1 **Impact of mechanical and microstructural properties of potato puree-food additive complexes on extrusion-**

2 **based 3D printing**

3 Iman Dankar[#&], Montserrat Pujolà[&], Fawaz EL Omar[#], Francesc Sepulcre[&], Amira Haddarah[#]

4 [#]Lebanese University, Doctoral School of Science and Technology, EDST, Hadath, Lebanon

5 [&] Departament d'Enginyeria Agroalimentària i Biotecnologia, Universitat Politècnica de Catalunya.

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7

8 **Abstract**

9 This paper studies the applicability of extrusion-based 3D printing for constructing novel shapes from potato puree

10 and the effects of four additives (agar, alginate, lecithin and glycerol) added separately at three concentrations (0.5,

11 1, 1.5%) on the internal strength, mechanical properties, microstructure and color of potato puree. The printability of

12 the potato puree and the mixtures was assayed by examining the consistency of the extrusions and the stability and

13 accuracy of the printed patterns. The results indicate that better printing was achieved at a nozzle height of 0.5 cm

14 and a nozzle diameter of 4 mm, with concentrations of alginate and agar between 0.5-1.5% and 0.5-1%,

15 respectively, providing the best printability and end-product stability, which was attributed to their respective high

16 mechanical characteristics and specific mechanical energy (SME) values. Scanning electron microscopy (SEM)

17 revealed that more convolutions were induced in the potato puree upon the addition of agar or alginate, which

18 increased the puree stability. Three-dimensional printing did not significantly affect the surface color parameters of

19 the final product. This study showed that the 3D printing process is a critical factor for initializing the production of

20 customized healthy products.

22 Corresponding author: Dr. Montserrat Pujolà

23 E-mail: montserrat.pujola@upc.edu

24 Postal address:

Campus del Baix Llobregat UPC
C. Esteve Terradas, 8 EdificI D4
08860 Castelldefels, SPAIN

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26   **Introduction**

27   There is a growing demand for the development of customized food for specialized dietary needs, such as

28   products for athletes for recovery after training or products for expectant mothers that vary nutrient component

29   levels by reducing amounts of undesirable ingredients and enhancing the presence of healthy ones (e.g., protein,

30   vitamins, fiber). Moreover, elderly people who are facing physiological changes that occur with aging such as

31   dysphagia and decreased sensory perception require special nutritive meals. Nevertheless, pureed food is

32   delivered to them in an unappealing and unappetizing way. Children are another group of people who require

33   special dietary intake. Children are more willing to consume healthy and nutritious snacks if they are presented

34   in an innovative and fun way (Dankar, Haddarah, Omar, Sepulcre, & Pujolà, 2018). However, the development

35   of such customized foods must be conducted in a very precise and inventive way, which is where the role of 3D

36   printing appears.

37   Three-dimensional food printing is an innovative technique that is of great potential interest and is continuously

38   under debate for both consumers and food scientists due to its broad array of uses (Severini, Derossi, Ricci,

39   Caporizzi, & Fiore, 2018). The application of 3D food printing could be summarized as the ability to provide

40   customized food to certain groups of people (de Roos, 2013) and to automatically generate a specific code to

41   adjust composition, density or structure to the preferences and needs of the user. Moreover, 3D printing has

42   demonstrated some interesting applications for industry by enhancing efficiency through the consolidation of

43   multiple steps or even entire food production processes (Bak, 2003; Sun et al., 2015). For instance, the PepsiCo

44   company decided to incorporate 3D printing in the manufacturing of its potato chips to save money and create

45   healthier food after suffering serious problems in the sales of sugary drinks and fatty snacks (Simon, 2015).

46   Extrusion printing through a syringe nozzle is the most popular technique employed because of its ability to

47   process the widest array of foods, such as printing with mashed potatoes (Southerland, Walters, & Huson,

48   2011), chocolates (Hao et al., 2010), cookie dough (Lipton et al., 2010), soft cheeses (Le Tohic et al., 2018),

49   hydrogels and fibers (Lille, Nurmela, Nordlund, Metsä-Kortelainen, & Sozer, 2017; Wang, Zhang, Bhandari, &

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50   Yang, 2018) and blends of fruits and vegetables (Severini et al., 2017), and if coupled with more than one

51   syringe, this technique can provide an infinite number of combinations of and a high degree of freedom for

52   foods.

53   On the other hand, important factors should be taken into consideration when extrusion printing. Maintaining

54   compatibility between specific printing parameters and the corresponding printed substance is crucial to ensure

55   high feasibility for 3D printing. The essential process parameters that can be modulated are the printing speed,

56   the distance between the nozzle and the printing bed and the nozzle size; these are critical criteria that influence

57   the final resolution of the constructed shape (Hao et al., 2010; Zhuo, 2015;Derossi, Caporizzi, Azzollini, &

58   Severini, 2018). Additionally, monitoring the properties and composition of the food material itself (ingredient

59   rheology, electrical conductivity, density, textural quality, and physiochemical and microstructural properties) is

60   imperative and aids in predicting the behavior of a particular food during 3D printing and in assembling a

61   complex shape with many layers that is stable enough to maintain its profile for a long time post-deposition (

62   Dankar et al., 2018; Godoi, Prakash, & Bhandari, 2016; Periard, Schaal, Schaal, Malone, & Lipson, 2007;

63   Yang, Zhang, Bhandari, & Liu, 2018).

64   Potato purees, now considered part of the nutritious ready-to-eat food market, could be combined with

65   hydrocolloids that interact with potato starches in an attempt to improve the overall product quality and

66   facilitate processing (Shi & BeMiller, 2002). Therefore, scrutinizing the effects that certain food additives have

67   on the starch structure and textural characteristics is important, because these effects affect the functionality of

68   the whole food product.

