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Rheological and textural properties of gluten-free doughs made from Andean grains

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Summary The objective of this research was to evaluate the rheological and textural properties of gluten-free doughs based on potato starch, which was partially substituted by different proportions of quinoa (10%, 30% and 50%), kiwicha (10%, 30% and 50%) or tarwi flour (10%, 20% and 30%). The influence of the substitution on the kinetics of the leavening process was studied as well. The back-extrusion technique was used to determine rheological and textural properties of the dough, and the leavening kinetics were modelled using the Gompertz equation. The results showed that textural properties such as firmness, consistency, cohesiveness and viscosity index, as well as the consistency index of the doughs increased as the level of substitution of the Andean grain flour in the formulation increased. It was determined that the formulations with an addition of 10% and 20% for quinoa or kiwicha flour, and 10% for tarwi flour would be most suitable for developing gluten-free breads.

Keywords Andean grains, gluten-free dough, kiwicha, leavening process, quinoa, rheological properties, tarwi, textural properties.

Introduction

Andean grains such as quinoa (*Chenopodium quinoa*) and kiwicha (*Amaranthus caudatus*) have proven to be sources of important nutrients such as proteins, lipids, fibre and minerals; the content of these nutrients is higher when compared to other cereals such as corn, wheat and rice (Repo-Carrasco-Valencia & Vidaurre-Ruiz, 2019; Repo-Carrasco-Valencia *et al.*, 2019). Protein quality is the main attraction of quinoa and kiwicha, due to the good balance of essential amino acids (Repo-Carrasco *et al.*, 2003). These crops present significant amounts of lysine and methionine, which are amino acids deficient in common cereals (Tanwar *et al.*, 2019). Another important characteristic of the proteins of the Andean grains is the low concentration of prolamins, making them appropriate for consumption by persons who suffer from coeliac disease (Zevallos *et al.*, 2014; Montemurro *et al.*, 2019; Velarde-Salcedo *et al.*, 2019).

Numerous researchers have revealed the excellent functional and nutritional properties of quinoa and kiwicha flour in the preparation of gluten-free breads, highlighting its application to increase the bread volume (Elgeti *et al.*, 2014), to soften the crumb texture (Alvarez-Jubete *et al.*, 2010; Turkut *et al.*, 2016) and to increase the nutritional value of gluten-free breads in relation to their protein and mineral content (Alvarez-Jubete *et al.*, 2009; Rybicka *et al.*, 2019).

Another Andean grain that originates from Peru and seems promising in the development of gluten-free products is tarwi (*Lupinus mutabilis*) (Atchison *et al.*, 2016; Vidaurre-Ruiz *et al.*, 2019b). This grain has a higher protein content (57.4–52.9%) than the other European commercial lupine species (*L. angustifolius, L. albus* and *L. luteus*), which may contain between 33.8–39% protein (Ballester *et al.*, 1980; Lqari *et al.*, 2002; Rosell *et al.*, 2009; Vidaurre-Ruiz *et al.*, 2019b). It is known that the techno-functional properties, such as solubility, water retention capacity and foaming capacity of legume proteins, have significant effects on the properties of the doughs, making them attractive to improve the nutritional and physical quality of gluten-free bread (Foschia *et al.*, 2017; Horstmann *et al.*, 2017; Boukid *et al.*, 2019). Although most of the research reported in the literature refers to the use of European lupine flour or protein, very little has been investigated on the effects of the addition of tarwi flour in the formulation of gluten-free breads.

