact depended on the cultivar and the specific environmental conditions
 324 of each year (Lahoz et al. 2016). The mean loss of productivity may seem low, but it is still too
 325 important for DI to be considered as a production alternative for farmers.

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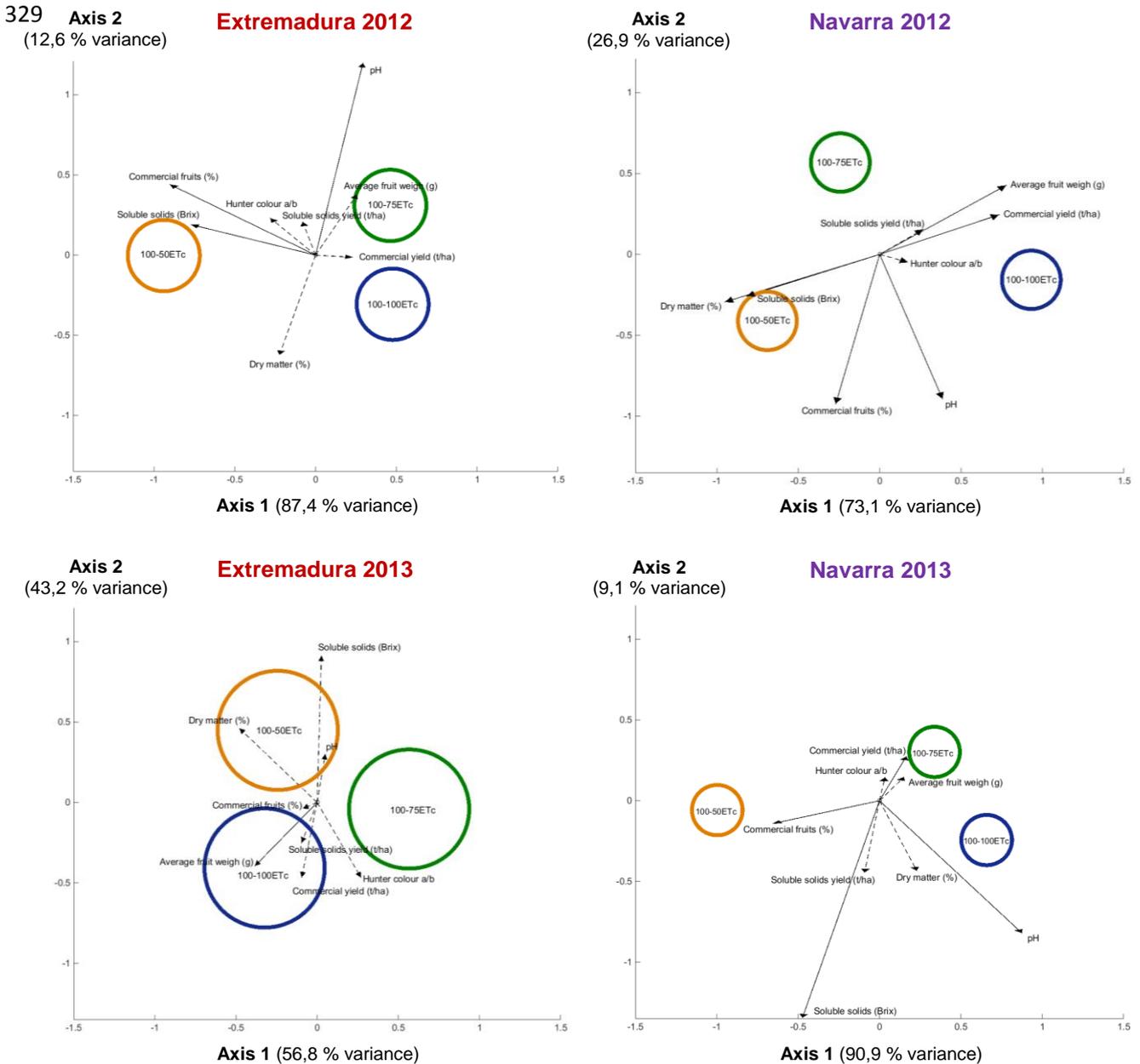


Fig. 2 MANOVA biplot representing the impact of mild 100-75% ET_c and moderate 100-50% ET_c controlled deficit irrigation applied after first fruit set, CDI, strategies over the control (100-100% ET_c) on agronomic performance and basic quality parameters. Discontinuous lines indicate a non-significant effect (ANOVA, p=0.05). Circles represent univariate confidence limits.