69   The objectives of this study were to study the effects of food additives (agar, lecithin, glycerol, and alginate)

70   and their concentrations on the mechanical and microstructural properties of potato puree, to evaluate the

71   feasibility of the substances for 3D printing, to characterize the printing process parameters, such as the distance

72   between the nozzle and the printing bed and the nozzle size and to investigate the effects of the printing process

73   on the superficial color of the final products.

74

75   **Materials and Methods**

76   **Sample Preparation**

77   Commercial potato powder and whole milk were purchased from the local supermarket. Agar-agar, soy bean

78   lecithin, sodium alginate and glycerol (food-grade) were procured from Sigma–Aldrich Co. The potato puree

79   samples were prepared according to the following procedure: 450 mL of milk and 50 mL of water were first

80   heated to 40°C, and then, 115 g of commercial potato powder was added. The mixture was then homogenized

81   using an electrical hand blender (Braun, Germany). The same procedure was followed for preparing the puree

82   samples with the different additives at concentrations of 0.5, 1.0 and 1.5% (Shi & BeMiller, 2002). Additives

83   were added at quantities corresponding to the desired concentrations to the warmed solution (milk and water)

84   prior to the incorporation of the potato powder. However, for the agar samples, the solutions were boiled to

85   100°C, and the dehydrated potato was then added. All prepared puree samples were placed in an incubator and

86   held at a temperature of 20°C preceding any measurements.

87

88   **Extrusion Parameters and Determination of Specific Mechanical Energy**

89   To optimize the 3D printing process, the effects of additives (agar, alginate, glycerol and lecithin), applied

90   speed (1, 2 and 4 mm·s^{-1}) and extruder hole diameter (3 and 5 mm) on the extrusion process were studied using

91   a TA.XT Plus Texture Analyzer (Stable MicroSystems, Godalwig. UK) device with a 50-kg cell load.

92   The specific mechanical energy (SME) was measured as an indicator of the energy efficiency and ease of flow

93   of materials in the extrusion process (Guerrero, Beatty, Kerry, & De La Caba, 2012). Potato puree samples with

94   and without additives were carefully scooped into acrylic cylinders to a height of 35 mm. The extrusion process

95   was carried out by locking the distance traveled by the compression disc along the cylinder to 20 mm. For each

96   extruder hole diameter (3 and 5 mm), speeds of 1, 2, and 4 mm.s^{1} were applied. The weight collected in kg and

97   the force (kg.ms^{-2}) applied during extrusion was measured. The SME was then calculated using the following

98   formula:

99   SME (kJ/kg) = [Force (kg.ms^{-2}) x Distance (m)] / Weight collected (kg)   *(Eq. 1)*

100

101   **Mechanical characteristics**

102   The mechanical characteristics of the additives alone at different concentrations (0.5, 1 and 1.5 g of additive in

103   100 ml of distilled water) and after being added to the potato puree were tested, including the firmness,

104   consistency and cohesiveness, using the aforementioned TA.XT Plus Textural Analyzer coupled with a back

105   extrusion cell and a 35 mm disc. Samples of potato puree up to 40 mm high were placed in a standard-size

106   cylinder. During the test, the disc penetrated a distance of 30 mm at a speed of 2 mm.s^{-1}, after which the probe

107   returned to the original position. The peak in the positive area is taken as the measurement of firmness (kg).

108   The area under the curve up to this point is defined as the consistency (kg.s). The maximum negative force is

109   taken as an indication of the cohesiveness (kg) (Angioloni & Collar, 2009). Each sample was tested at least 5

110   times.

111

112   **Scanning Electron Microscopy (SEM)**

113   Scanning electron microscopy (SERON SCI2100) was used to determine the surface structures of all the puree

114   samples, which were first subjected to vacuum in a vacuum chamber to be dehydrated to avoid swelling in the

115   microscope. Samples were then mounted on circular aluminum stubs with double-sided adhesive tape and

116   coated with 20 nm of gold prior to observation. The SEM experiments were carried out at 15 kV and 4.0 K.

117

118   **Color Measurements of Potato Puree Samples**

119   To evaluate the color properties of the puree samples, a MINOLTA tristimulus colorimeter CR-400

120   (MINOLTA camera, Osaka, Japan) calibrated with a white ceramic standard was used. The luminosities *(L*)*

121   *a**, *b** of the samples were measured, and the chroma (C=(a*^{2}+b*^{2}) ^{½} (saturation) and hue angle (H=arctan

122   (b*/a*) (matrix color)) were calculated. The color measurement values presented are the means of 6 tests

123   performed before and after 3D printing.

124

125   **3D Food Printing conditions**

126   A RepRap BCN3D+ printer (designed by CIM Foundation) coupled with a syringe tool (100 mL volume and 4

127   cm diameter) was used to 3D print the potato purees. The 3D printing process is based on extrusion and works

128   through the principle of joining materials layer-by-layer to make a final 3D object. The code for the desired 3D

129   object is transferred through an SD card from a CAD program (CURA 15.02.01). Speeds set in the CURA

130   program were as follows: travel speed= 100 mm.s^{-1}, infill speed= 40 mm.s^{-1}, printing speed= 40 mm.s^{-1}, flow

131   %= 100 and retraction speed= 40 mm.s^{-1}.

132

133   **Statistical Analysis**

134   Statistical analyses of the data were conducted on Minitab 18 (Minitab lnk. Conventry, UK). Data concerning

135   SME, textural characteristics and color assessment were tested for significant differences ($p<0.05$) using

136   analysis of variance, one-way ANOVA and Tukey's HSD comparison test.

137

138   **Results and Discussion**

139

140   **Effects of the Extrusion Parameters on Specific Mechanical Energy values of potato puree**

141   Varying the extruder hole diameter at a constant extrusion speed showed that decreasing the diameter of the

142   extruder hole caused an increase in the SME of the samples due to higher acquired friction during extrusion,

143   which necessitates an increase in the applied force (Table 1). Thus, a larger hole diameter (5 mm) facilitated

144   extrusion with proper ordering of the layers. Moreover, significant differences were seen in the SME exerted at

145   various extrusion speeds at a fixed extruder hole diameter; the SME and the extrusion speed were found to be

146   inversely proportional, where the highest value for the SME was recorded at the lowest speed and gradually

147   decreased significantly as the speed increased (Table 1). These results are in agreement with Chen et al.,

148   (2010) and Guerrero et al., (2012), who reported that increasing the speed facilitated the flow of soybeans,

149   hence decreasing the SME and the force required for extrusion.

