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Tomato fruit quality and processing ability are impacted by irrigation regime as well as genotype and maturity stage.

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Abstract

In order to investigate how pre-harvest conditions impact fresh fruit quality, and especially their quality attributes related to industry use, we identified and quantified fresh fruit traits which are impacted by low water supply and their consequences on puree quality, with a focus on viscosity, sugar/acid balance and carotenoid content. A first trial in 2016, indicated that lowering water supply to 50% of the evapotranspiration (ETP) all along the fruit development impacted plants without significantly affect yields, but impacted the fruit reactivity to the process. To confirm these results, and seek for the limits of reducing water supply, the same experimentation was design except that a more severe water deficit was applied. Control plants were irrigated in order to match 100% of the (ETP). Water deficit (WD) plants were irrigated as control plants was until anthesis of the first flowers, and then, the irrigation was reduced to 50% of the ETP. The results obtained in 2017 were compared to those obtained in 2016 on the basis of same variables. Soil humidity, leaf conductance, leaf and fruit water potential and fruit growth were monitored revealing interactive effects between crop and process management. It pointed out links between fresh fruit characteristics and puree quality, depending on genotype and watering regime. As in 2016, WD hardly reduced yield, but increased dry matter content. The puree viscosity strongly depended on the genotype, and the viscosity was disconnected from the soluble solid content (brix). The fruits enzymatic reactivity, estimated through the difference of viscosity measured between hot-break and cold-break purees were reduced dramatically under WD for all the genotypes. This work opens new perspectives for managing puree quality in the field and for reducing water use in the pre-harvest period and energy cost during processing.

Keywords: Quality, *Solanum lycopersicum*, deficit irrigation, pre- and post-harvest links, antioxidants, thermal processing, consistency

INTRODUCTION

Processing tomato is a major crop that represents the principal source of important phytonutrients such as β -carotene and lycopene (Dorais, Ehret et al. 2008). The main part is consumed as tomato puree, paste, or sauce (Mirondo and Barringer 2015). Tomato culture is concerned by the agricultural use of fresh water for irrigation (Postel, Daily et al. 1996). Water resources are indeed under threat and the gap between water availability and demand is exacerbated by global climate changes (Afzal, Battilani et al. 2016). Processing tomato, an intensive production in terms of water use, is highly concerned with this issue (Rinaldi, Ventrella et al. 2007). The yield reduction depends on water deficit intensity and duration as well as on its timing during tomato development (Rinaldi, Ventrella et al. 2007; Patane and Cosentino 2010).

51 Water availability is one of the main factor impacting plant growth and consequently
52 harvestable yield (Boyer 1982; Tardieu, Granier et al. 2011; Katerji, Campi et al. 2013; Ripoll,
53 Urban et al. 2014). WD reduces the weight of individual fruits more than the number of fruits
54 per plant (Casa and Rouphael 2014). Because mild WD decreases fruit water accumulation more
55 than dry mass accumulation, the decrease in yield may in fact turn out positive for processing.
56 Indeed, tomato process includes a phase of dehydration/concentration, and reducing water
57 content of raw material makes the process more efficient. Large variations in paste quality traits
58 (color, consistency, soluble solid content, pH and titratable acidity) were found among cultivars
59 (Garcia and Barrett 2006). High viscosity, fresh flavor and retention of natural color are
60 important quality traits of ketchup and tomato puree (Chong, Simsek et al. 2009). Concerning
61 viscosity, dehydration during processing has a major influence. However, relationships between
62 dry matter content and viscosity on one hand, and between dry matter content and soluble solid
63 content (SSC, in °Brix) on the other hand, are well-known from manufacturers since puree price
64 is based on °Brix. However, SSC is not the only factor affecting rheology (Barrett, Garcia et al.
65 1998). Processing parameters such as breaking temperature and dynamic sieving modify the
66 water soluble/insoluble solid content ratio, particle sizes and pectin state, which, in turn, affect
67 the puree rheology (Sanchez, Valencia et al. 2002; Moelants, Cardinaels et al. 2014). Those
68 physicochemical variables depend on the biological structures of fruit tissues and their reactivity
69 to the process. For example, breaking temperature is currently used to modulate the consistency
70 of tomato products: a high temperature treatment, immediately after fruit crushing (hot break,
71 HB: 90°C) produces much more viscous purees than cold break (CB) treatment, where fruits are
72 first crushed and then macerated at moderate temperature (70°C; Moelants et al., 2014). The
73 quality of tomato puree is built throughout the food chain. Currently, in industry, the quality of
74 processed fruits is assessed through the color and Brix index only, whereas other physical,
75 structural and biochemical traits are overlooked. Insights into interactions between factors that
76 drive fruit quality during the growing season and those that operate during processing must be
77 more mastered, so in this work we investigated fruit quality in response to water supply and
78 genotypes for the second year in a row, and we assessed their impact on puree quality obtained
79 from HB and CB processes at the maturity to confirm data obtained in the previously season
80 published by Vilas Boas et al, 2017.