In the development of gluten-free bread products, the study of the rheology and texture of gluten-free

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doughs is crucial to predict the final characteristics of bread (Ziobro *et al*., 2016; Vidaurre-Ruiz *et al*., 2019a). The evaluation of the textural properties of gluten-free doughs does not have a standard or defined procedure, in contrast to wheat doughs in which consistency (textural parameters) can be measured using the Brabender Farinograph (Schober *et al*., 2005). Various empirical methods have been used to evaluate the texture of gluten-free doughs, from the use of simple penetrometers (Sanchez *et al*., 2002) to more sophisticated equipment such as forward extrusion cells (Moore *et al*., 2004; Sciarini *et al*., 2010a) or back-extrusion analysis (Encina-Zelada *et al*., 2018, 2019). This last procedure has been used more frequently in the evaluation of texture of fluid and viscous foods (Ronda *et al*., 2017), because four textural parameters can be analysed: firmness, consistency, cohesiveness and viscosity index, which allows to fully explain the textural properties of a food.

Although there are reports of the rheological and textural properties of gluten-free doughs that contain Andean grain flour (Turkut *et al*., 2016; Encina-Zelada *et al*., 2018), many of these doughs are made with more than two ingredients forming complex systems, which makes it difficult to explain the contribution of each of them. Therefore, the objective of this research was to evaluate the rheological and textural properties of gluten-free doughs based on potato starch with single substitution of quinoa (10%, 30% and 50%), or kiwicha (10%, 30% and 50%) or tarwi flour (10%, 20%, 30%), and to study the effect of the substitution on the kinetics of dough growth during the leavening process.

Materials and methods

Materials

Quinoa grains (*Chenopodium quinoa* Willd.) Pasankalla variety (14.4% proteins, 2.3% ash, 7.2% crude fibre, 7.2% lipids, 60.9% carbohydrates, 8.0% moisture, water absorption capacity (WAC): 0.69 mL water/g solids) and kiwicha (*Amaranthus caudatus* L.) Centenario variety (11.8 % proteins, 2.3% ash, 2.6% crude fibre, 12.2% lipids, 58.1% carbohydrates, 13.0% moisture. water absorption capacity (WAC): 0.95 mL water/g solids) were provided by the Native Cereals and Grains Program of Universidad Nacional Agraria La Molina. Tarwi grains (*Lupinus mutabilis* Sweet) Blanco de Yunguyo variety (52.9% proteins, 2.8% ash, 7.2% crude fibre, 21.6% lipids, 5.6% carbohydrates, 9.9% moisture, water absorption capacity (WAC): 2.23 mL water/g solids) were purchased from a local market in Cajamarca, Peru, and conditioned, in order to remove the alkaloids, according to the procedure described by Jacobsen & Mujica (2006). In the case of quinoa, the grains were washed for 30 min to remove the saponins and in the case of kiwicha, it was washed to eliminate any impurities. Grains were dried using a convective dryer (Tray dryer G-5 I/C, Vulcano Tec, Lima, Peru) for 8 h at 40 °C. All dried grains were ground using a hammer mill (Retsch SR 300, Haan, Germany) using the following screen sizes: 0.5 mm for quinoa and kiwicha flour and 0.75 mm for tarwi flour. Potato starch (ARO®, Makro, Lima, Peru), water (San Mateo S.A, Backus, Huarochirí, Peru, water absorption capacity (WAC): 0.57 mL water/g solids), salt (Lobos®, K + S company, Santiago, Chile), soybean oil (Primor®, Alicorp, Lima, Peru), white sugar (Cartavio®, Grupo Gloria, La Libertad, Peru), dry yeast (*Saccharomyces cerevisiae*) (Fleischmann®, CALSA S.A.C., Callao, Peru) and xanthan gum (Frutarom®, Lima, Peru) were purchase from the local market.

Dough preparation

Doughs were developed with different substitution rates of potato starch for quinoa (10%, 30%, 50%), kiwicha (10%, 30%, 50%) and tarwi flour (10%, 20% and 30%), keeping constant the other ingredients as follows (% based on flour and starch): 3% yeast, 3% sugar, 2% salt, 6% soy oil, 0.5% xanthan gum and 75% water. The maximum substitution of potato starch with quinoa and kiwicha flour was guided by the previous work carried out by Alvarez-Jubete *et al.* (2010), whereas lower level of tarwi flour was considered to substitute potato starch because this raw material contains a high percentage of protein and fat and has a low starch content. All recipes were produced three times.