150

151   **Effects of additives on specific mechanical energy value of potato mixtures**

152   Table 2 shows the comparison between the potato puree and the potato purees with concentrations of 1% of

153   different additives (alginate, agar, glycerol or lecithin) at an extruder hole diameter of 3 mm and an extrusion

154   speed of 2 mm.s $^{-1}$. The SME value for the potato puree decreased significantly when 1% glycerol or lecithin

155   was added (Table 2). This decrease could be attributed to the ability of glycerol and lecithin to retain moisture

156   via the destabilization of the internal microstructure of the starch granules, therefore softening the material in

157   accordance with Dankar et al., (2018) and Guerrero et al., (2012). Conversely, the addition of 1% alginate or

158   agar in potato puree significantly increased the SME compared with the potato puree alone (Table 2). This

159   result could be due to the tendency of hydrocolloids (agar or alginate) to form a continuous network of

160   entanglements with starch molecules upon their addition to potatoes, leading to higher tensile strength and

161   hardness and requiring a greater force to push the material out of an extruder (Fang, Zhang, & Wei, 2015).

162   However, agar has demonstrated the ability to form a more complex gel network with starch molecules by

163   previously providing the highest values for yield stress and thixotropy (Dankar et al 2018). Therefore, the

164   SME results allowed for classification of the samples based on their internal mechanical strengths as follows:

165   glycerol≤ lecithin≤ potato puree< alginate< agar.

166   Furthermore, greater stability in the shape of the extruded layers occurred when alginate or agar was added to

167   the potato puree, since the layers obtained were more consistent and able maintain their shape for a long time

168   post-extrusion; although the extrusions of the puree alone and the puree with glycerol or lecithin were

169   smoother, the extruded layers of these samples collapsed and recombined a few minutes after extrusion.

170

171   **Mechanical Characteristics of Potato Purees Combined With Additives**

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173   The characterization of the mechanical properties of food is important and aids in assessing the behavior of the

174 food during processing and consumption. The mechanical characteristics of the food additives alone and at the three

175 different concentrations were first measured to understand the effects of the additives on the potato puree. The

176 results showed that the mechanical strength of the agar additive was significantly different ($p<0.05$) from the other

177 additives used in this work. On the other hand, the mechanical characteristics of the glycerol, lecithin and alginate

178 additives showed no significant differences when the concentrations were changed from 0,5, to 1 and to 1,5%,

179 whereas significant differences were detected in the mechanical properties of the agar measured at the different

180 concentrations (Table 3).

181   The firmness, consistency and cohesiveness of the potato puree alone and the potato purees with the additives are

182   summarized in Figure 1. The results of statistical analyses showed no significant differences ($p < 0, 05$) between the

183   firmness, cohesiveness and consistency of the potato puree and the purees with lecithin or glycerol at concentrations

184   of 0.5, 1.0 and 1.5%. The addition of glycerol or lecithin to potato puree promotes more swollen starch granules

185   (Dankar et al., 2018) with a wider spread in the particle size distribution, giving rise to low values for firmness,

186   cohesiveness and consistency (Afoakwa, Paterson, Fowler, & Vieira, 2008) since these additives have emulsifying

187   effects and the ability to lessen the structural integrities of foods such as waxy maize starch, cocoa spread cream,

188   cassava starch and dark chocolate (Afoakwa, Paterson, Fowler, & Vieira, 2009; Souza et al., 2012 Koushki & Azizi,

189   2015; Yang et al., 2016). On the other hand, the addition of alginate or agar significantly increased the mechanical

190   values of the potato puree, with this elevation being enhanced when the concentrations of the additives were higher.

191   However, the only significant difference in the consistency and cohesiveness between the agar and alginate samples

192   was obtained at the concentration of 1%, which was marked by a higher consistency (Fig. 1). This behavior is

193   attributable to the conveyed network structure that occurs between polysaccharide chains and the large-sized long

194   additive molecules (agar or alginate) within the matrix and to the enhancement of the particle-particle surface

195   contact (Huang, Kennedy, Li, Xu, & Xie, 2007; Dankar, et al. 2018). Similar mechanical strength results are

196   obtained when carboxy-methyl cellulose, xanthan or carrageenan are added to sweet potato puree, whipped cream

197   and carrots, respectively (Truong & Walter, 1994; Zhao, Zhao, Yang, & Cui, 2009;Sharma et al., 2017). The

198   alginate alone showed mechanical property values similar to that of the glycerol and lecithin, but when the alginate

199   was incorporated in the potato puree, the resulting mixture had high mechanical property values comparable with

200   that of the agar.

201   This difference could be related to the interaction of the alginate with the calcium ions abundantly present in the

202   milk and the potatoes used in the preparation of the samples, which consequently enhanced the textural strength and

203   viscoelastic properties of the puree as also reported by Truong et al. (1995) and Fasina et al. (2003). On the other

204   hand, the agar solely formed a gel that, upon interaction with other molecules, formed a more complex entangled

205   network, which enhances its thickening ability (BeMiller, 2011; Milani & Maleki, 2012).

206

207   Thus in terms of mechanical strength, the greatest strengthening effect exerted by the agar and the alginate on

208   the potato puree allows for products with the sufficient mechanical integrity to support a built-up layered

209   geometry without deformation, in contrast to those with glycerol and lecithin.