81 82 **1. MATERIALS AND METHODS**

83 Four industry-type (determinate) cultivars of *Solanum lycopersicum*, namely “H1015,”
84 “H1311,” “Miceno,” and “Terradou” were used following the criteria of choice of the previous
85 experiment in the year 2016 (Boas, Page et al. 2017). All seeds were germinated under standard
86 glasshouse conditions (25°C day, 15°C night) near Avignon, France, in April 2017. Plant were
87 transfer to field by the beginning of June.

88 Two blocks of 1,800 plants each (450 plants per cultivar) were designed in an
89 experimental field near Avignon (43°54'N 4°52'E), France. Each block was 7 m wide and 90 m
90 long and surrounded by border tomato plants. The four genotypes and the two irrigation
91 regimes were randomly distributed within the two blocks. All plants were grown under
92 conventional tomato management in France. Irrigation was supplied by a drip irrigation system.
93 It was scheduled daily to compensate the evapotranspiration loss from tomato crop (ETP). ETP
94 was determined daily using reference evapotranspiration estimated from the Penman–Monteith
95 equation (Monteith 1965) and taking into account crop coefficient (Kc) and precipitations.
96 Water was first supplied every day in order to fully fit 100% of ETP. Forty-five days after sowing,
97 two levels of irrigation were applied: (1) water deficit (50% replacement of ETP) and (2) well-
98 watered (control) to match 100% replacement of ETP. To mimic current production practices,
99 irrigation was stopped two weeks before harvest. The soil water potential was recorded hourly
100 using Watermark (Campbell Scientific, Antony, France) soil moisture sensors (six per water
101 regime), which were installed at 25 and 50 cm depths.

102 **1.1 Plant and fresh fruit measurements**

103 During the WD treatment, from June to August 2017, the records showed reduced soil
104 humidity at 25 cm depth when compared to the control. Control plants experienced higher soil
105 water potentials than plants under WD at 25 cm depth. Under well-watered condition, 50% of
106 the data (between the upper and the lower quartile) ranged from -38 to -13 kPa, while under
107 WD 50% of the data ranged from -57 to -27 kPa. At 50 cm depth, soil water potentials remained
108 similar between the two irrigation treatments.

110 **1.2 Fresh fruit quality**

111 Dry matter and soluble solid content (SSC) were measured at the harvest. The dry matter
112 content was determined by weighting 3 g of fruit pericarp pieces before and after drying at 85°C.
113 The SSC was measured by refractometry with an ATAGO PR-1000 digital refractometer with
114 automatic temperature compensation at 25°C and results were expressed in degree Brix,
115 according to AOAC (2002) (AOAC 2002) after the fruits are mixed in a blender.