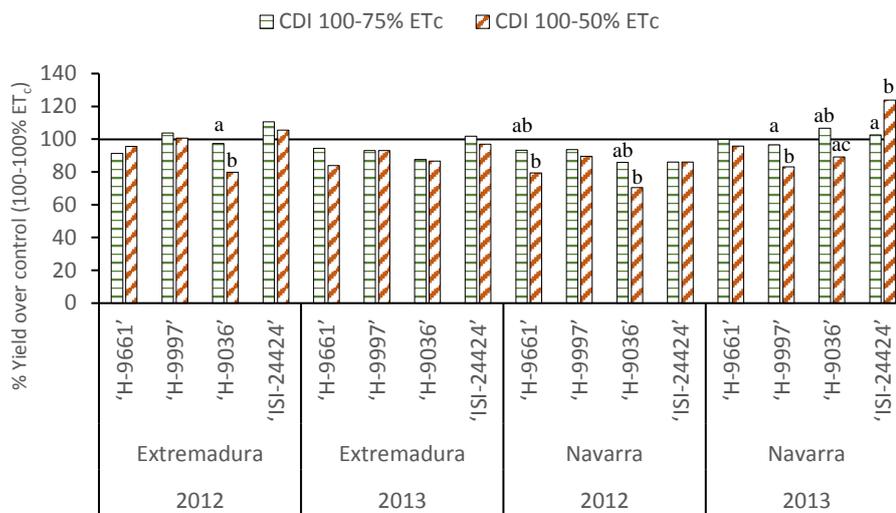


Fig. 3 Relative commercial yield of CDI treatments compared to the control receiving 100% ET_c (horizontal thick line) during the whole cycle. For each cultivar, no letters: non significant effect of water dose (ANOVA, p=0.05); a: no significant differences with 100% ET_c control; b or c: significant differences with other treatments (Tukey, p=0.05).

In the present work, using similar materials and areas of production, CDI, with water restrictions applied only after fruit set, has proved to be a better strategy to reduce water usage in tomato production and minimize the impact on yield. Mild CDI levels, 100-75% ET_c resulted in a mean reduction of water usage of 13.0%, and in the specific conditions of Navarra a mean reduction of 14.2%. At the same time, this water saving was obtained with no significant impact on commercial yield. A higher CDI level would double water savings (mean 26.1% reduction in water use), but it would imply a mean reduction in yield of 10.9%. Interestingly, the effect of CDI was strongly dependent on the cultivar considered. Highly productive materials seem to be more sensitive to water shortages than cultivars with lower production levels and consequently, CDI strategies are more suitable for quality-based markets, rather than quantity-based markets.

It is true that DI and CDI were not contrasted in the same environmental conditions, but both studies included four cultivars and two years of cultivation, thus the results are quite robust. That would mean that a CDI strategy with a higher water restriction level (100-50% ET_c) following fruit set would probably lead to approximately the same water saving than applying a milder water reduction during the whole cycle (75% ET_c) and the effects on productivity would be more limited. Anyway, a CDI level of 100-50% ET_c would still be too harsh for farmer adoption, at least in Spanish conditions, and a milder reduction would represent the best deficit irrigation strategy to contribute to reduce water use and still represent a real alternative for farmers.

In other conditions, the impact of DI and CDI strategies seem to be lower. For example, in Italian conditions, Favati et al. (2009) found that continuous DI with moderate restrictions (50% ET_c) led to a clear decrease of production (37.6% and 46.2% in a two year study), while a CDI strategy (100-50% ET_c) had no significant effect one year and slightly reduced yield, a 7% during the other year. Also in Italy, Patanè et al. (2011) found an even lower impact of DI strategies, as

380 continuous restriction down to 50% ET_c did not significantly affect yield. Similarly, under Indian
381 conditions, a continuous DI of 80% ET did not have a negative impact on commercial yield, but
382 further restrictions (60% ET) did have a negative effect, reducing yield by 24.8% (Nangare et al.
383 2016). In the same conditions, a CDI of 60% ET during the fruiting stage had a limited impact in
384 yield (5.4%).