210

211 **Scanning Electron Microscopy (SEM)**

212 The SEM micrographs highlighted clear microstructural differences between the different puree samples. At

213 0.5%, the puree sample with lecithin was comparable to the potato puree alone but had a more cotton-like

214 texture, whereas more noticeable changes in the potato puree were detected with the additions of the glycerol,

215 agar and alginate. The alginate induced more folding, while the agar and glycerol yielded fibrillary network-like

216 structures (Fig. 2b1, d1). However, this network-like structure was more compact in the sample with glycerol,

217 which could be due to the ability of glycerol to enter the interior of polysaccharide chains and disrupt inter- and

218 intra-molecular hydrogen bonds, making the polymer more elastic (Mali, Sakanaka, Yamashita, & Grossmann,

219 2005). An expanded network with tiny wrinkles on the surface was produced by the agar. As the concentration

220 of the agar increased, these tiny wrinkles evolved into a continuous phase with more folding and convolutions

221 (Fig. 2d1, d3), which was the result of intense interactions between the starch and the agar (Phan, Debeaufort,

222 Luu, & Voilley, 2005), agar gel formation and agar-agar interactions at higher concentrations (Dankar et al.,

223 2018). Therefore, a firmer and more complex network of interactions was seen in the structure of the puree with

224 1.5% agar, as revealed in the figures.

225 Similarly, the folding formed upon the addition of 0.5% alginate could be attributed to the formation of

226 alginate-cation-polysaccharide complexes (Truong et al., 1995). When the concentration of alginate was

227 increased to 1%, a more consistent and firm structure was formed. This result reflects the characteristic

228 mechanical behavior of alginate; at concentrations of 1%, significant differences were detected between the

229 agar and alginate samples, with a higher consistency value for the alginate, compared with a more cohesive

230 structure for the agar that was expressed through higher folding formation. At 1.5% alginate, internal folding

231 and convolutions were observed within the structure. The addition of additives at higher concentrations results

232 in a greater availability of reactive sites and hence, increases their mode of functionality (Chen, Dickinson,

233 Langton, & Hermansson, 2000). In fact, these convolutions largely explain the increase in the internal strength

234 and mechanical characteristics of potato puree upon the addition of agar or alginate. In contrast, when the

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concentration of lecithin in the potato puree was increased, a smooth surface with tiny pores was produced (Fig. 2c1, c2). This behavior was ascribed to the two internal modes of action of lecithin. First, as regards the starch structure, lecithin can penetrate the starch molecules and induce modifications within the internal amylose-amylopectin and amylopectin-amylopectin bindings (Dankar et al., 2018). Consequently, more water molecules are able to penetrate the starch granules, leading to a more swelled starch structure that promotes the smoothness observed in the SEM figures (Fig. 2c1). Second, the emulsification properties of lecithin promoted the assembly of fine droplets that are an indication of a uniformly dispersed structure inside the food matrix (Afoakwa et al., 2009; Koushki & Azizi, 2015). Likewise, increasing the concentration of the glycerol induced a similarly smooth surface comparable to that of the potato puree. These factors explain the absence of significant differences between the mechanical characteristics of the potato puree alone and those for potato puree with glycerol or lecithin added. The microstructures of the potato puree samples combined with the textural data provide vital input for the 3D printing process, since formation of strong networks like those displayed in the samples with agar or alginate additions could be used to yield integrated shape-retention properties with stabilizing effects.

3D printing Conditions for potato puree and potato puree with additives

Many trials were performed on the BCN3D+ printer system to obtain the best printed product. When the distance from the nozzle to the printed bed was ≥ 1 cm, the flow of material was irregular due to delayed deposition, and the layers extruded were breakable and incompatibly attached to the previous layers for all the puree samples. After many trials, the critical nozzle height for high-quality printed potato purees was determined to be 0.5 cm. Similar results were obtained by Wang et al. (2018) and Hao et al. (2010) when printing surimi and chocolate gels, respectively; they found that the nozzle height critically affects the final geometry of the product.

The second optimization was the nozzle diameter, which directly affects the surface roughness and precision of printed objects (Yang et al., 2018). Because the 3D printer and the textural analyzer have different nozzle diameters, using the same diameter for both tests was impossible. This difference was minimized by using similar sized diameters, in both cases in the same range: 3 and 5 mm in the case of textural analyzer and 2 and 4 mm for the 3D printer.

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Using a 2 mm nozzle, printing with the potato puree and the potato purees with additives produced poor-quality products in which the layers did not overlay with one another properly, and the shape was not well-maintained, leading to a poor product mainly because the thin filament size that was extruded was not large enough to support the desired final structure for the potato puree. Whereas when a 4 mm nozzle was used, all the puree samples showed better printing quality. This result validates what was hypothesized while determining the extrusion parameters and SME values, where extrusion with the larger diameter size of 5 mm provided better layer organization than extrusion with a 3 mm diameter nozzle (refer to the SME results). A 4 mm nozzle is sized within the range of these two values and hence, the 2 mm nozzle was excluded. The critical nozzle diameter is specific to the particular type of food extruded, as has been stated by several authors (Hao et al., 2010; Yang, Zhang, Bhandari, & Liu, 2018).

Another consideration for the printing process is the type of substrate to be printed. Of the mixtures prepared, the potato purees with the agar or alginate at the different concentrations tested were able to be printed in stable structures with many built-up layers that held their shape for a long time without collapsing (Fig. 3a and 3b, puree with 0,5% alginate and potato puree alone, respectively). This result could be directly attributed to the high internal strengths, demonstrated by the highest values measured for the textural properties (firmness, consistency, cohesiveness) and the high SME values exhibited by the purees with agar or alginate; the incorporation of gums into mashed potatoes has reportedly generally increased their resistance to deformation (Liu, Zhang, & Bhandari, 2018). Furthermore, the stabilization of the final shapes printed with the purees with the alginate or agar increased with increasing additive concentration in the potato puree, except for the 1.5% agar, which displayed high SME and mechanical values compared with the other additives and in which the sample was more solid-like, retarding the process of printing.