117 **1.3 Tomato processing and quality**

118 Purees from red ripe fruits were prepared by either hot break (HB) or cold break (CB)
119 treatment according to a laboratory scaled method described by Page et al. (2012). Fruits were
120 cut into large pieces (around 2 cm³), mixed altogether, and split into two identical batches of
121 400g each. For HB, one batch was first heated until boiling temperature in a microwave oven
122 (900w, full power, 0.9s.g⁻¹ of tomato), then chopped for 30 s in a Waring® blender. For CB, the
123 other batch was first chopped at room temperature for 30s in the same Waring® blender and
124 then heated for the same duration and conditions than for HB. Both purees were then passed
125 through a hand-held potato masher with a 2mm grid to remove skins and seeds, stored into a
126 500 ml glass jar with sealed lid, sterilized for 15min at 100°C in a laboratory scaled autoclave,
127 and stored at 4°C before analysis. The grinding step at room temperature in CB process allowed
128 for the reaction of fruit intrinsic enzymes (especially polygalacturonase and pectin-methyl
129 esterase) on cell walls, and therefore leads to lower consistency of purees compared to HB ones
130 (Anthon et al., 2002). Consequently, the enzymatic potential of fruits was indirectly estimated as
131 the difference in puree consistency between HB and CB processes, in our standardized
132 conditions. The color of the purees was measured with a Minolta CR.400 using a specific cuvette
133 for measurement of liquid or paste color and calibrated against a white background. Color
134 results were expressed in the CIE L * a * b * color space. Color coordinates were used to calculate
135 the hue angle (H°), which identifies the color at a 360° angle (McGuire 1992). The dry matter
136 content was determined by weighting around 3 g of fruit puree before and after drying for 3
137 days at 85°C. The soluble solid content (SSC) was measured by refractometry with an ATAGO
138 PR-1000 digital refractometer with automatic temperature compensation at 25°C and results
139 were expressed in degree Brix, according to AOAC (2002). The pH was determinate using a ph
140 meter. Rheological behavior of the puree was assessed through characteristic measurements:
141 the viscosity was calculated from a steady state measurement performed on an Anton Paar MCR
142 301 viscosimeter (Graz, Austria), with a double ribbon impeller (with an inner radius of 11 mm,
143 a pitch of 45 mm, a length of 45 mm, and an outer stationary cup with an outer radius of 14.46
144 mm). A flow curve was registered between 0.1 and 100 s⁻¹, 50 points and 5 s per point. Flow
145 properties were described by the Herschel-Bulkley model (Espinosa, To et al. 2011).

147 **1.4 Data analyses**

148 Data were analyzed using R statistical software (<http://www.R-project.org>).
149 Physiological traits, data of yield, and quality traits were analyzed by analysis of variance (the
150 agricolae R package and aov function; De Mendiburu, 2014). Heteroscedasticity and normality
151 tests were performed before model evaluation. When the ANOVA F-test showed no significant
152 difference in means between the blocks, data from block 1 and 2 were pooled. Multiple
153 comparison of means was performed using the Least Significant Differences (LSD) test ($\alpha =$
154 0.05). When heteroscedasticity was detected, we used the Kruskal-Wallis non-parametric test
155 followed by multiple comparisons of means through a t-student test on the ranks ($\alpha = 0.05$).

156 **2. RESULTS AND DISCUSSION**

157 Univariate ANOVAs were performed on plant and fruit traits to analyze the effects of WD,
158 genotype, cooking, blocks and their interactions. Results were compared to those obtained in
159 2016 by Boas et al (2017).

160

161 **2.1 Fresh Fruits Biomass and Quality Affected by Water Deficit**

162 To the contrary of what was observed in the 2016 experiment, in 2017 the fresh fruit
163 biomass decreased in production when the plants were exposed to water deficit (figure 1A). The
164 WD treatment produced -11% for “H1311”, -30% for “Miceno”, -24% for “Terradou” and -34%
165 for “H1015”. However, analyzing dry weight yield, the results went to the same direction as
166 observed in the experiment of 2016 with the WD slightly increasing the total dry fruit biomass
167 for H1015 (+29%) and H1311 (+11%), but no differences were revealed for “Terradou” and
168 “Miceno” (figure 1B). With this result, it can be stated that even with a decrease in the
169 production of fresh biomass, which is expected when a water deficit is applied, the total dry
170 biomass remained at least at the same level as the control plants.

171 Water deficit also slightly increased the fruit dry matter content (DMC) (Figure 2A) and
172 fruit soluble solids content (SSC) (Figure 2B). These results are in agreement with previous
173 works on the effects of moderate deficit irrigation on processing tomato (Boas, Page et al. 2017),
174 and correspond to the objective of the industry consisting in saving energy for water
175 evaporation by treating raw fruit with higher dry matter content. The increased of the fruit DMC
176 was up to +30% for “Miceno”, +29% for “H1015”, +24% for “Terradou” and +22% for “H1311. It
177 is important to note that there was an increase of approximately two points in the value of SSC
178 in the year 2017, compared to the year 2016, in particular, H1311 closed a gap with Terradou,
179 while it was 2 points lower in our previous study. It seems that H1311 is more sensitive to
180 environmental factors than Terradou.