The ingredients were calculated based on the weight of starch and flour (500 g). Dry ingredients such as starch or Andean grain flour, gums and salt were mixed for 1 min at low speed in a planetary mixer (KMX93, Kenwood, Hampshire, UK). Yeast was previously dissolved in water and mixed with sugar. Then, water and soybean oil were incorporated into the container and mixed for another 3 min at high speed. The dough obtained was immediately used for subsequent analysis.

The selection of potato starch as the main ingredient of gluten-free doughs formulation was due to the fact that this starch presented better viscoelastic and pasting properties than corn starch when it interacted with xanthan gum according to previous work carried out (Vidaurre-Ruiz *et al*., 2019a). Likewise, with the control formulation, it was possible to produce gluten-free bread with a high specific volume and good crumb structure.

Textural properties of the dough

The textural properties of the doughs were measured using the INSTRON Universal Texturometer and back-extrusion accessory (Model 3365, Canton MA, USA), following the procedure described by Angioloni & Collar (2009). A portion of dough (130 g) was deposited in the back-extrusion cylinder (Diameter 50 mm, height 70 mm) and was penetrated up to 50% with a plunger (diameter 42 mm) at a speed of 60 mm/min and a preload of 10 g. Finally, the plunger returned to its original position at the same speed. With the data obtained, the textural parameters of the dough were calculated, which were as follows: firmness (maximum force obtained during compression), consistency (area under the first curve), cohesiveness (minimum value obtained during the recoil cycle) and viscosity index (area drawn on the return of the probe).

Rheological properties of the dough

To determine the flow properties of gluten-free doughs, back-extrusion accessory (Model 3365, Canton MA, USA) was used, following the procedure described by Alviar & Reid (1990) and Gujral & Sodhi (2002). The method consisted of filling up to 80% of the cylinder (diameter 50 mm, height 70 mm) with the gluten-free dough (approximately 130 g) and using a spatula to remove the air that could have been trapped. Then, the dough was penetrated to 50% at different speeds (50, 200, 350, 500, 650, 800 and 1000 mm/min) using a plunger (diameter 42 mm). The data recorded were the maximum force of the dough (Ft) and the displacement performed by the plunger (Lp). The equations described by Osorio & Steffe (1987) were used to determine the flow behaviour index (n) and the consistency coefficient (K) (Eq. 1).

$$\sigma = K\gamma^n \tag{1}$$

Further details of the calculations performed to determine shear rate (γ) and shear stress (σ) are found in Osorio & Steffe (1987) and Toledo *et al.* (2018).

Kinetics of dough growth during the leavening process

The kinetic of doughs growth during the leavening process was performed by image analysis, measuring the increase in area during the fermentation period, following the procedure described by Conte *et al.* (2018) and Vidaurre-Ruiz *et al.* (2019a). The test consisted of placing a portion of dough (10 g) in a mould (hollow cylinder, Ø 2.7 cm) in the centre of a Petri dish; then, the mould was removed and the dough was allowed to ferment in a climate chamber at 30 °C and 80–90% RH for 60 min. Every 10 min, three Petri dishes were scanned at 300 dpi with a scanner (Canon MG3610, Japan) and the increase in area (A_t) was determined at each time, using ImageJ software 1.51j8 (National Institutes of Health, USA). The results were modelled using the Gompertz equation (2) (Labuza & Fu, 1993).

$$A_t = A_0 + C \cdot \exp\left(-\exp\left(-V_{\max} \cdot (t - X)\right)\right) \tag{2}$$

where Ao is the initial area, C represents the asymptotic amount of increase that occurs when time (t) increases indefinitely, $V_{\max}$ is the maximum growth rate of the area, and X is the time when the absolute growth rate is maximum.