The potato puree and the purees with glycerol or lecithin showed different behavior, in which printing a multiple-layered 3D structure started well with a smooth flow of potato paste (Fig. 3d). Nevertheless, when the structure reached its final stage, the many layers that were printed collapsed into each other (Fig. 3e), resulting in a poorly defined and deformed product, due to the low firmness, consistency and internal stability possessed by these samples, which confirms the previous results concerning the shape stability of the extruded layers

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290   from the texturometer. Conversely, these materials behaved well during the printing of flat structures with few

291   layers. Thus, the stability of the final product depends not only on the substrate properties but also on the

292   targeted geometry shape to be printed. The effect of the printed substrate on the quality of the final product has

293   been reported by several authors. Yang et al. (2018) and Liu et al. (2018) observed that the addition of potato

294   starch in certain concentration ranges in lemon juice and mashed potatoes, respectively, increased the viscosity

295   of the printed substrate and therefore, ensured the delivery of more stable end-products. These results confirm

296   that alginate and agar serve as better additives in food technological applications like 3D printing.

297   **Characteristics of the Final 3D Printed Products**

298   The color surface parameters for the puree samples, including the Luminosity, Chroma and hue angle, are

299   dependent on the particulate distribution, absorptivity and scattering coefficients (Hutchings, 2011).

300   Each food additive used had a different effect on the surface color of the potato puree due to their distinct

301   effects on the starch structure and the distribution of the particles and their respective arrangements. Only the

302   alginate and agar produced significant differences ($p < 0.05$) in the luminosity parameters of the potato purees,

303   with decreases in their values (Fig. 4), which could be attributed to alterations of the starch globule sizes and

304   morphologies. Additionally, solely the agar exhibited an effect on the hue angle of the puree by elevating the

305   level. The glycerol and lecithin produced significant differences in the Chroma of the potato purees by

306   decreasing the saturation property, which could be ascribed to changes in the starch granule morphologies and

307   sizes and the starch internal networks (Dankar et al., 2018). However, Afoakwa et al., (2008) reported that the

308   addition of lecithin did not affect the luminosity, Chroma or hue angle of dark chocolates.

309   Generally, increasing the concentration of the additives in the potato puree did not cause any significant

310   differences in the luminosity or hue angle. However, increasing the concentration of lecithin to 1.5% produced

311   a significant difference in the Chroma of the potato puree by further decreasing the degree of saturation (Fig.

312   4). This result could be attributed to the lecithin (at 1.5%) producing increased modifications of the internal

313   starch granule interactions, yielding a dull surface appearance (less saturated).

314   On the other hand, Le Tohic et al. (2018) found that the printing process affected the surface color of printed

315   cheeses, inducing a small decrease in the luminosity in contrast to our work, where the 3D printing process had

316   no significant effect on any of the color parameters studied for all the puree samples. Thus, the 3D printing

317　process was proven to not influence the surface color of printed potato purees, which satisfies some consumers

318　and companies.

319　Additionally, several attempts have been made to design soft and tasty products to satisfy the desires of the

320　elderly and those facing swallowing and mastication problems, enhancing their appetites with safe, novel and

321　nutritious foods (Aguilera & Park, 2016). Table 4 presents the firmness values for all the puree samples in kPa,

322　which were converted according to the following formula:

323　kPa= kg/cm^2× 98.0665　　　　　　　*(Eq. 2)*

324　The accessible range of consumption for elderly or people facing mastication problems is within the firmness

325　value range of 20 to 40 kPa (Serizawa et al., 2014), and all the tested puree samples fit well within this

326　acceptable range. Although the maximum firmness for agar was measured at the concentration of 1.5% (25.8

327　kPa), no significant difference was detected between the firmness values of the purees with agar or alginate at

328　1.5% (Table 4). Similar work was conducted by Serizawa et al. (2014) to study the feasibility of printed

329　hydrocolloids, agar and gelatin at different concentrations for the elderly. The higher the concentration of agar

330　in water, the higher its hardness, such that 20% agar possessed the highest hardness of the tested samples (45

331　kPa). The addition of gelatin demolishes the strength of the agar, which was demonstrated by a decrease in the

332　hardness of the samples. This result confirms the results showing that the agar was the additive that increased

333　the firmness and mechanical properties of the potato puree. The purees with 1.5% glycerol or lecithin showed

334　the lowest firmness pressures, approximately equal to 3.82 kPa; however, neither functioned as proper

335　additives for maintaining the stability and structure of the 3D products post-printing.

336　Potato purees could also serve as a healthy customized food for the second most susceptible sector of people,

337　children. Studies have reported that children are willing to try a wider variety of foods if they are plated in an

338　aesthetic and funny way (Zampollo, Kniffin, Wansink, & Shimizu, 2012).

339

340　**Conclusion**

341　Alginate (from 0.5% to 1.5%) and agar (0.5 and 1%) were the additives that provided more stability for printed

342　products with corresponding increases in specific mechanical energy (SME).

343　The mechanical characteristics of firmness, consistency and cohesiveness showed significant differences

344　(p<0.05) after the addition of agar or alginate to potato purees, and the effect was greater at higher

345   concentrations. Nevertheless, when not mixed with potato puree, only agar had a significant difference in

346   mechanical characteristics among the additives.

347   The SEM figures demonstrate the different microstructural characteristics within the potato puree samples,

348   wherein lecithin produced a cotton-like structure, alginate produced more folding, glycerol induced a more

349   continuous network-like structure due to its ability to disrupt the inter- and intra-network interactions between

350   the polysaccharide chains, and agar induced more folding and convolutions, which complements the textural

351   value results.

352   The best extrusion conditions for the 3D-printed potato purees were achieved with a nozzle size of 4 mm and a

353   critical nozzle height of 0.5 cm using a printing substrate of potato puree mixed with alginate (0.5 to 1.5%) or

354   agar (0.5 and 1%) to provide the finest resolution of stable end-products with many built-up layers.