181 The increase in fruit dry matter content in response to WD is well-known (Ripoll et al.,
182 2014). Ripoll et al. (2016)(Ripoll, Urban et al. 2016) have already underlined that beneficial
183 effects of moderate WD on fruit sugar, acid and carotenoid contents, reported on a fresh weight
184 basis, mainly results from a dehydration effect, which is confirmed by Boas et al (2017) and in
185 this study. In addition, effects of WD on fruit DMC strongly depend on genotype and stress
186 intensity (Ripoll et al., 2016). In our study, the WD applied from flowering to harvest did not
187 modify the ranking of genotype in terms of DMC and SSC. The reduction of fresh fruit yield has
188 been already obtain in industry type tomato, but, here we demonstrate that significant gain in
189 tomato watering can be obtain without any loss of dry matter production per ha, if WD is
190 monitored all along the fruit development (Stikic, Popovic et al. 2003; Patane and Cosentino
191 2010)

192 **2.2 Genotype Controlled Puree Quality While WD Improved Rheological Properties**

193 Tomatoes fruits were processed through CB and HB methods and puree quality
194 was assessed based on puree viscosity, puree dry matter content (DMC), puree soluble
195 solids contents (SSC) and color parameters (H°). In all tests, no bloc effect was found,
196 except for SSC and color. We further analyzed the interactions between genotype and
197 irrigation treatment, and their effects on puree rheological properties (Figure 3). For
198 viscosity, the genotype, irrigation and cooking effects were significant. Cultivar was the
199 main effect, and especially “H1311” produced the most viscous purees in all situations
200 (Figure 3A), as already obtained. Regarding the fruit composition, the difference of
201 viscosity cannot be related to dry matter content of the fruits or soluble solid content, as
202 minor difference of dry weight content was observe between H1311 and other cultivars,
203 indicating that, other mechanisms governed viscosity changes in tomato purees. This
204 result is consistent with result obtain for apple purees (Espinosa-Munoz, Symoneaux et
205 al. 2012; Leverrier, Almeida et al. 2016) were particle structure and serum viscosity are
206 pointed out as primary factors determining puree viscosity. As observed in the 2016
207 experiment, the WD applied in our experiment improved puree viscosity of all cultivars,
208 despite no change in fruit composition (on a dry weight basis) and no correlation

209 between fruit dry matter content and puree viscosity. WD led to significant higher
210 viscosity of purees, presenting +57% in “H1015”, +33% for “Terradou”, +10% at
211 “H1311”, +9% in “Miceno”. Puree dry matter content confirmed indeed that WD purees
212 contains higher DMC as was fruit dry matter content (fig 4A). Interestingly only results
213 between genotypes showed significant differences for the differences of viscosity
214 between HB and CB process (figure 3B), which leads to a different response to what was
215 observed in the year 2016, where also the cooking processes affected the difference of
216 viscosity. Here, to the contrary, the higher viscosity may be related to the higher dry
217 matter content of fruit, as our experimental purees are not further concentrated after
218 fruit chopping, heating and sieving.

219 We still propose that the effect of WD on puree rheology was driven by changes
220 in pectin composition, and by changes in particle size and shape. Indeed, transcriptome
221 analysis has revealed that plant response to drought includes differential cell wall
222 synthesis and remodeling (Tenhaken 2015). The difference in rheology after HB and CB
223 treatments is attributed to temperature effects on endogenous pectinolytic enzymes,
224 namely polygalacturonase (PG) and pectin methyl-esterase (PME) involved in fruit
225 softening (Anthon and Barrett 2002; Moelants, Cardinaels et al. 2014). The involvement
226 of these enzymes has been confirmed by HB/CB processing of genetically modified
227 tomatoes (Errington, Tucker et al. 1998), but the exact relationship between PG, PME
228 and rheology remained partially obscure. Indeed CB treatment leads to different
229 biochemical and physical properties of water soluble pectins when compared to HB (Lin,
230 Aizawa et al. 2005; Lin, Qin et al. 2005). The proportion of water insoluble solids is not
231 significantly different between CB and HB purees (Sanchez et al., 2002), but particle size
232 and shape are also impacted by the breaking temperature (Errington et al., 1998). It has
233 been shown in other plant species, that pectin-degrading enzymes can be down-
234 regulated by water stress (Le Gall, Philippe et al. 2015). Thus, the activity of pectin-
235 degrading enzymes in response to WD should be analyzed in further details to
236 disentangle the effect of pectinolytic enzymes from the effect of particles.