385 In their review on DI strategies, Geerts and Raes (2009) concluded that DI was successful in
386 increasing water productivity for various crops without causing severe yield reductions if a certain
387 minimum amount of seasonal moisture is guaranteed. Nevertheless, the authors stated that DI
388 strategies are targeted to maximize water productivity and to stabilize, rather than maximize,
389 yield. This conclusion is strongly supported by the present and previous works. Effectively, DI
390 strategies based on mild restrictions optimize the use of water with a slight impact on yield and
391 could be an option for certain areas. On the other hand, mild CDI strategies entail a lower
392 reduction in water use but at the same time have no impact on yield, being a better option for
393 quantity based agricultural systems.

394

395 3.3. *Effect on sugar and acid accumulation*

396 Apart from reducing the use of water, DI has been proposed as an alternative to offer high quality
397 products. An approach that has also been pursued in other studies promotes the use of saline water
398 (De Pascale et al. 2001). A moderate level of continuous DI (50%) proved to increase dry matter
399 and soluble solids in Italian conditions, an effect that could also be achieved applying water
400 restriction during the last phases of the cycle following a CDI approach (Favati et al. 2009). In
401 that study, the mean increase with CDI, 8.1%, was considerably lower than using a DI strategy,
402 13.5%, and highly dependent on environmental conditions. In Spanish conditions, a mild level of
403 DI also led to a modest mean increase in the soluble solids content of 8% (Lahoz et al. 2016). The
404 present study confirmed that moderate CDI levels (100-50% ET_c) increase dry matter (3.8%) and
405 soluble solids content (8%), thus reaching the same improvement as with mild (75%) DI.

406 Other studies have reported a larger effect. In this sense, Nangare et al. (2016) found that DI with
407 80% ET_c increased soluble solids content by 50%, though further restrictions (60% ET_c) had a
408 similar effect (60% increase). This effect could also be achieved with a CDI of 60% ET_c (56%
409 increase). Not always has continuous DI been related to these effects. For example, Pernice et al.
410 (2010) found that a reduction of 50% of water usage compared to normal irrigation had no effect
411 on dry matter and soluble solids content neither in processing nor fresh tomatoes.
412 Notwithstanding, other authors have found more marked differences. Ripoll et al. (2016) found
413 that a restriction of water usage (40%) specifically during the maturation stage would lead to an
414 increase of 17.6% of dry matter, an effect not achieved if the restriction was applied in earlier
415 stages. Nevertheless, in that case, soluble solids content was not affected.

416 In our work, MANOVA test confirmed that the site and year of cultivation, irrigation dose, and
417 genotype all had a significant effect on the accumulation of sugars and organic acids (Pillai trace,
418 $p < 0.01$).

419 Individual ANOVAs confirmed a significant effect of the year on the concentration of all
420 compounds with the only exception of citric acid (Table 2). The year 2012 was more favorable
421 for the accumulation of glutamic acid, while the year 2013 showed higher contents of sugars,
422 malic acid.

423 The site of cultivation had a significant effect on the contents of organic acids (Table 2). The
424 higher contents in citric and glutamic acid found in Navarra, and the lack of effect of the site of
425 cultivation on sugar accumulation, would imply lower sugar to acid ratios in this location. The
426 conditions of Extremadura were more favorable for the accumulation of malic acid.

427 The effect of irrigation dose was limited since it was only significant for the accumulation of
428 malic acid, with higher contents in the control dose, 100-100%ET_c (Table 2). The highest effect
429 on sugar and acid accumulation, in fact, depended on the genotype. The conventional cultivar ‘H-
430 9036’ showed the highest levels of sugars and glutamic acid. The high lycopene cultivar ‘ISI-
431 24424’ was outstanding for sugar accumulation and showed the highest malic acid contents and
432 the lowest citric acid contents. The high lycopene cultivar ‘H-9997’ showed the highest citric acid
433 content. The conventional cultivar ‘H-9661’ had high glutamic acid content and low sugar
434 accumulation, which imply low sugar to acid ratios.

435 Significant year x site of cultivation, year x genotype, and site of cultivation x genotype
436 interactions were detected. There were no interactions with irrigation dose, which confirmed that
437 the low impact of CDI on sugar and acid accumulation was independent of the genotype or
438 environment considered (Table 2).

439 Altogether, these results show that even achieving a modest increase in soluble solids, this
440 increase would not be due to a higher accumulation of sugars and acids, as the effect of irrigation
441 dose on the accumulation of fructose, glucose and citric acid was not significant, and the contents
442 of malic acid were only slightly reduced. Therefore, CDI even at moderate levels, would not
443 promote the accumulation of taste-related compounds in processing tomato.