355   The optimal mechanical characteristic values for obtaining good quality 3D printed potato purees with

356   additives fall within the following ranges: a firmness between 0.94 and 2.10 kg, a consistency between 11.6

357   and 26.5 kg·s and a cohesiveness between 0.9 and 2.1 kg. The color of the final product is not affected by the

358   3D printing process and all the printed samples showed good firmness values that fit well within the range of

359   the maximum lingual pressure (20-40 kPa), thus enabling potato puree or other foods to be used in innovative

360   designs to produce a good substitute for the unappealing meals available for people facing mastication

361   problems.

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Extrusion conditions		Parameters		
Diameter hole	Speed (mm.s^{-1})	Force (kg.ms^{-2})	Weight collected (g)	SME (KJ.kg^{-1})
5mm	1	113.4 ±0.6^a	36.6 ±0.3^a	62.0±0.2^a
	2	86.1 ±1.6^b	35.5 ±0.4^a	48.5±1.5^b
	4	68.1 ±1.3^c	34.0 ±1.5^a	40.1±1.0^c
3mm	1	198.2 ±7.8^A	35.0 ±2.1^{a,b}	120.8±3.1^A
	2	141.9 ±2.2^B	31.0 ±0.7^{b,c}	91.7 ±3.5^B
	4	107.5 ±2.7^C	31.8 ±0.7^{b,c}	67.7±0.1^C

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511   Values are mean of three replicates ± standard deviation.

512   Different letters of Mean values in the same column differ significantly ($P<0.05$) (small and
513   capitals letters for 5 and 3 mm diameter hole respectively)

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527 Table 2 Values of extrusion parameters and Specific Mechanical Energy (SME) obtained at 3mm hole
528 diameter and 2mm.s^{-1} speed printer of potato puree with 1% of different additives

Samples	Force applied (kg.ms^{-2})	Weight collected (g)	SME (kJ.kg^{-1})
potato puree	141.9±2.2^c	31.0±0.7^b	91.7±3.5^c
potato puree+1% alginate	261.6±3.8^b	32.2±1.3^{a,b}	162.4±10.1^b
potato puree+1% agar	332.1±10.6^a	30.6±1.0^{a,b}	217.0±0.3^a
potato puree+1% glycerol	82.3±1.0^d	31.7±0.5^{a,b}	51.9±2.1^d
potato puree+1% lecithin	86.5±2.8^e	33.3±0.8^a	52.0±0.6^d

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531 Values are mean of three replicates ± standard deviation.

532 Different letters of Mean values in the same column (corresponding to the same parameter) differ
533 significantly (P<0.05

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Table 3 Values of Mechanical Characteristics: firmness, consistency and cohesiveness of additives at 0.5,1 and 1.5 % concentration

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Additive	Concentration (%)	Firmness (g)	Consistency (g.s)	Cohesiveness (g)	
Glycerol	0.5	15.4 ± 0.9^{a}	275.0 ± 29.2^{a}	-3.6 ± 3.0^{a}	554
	1	15.0 ± 1.4^{a}	293.8 ± 36.4^{a}	-2.4 ± 0.4^{a}	
	1.5	13.5 ± 1.5^{a}	249.5 ± 43.1^{a}	-2.5 ± 0.9^{a}	Val
Lecithin	0.5	13.9 ± 0.9^{a}	255.0 ± 25.5^{a}	-3.1 ± 0.5^{a}	ues
	1	14.7 ± 1.4^{a}	269.8 ± 13.5^{a}	-2.4 ± 0.4^{a}	are
	1.5	14.2 ± 0.9^{a}	275.2 ± 29.2^{a}	-2.3 ± 0.6^{a}	mea
Agar	0.5	336.0 ± 54.9^{b}	2347.0 ± 699.5^{b}	-74.0 ± 36.5^{b}	n of
	1	1202.3 ± 158.8^{c}	11858.7 ± 417.5^{c}	-245.3 ± 31.7^{c}	thre
	1.5	5864.7 ± 193.6^{d}	55070.0 ± 1714.5^{d}	-687.7 ± 86.5^{d}	e repli
Alginate	0.5	13.5 ± 1.3^{a}	204.2 ± 50.0^{a}	-3.4 ± 0.5^{a}	cate
	1	16.0 ± 0.8^{a}	313.7 ± 34.5^{a}	-4.3 ± 0.5^{a}	s ±
	1.5	15.3 ± 0.6^{a}	291.2 ± 13.2^{a}	-2.7 ± 0.4^{a}	stan dard

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deviation.
Different letters of Mean values in the same column (corresponding to the same parameter) differ significantly (P<0.05)

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Table 4 Firmness values (kPa) of potato puree samples with glycerol, lecithin, agar and alginate at
0.5, 1 and 1.5% concentration

Sample	Concentration (%)	Firmness (kPa)
Potato puree +Alginate	0.5	10.0^c
	1	$13.2^{b,c}$
	1.5	22.7^a
Potato puree +Agar	0.5	10.9^c
	1	17.1^b
	1.5	25.8^a
Potato puree +Lecithin	0.5	4.3^d
	1	4.4^d
	1.5	3.6^d
Potato puree +Glycerol	0.5	5.0^d
	1	4.2^d
	1.5	3.8^d
Potato puree	-----	$5,5^d$