237 PH of purees showed high variability of values between cultivars. PH ranged from 4.28
238 (“Miceno”) to 4.46 (“H1311”). PH was not influenced by WD for any of the cultivars (data not
239 shown). However, when regarding the cooking processes we obtained a significant pH
240 differences (from 0.2 to 0.4 more for HB compared to CB). This result is consistent with previous
241 result indicating that no significant effects on fruit biochemical composition were detected
242 between WD and control. The higher pH of HB purees may be a problem especially for cultivar
243 exhibiting pH close to the value of 4.5, generally considered as a limit for the self-protection of
244 acid-food (like tomato puree are) regarding microbiological contamination.

245 About the color parameters, Hue angle (H°) values were significantly affected by
246 genotype, cooking, irrigation and blocks. Despite the differences between the blocks, the
247 behavior of the puree’s colors paralleled in both, with purees from “H1311” fruits presented the
248 lowest values of H° , and consistently with the higher content of lycopene of this cultivar. All
249 H1311 are more red than the others, which was also verified in the experiment of the year 2016.

250

251 3. CONCLUSION

252 Results obtained in 2017 confirmed the results already presented in the year 2016
253 indicating that tomato fruit quality and processing ability are impacted by irrigation regime as
254 well as genotype. The same variations between genotype, treatments and cooking process were
255 observed showing fruits from a water stress with higher contents of dry matter, soluble solids
256 and a higher viscosity. On the other hand, there is still no complete link between dry matter
257 content and viscosity, and so, in perspective, we have to analyze other quality components
258 (particle size, their distribution between large and small, serum viscosity) to understand what
259 changes the textures and how crop conditions influence these parameters.

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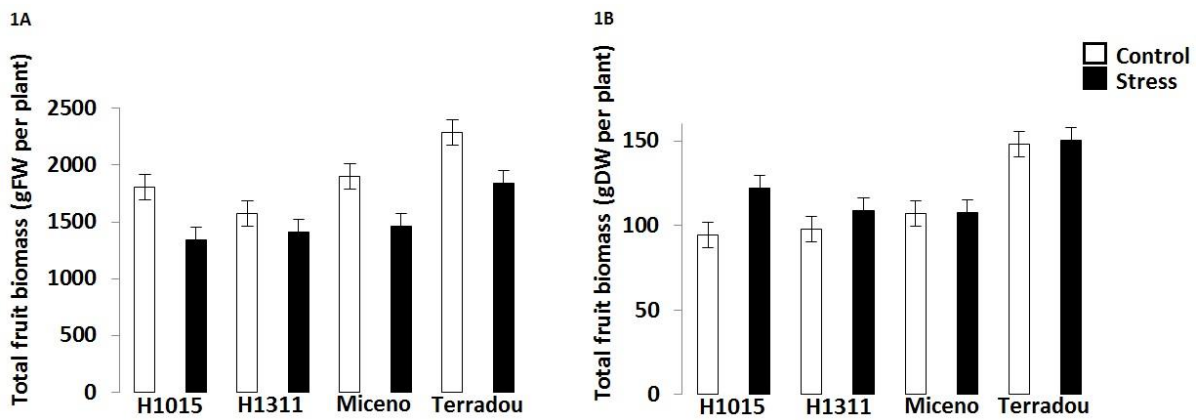
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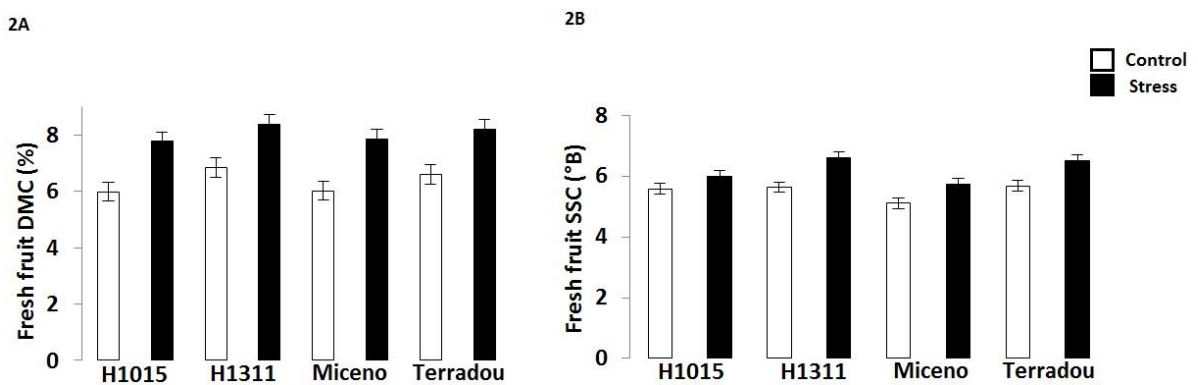
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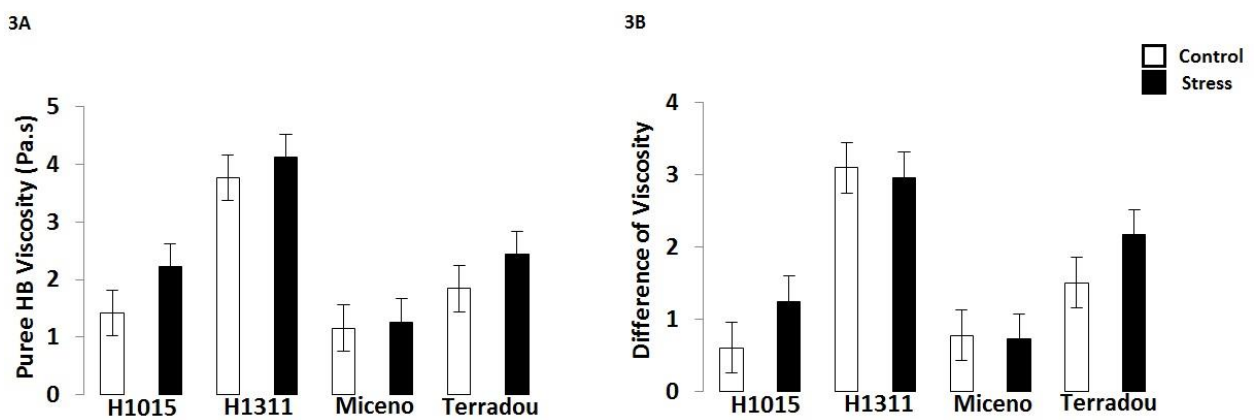
325 Figure 1. Impact of water deficit and cultivar on fresh (A) and dry (B) yield expressed as total fruit biomass (g) per plant. Note that
 326 the color code blue is for well-watered plants and gray for plants under water deficit