444 As reviewed by Ripoll et al. (2014) water deficit entails an increase in sugar content, especially
445 when deficit affects the last stage of fruit ripening. For organic acids, the effects of water deficit
446 are less clear as some studies correlate with higher contents and other with the opposite. In fact,
447 moderate water deficit has been suggested as a useful tool to improve fruit quality, mainly by
448 metabolic effects, especially for sugars and acids related to taste, as no positive impact is expected
449 regarding carotenoid and ascorbic acid contents (Ripoll et al. 2016). In this latter study contents
450 of fructose and glucose tended to increase, while citric and malic acid tended to decrease, though
451 the response was higher in less tasty cultivars than in tasty ones. It was also suggested that
452 different cultivars would show a different rate at which they develop adaptive responses to water
453 deficit. In the present study, the sugar content was not significantly increased independently of
454 the sugar accumulation capacity of the cultivars, as important differences were found for fructose
455 and glucose contents among cultivars in the control treatment. It seems then, that the CDI levels
456 applied here would not be as intense as to provoke changes in sugar and acid accumulation or that
457 the cultivars included in the study would have a slow adaptive response.

458 With respect to other quality parameters, Zegbe-Domínguez et al. (2003) found that DI or partial
459 rootzone drying led to maintenance or increase of the redness of fruit. Favati et al. (2009) stated
460 that the redness of the fruit only increased with moderate DI regimes (50% ET_c). Lahoz et al.
461 (2016) also found a small increase with milder DI treatments (75% ET_c), but the effect on
462 lycopene accumulation was not significant. In the present work, the color of tomatoes was not
463 affected by CDI, not even with the higher level. The evaluation of CDI on functional value already
464 had confirmed that CDI would not have a significant effect on the accumulation of carotenoids
465 (Martí et al. 2018). However, they also confirmed a positive effect on the accumulation of the
466 hydroxycinnamic acids chlorogenic and ferulic acids, the flavonoid rutin and L-ascorbic acid.
467 That means, that despite not influencing the accumulation of taste-related compounds, CDI would

468 represent an added value increasing the levels of hydroxycinnamic acids and flavonoids related
469 with the prevention of cancer (Martí et al. 2016) and other degenerative diseases (Martí et al.
470 2019). Nonetheless, this positive effect on the functional value of tomato would be highly
471 dependent on the genotype and environmental conditions, with Navarra conditions and mild CDI
472 level (100-50% ET_c) being more favorable (Martí et al. 2018).

473

474 **4 Conclusions**

475 CDI strategies applying the same level of water restrictions after fruit set seem to have a lower
476 impact on yield than DI strategies based on a continuous water restriction. In the present work,
477 moderate CDI levels (100-50 ET_c) led to considerable water savings but had a significant negative
478 impact on yield. Nevertheless, this effect was highly dependent on the environment and cultivar
479 considered. In Navarra, with environmental conditions leading to maximum productivity, the
480 effects of moderate levels of CDI were noted, while in conditions such as those of Extremadura
481 the effect was be limited. In both environments, moderate levels of CDI had a higher impact on
482 high-yielding cultivars. This fact could represent a considerable handicap restraining farmer
483 adoption of the strategy, as quantity still seems to be more valued than quality. On the other hand,
484 CDI would have a slight positive impact on soluble solids content. Nevertheless, irrigation dose
485 had no significant impact on the accumulation of fructose, glucose, citric and glutamic acids and
486 reduced the levels of malic acid. Accordingly, the positive impact on soluble solids would not
487 necessarily result in better organoleptic quality. Milder CDI levels (100-75 ET_c) had no impact
488 on the accumulation of sugars and acids, nor on soluble solids, but more importantly, it had no
489 impact on commercial yield. At the same time, considering previous results mild levels of CDI
490 would increase the functional quality of the production increasing the levels of polyphenols and
491 L-ascorbic acid. Consequently, this would represent the ideal deficit irrigation strategy to combine
492 sustainability both from the environmental and the farmer point of view. Thus, it would be easy
493 to be assimilated by farmers, contributing to save an increasingly scarce resource, water, and to
494 contribute to enhanced health benefits of tomato intake on consumers.

495

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500 **Conflicts of Interest** The authors declare that they have no conflict of interest.

501

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