Values are mean of three replicates

Different letters with Mean values in the same column (corresponding to the same parameter) differ
significantly ($P<0.05$)
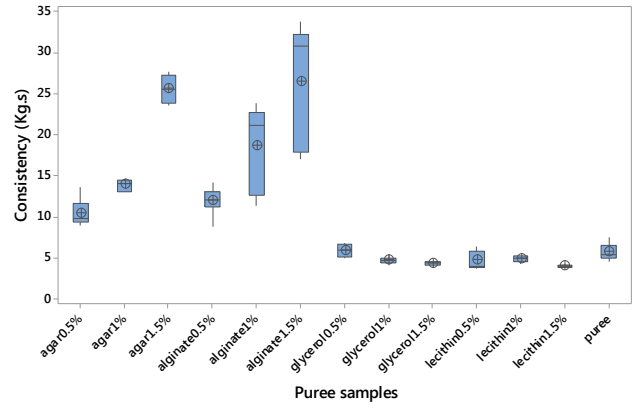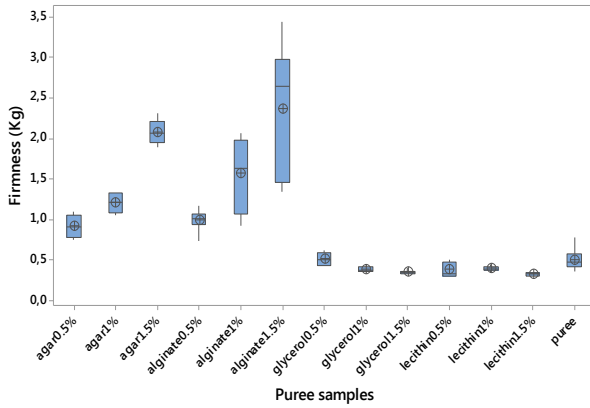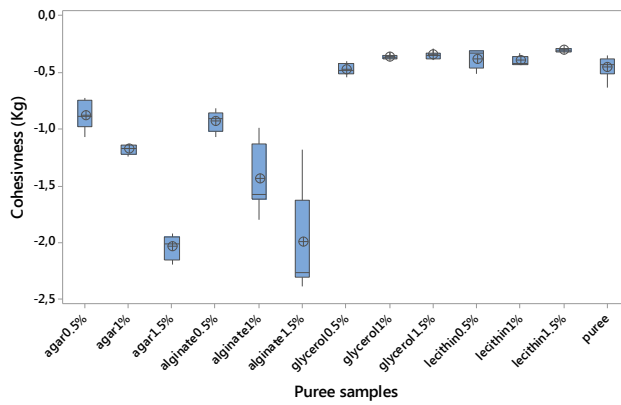
Fig.1 Box plot analysis of the mechanical characteristics firmness (a), consistency (b) and cohesiveness (c) of potato puree and potato puree with agar, alginate, glycerol and lecithin at concentration of 0.5, 1 and 1.5 % .

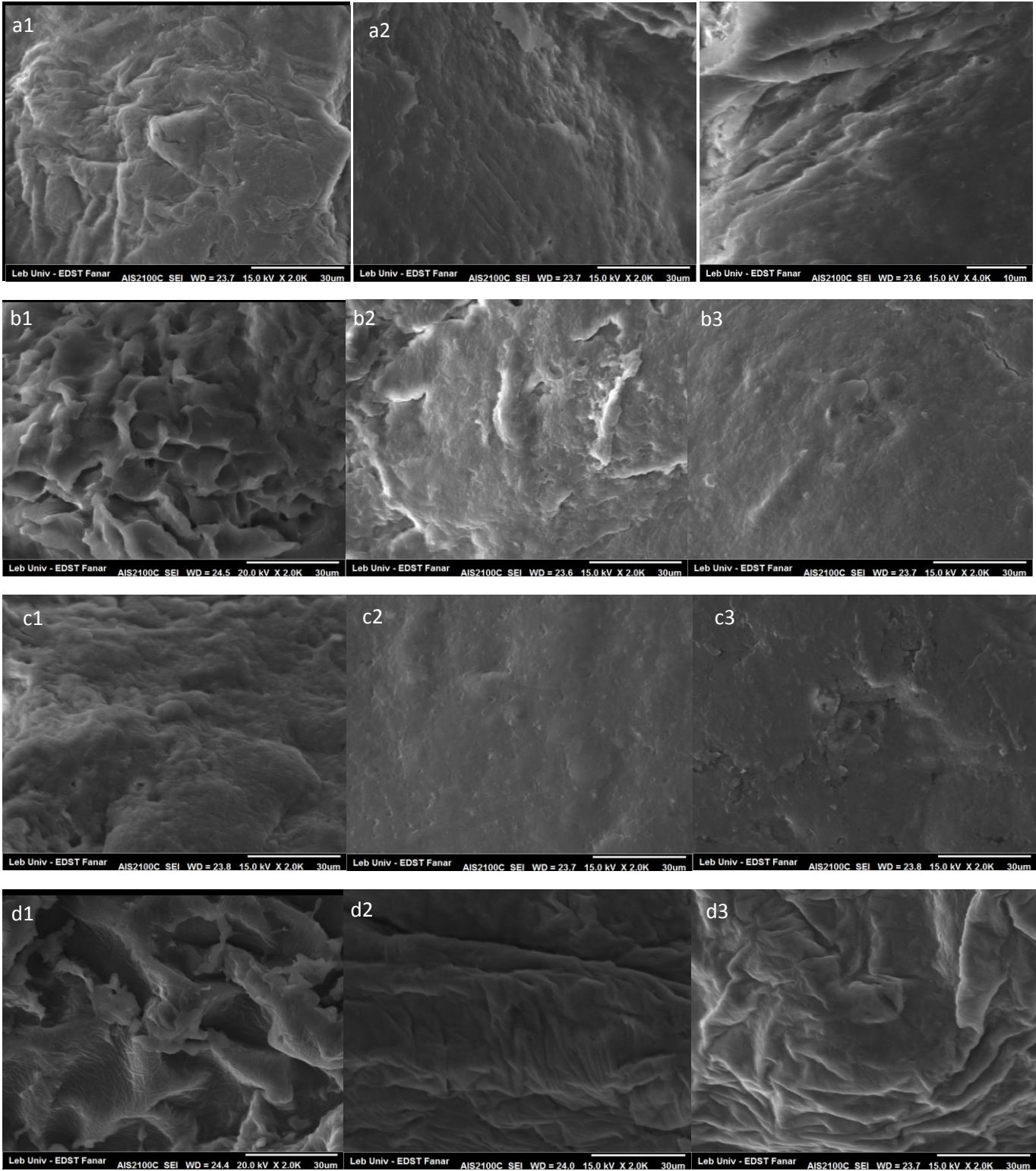**Fig. 2** Scanning electron microscopy analysis of potato puree samples   with 0.5% (column 1), 1% (column 2), and 1.5% (column 3) of additive concentration: a1, a2,   a3 potato puree with
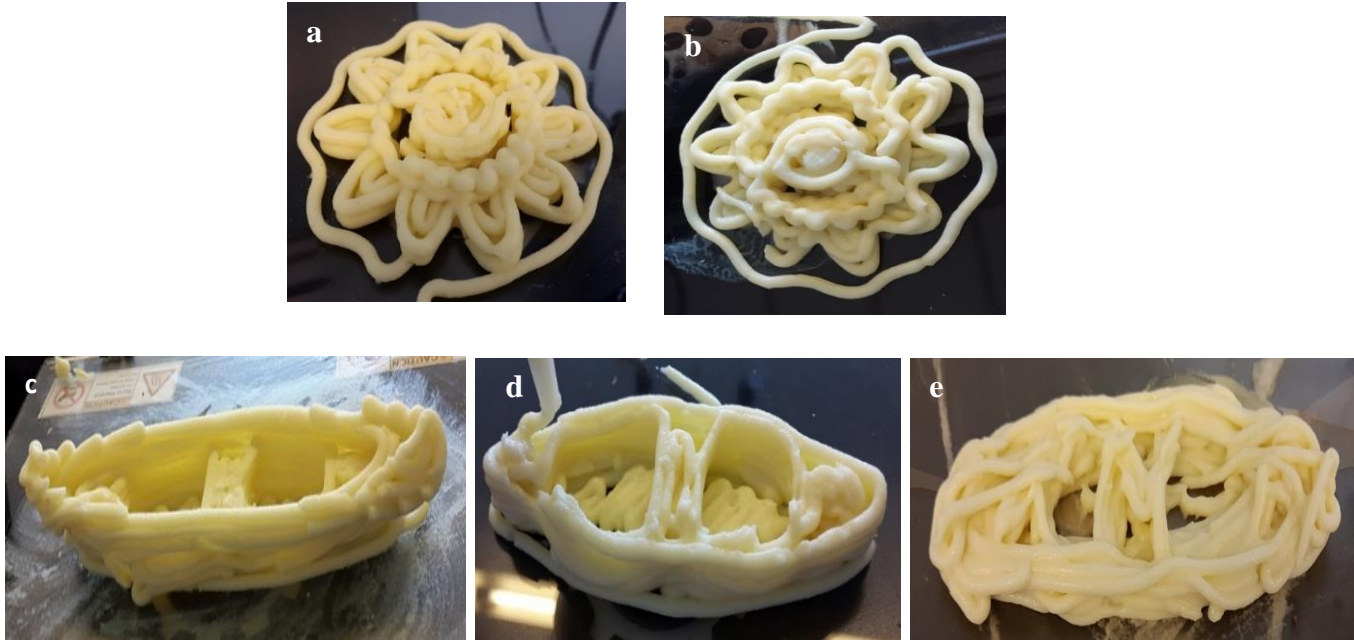
alginate; b1, b2, b3 b potato puree with glycerol; c1, c2, c3 potato puree with lecithin; d1, d2, d3 potato puree with agar. *arrows correspond to pores formation within lecithin*.