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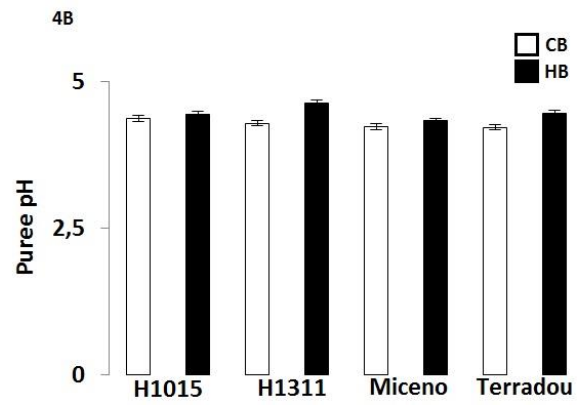
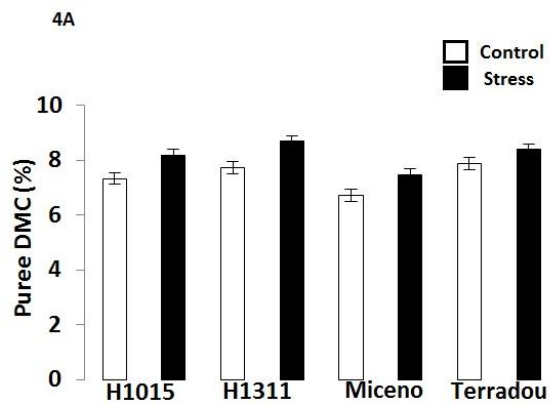
328 Figure 2. Changes in yield-related traits determined for the four cultivars conditions and under the two water regimes (control in
 329 white and water deficit in black): individual fruit fresh weight (FW) (A) and dry matter content of fruit pericarp collected at 55 DAA

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331 Figure 3. Impact of water deficit and genotype on the rheology and changes in "Hot Break" puree (A). Difference of consistency
 332 between "Cold break" and "Hot break" purees obtained from fruits collected at harvest (B).

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Figure 4. Impact of water deficit and genotype on the puree dry matter content (DMC) (A). Difference of pH between Cold break and Hot break purees obtained from fruits collected at harvest (B).