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Fig. 3 The influence of the substrate and shape design on 3D printed products of potato puree alone or with additives when is extruded at 4mm nozzle. Fig 3(a, b) Influence of substrate printed : (a) potato puree with0.5% alginate, (b) potato puree alone, Fig 3 (c, d, e) Influence of shape design (c) potato puree with 1% alginate, (d) potato puree alone at primary stages of printing and (e) potato puree alone at final stages of printing.

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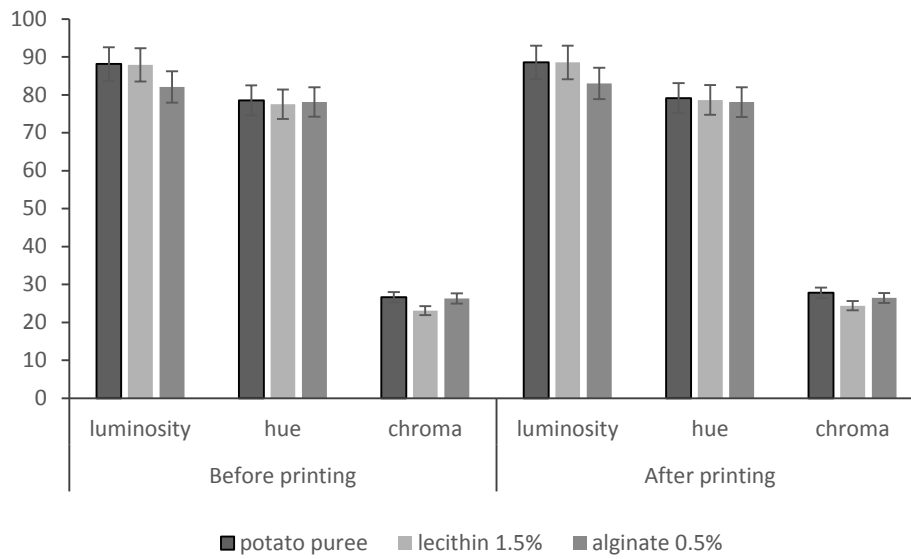
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672 **Fig. 4** Values of Luminosity, Chroma and Hue angle in color surface of potato puree alone, potato puree
673 with 1.5% lecithin and potato puree with 0.5% alginate before and after 3D printing. Values are mean ±
674 standard deviation (n=6)

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