Statistical analysis

The results were analysed using Statgraphics Centurion XVII (StatPoint Technologies Inc., Warrenton, Virginia, USA) for one-way analysis of variance (ANOVA) with separation of means using the Tukey test ($P < 0.05$), and Statistica 7.0 (StatSoft, Inc., Tulsa, USA) was used for nonlinear regression analysis to determine the fitting of the flow model and the kinetic parameters of the leavening process. All analyses were performed at least in triplicates for each recipe; mean values ± standard deviation are presented.

Results and discussion

Textural properties of gluten-free doughs made with Andean grain flours

The textural properties of gluten-free doughs made with different concentrations of quinoa (10%, 30% and 50%), kiwicha (10%, 30% and 50%) and tarwi flour (10%, 20% and 30%) are shown in Table 1. According to the results obtained, the least firm dough (2.07 N) was the control dough, which was made with 100% potato starch. As the level of substitution for quinoa flour increased, the firmness of the dough increased progressively. In the case of kiwicha doughs, the inclusion of 10% and 30% of this flour produced doughs with similar firmness, this could be related to the oil content of kiwicha (12.2%), which can decrease the firmness of the dough when mixed with the other ingredients. In the case of doughs with tarwi flour, the inclusion of 10% of this flour recorded firmness values (5.07 N) similar to the doughs with 10% quinoa flour (4.83 N) and 10% kiwicha (5.53 N); however, as the level of tarwi flour increased, the doughs showed very high firmness (14.27 N for the dough with 20% tarwi flour and 29.63 N for the dough with 30% tarwi flour).

It is possible to find works that determine the extrusion force (firmness) of gluten-free doughs using the forward extrusion test. Sciarini *et al.* (2010a) reported that the extrusion force for the gluten-free control dough, made with 100% rice flour, was 2.62 N and for gluten-free doughs that contained different concentrations of corn or soy flour, the extrusion force

Table 1 Rheological and textural properties of gluten-free doughs made with different concentrations of quinoa, kiwicha and tarwi flour

	Dough textural properties				Dough flow properties		
Formulation	**Firmness (N)**	**Consistency (N.s)**	**Cohesiveness (N)**	**Viscosity index (N.s)**	**K (Pa.s^n)**	***n***	**R^2***
GFD-Control	2.07 ± 0.06^{a}	111.41 ± 5.43^{a}	2.27 ± 0.20^{g}	67.47 ± 0.57^{f}	31.38 ± 2^{a}	0.36 ± 0.04^{abc}	0.99
GFD-Q-10%	4.83 ± 0.13^{b}	162.92 ± 6.88^{b}	3.73 ± 0.29^{f}	101.80 ± 4.48^{e}	40.11 ± 2^{b}	0.40 ± 0.02^{bc}	0.98
GFD-Q-30%	7.52 ± 0.31^{d}	253.94 ± 1.39^{d}	6.44 ± 0.41^{d}	148.73 ± 2.27^{c}	66.27 ± 3^{c}	0.36 ± 0.05^{abc}	0.99
GFD-Q-50%	9.07 ± 0.19^{e}	309.41 ± 4.85^{e}	7.89 ± 0.41^{c}	161.92 ± 9.40^{c}	65.81 ± 4^{c}	0.42 ± 0.04^{bc}	0.97
GFD-K-10%	5.53 ± 0.25^{bc}	163.92 ± 5.71^{b}	3.54 ± 0.33^{f}	92.37 ± 5.53^{e}	32.56 ± 3^{a}	0.40 ± 0.01^{bc}	0.94
GFD-K-30%	5.76 ± 0.50^{c}	212.99 ± 10.04^{c}	4.96 ± 0.13^{e}	126.33 ± 7.23^{d}	47.24 ± 3^{b}	0.37 ± 0.02^{abc}	0.98
GFD-K-50%	9.22 ± 0.27^{e}	312.43 ± 10.36^{e}	7.85 ± 0.16^{c}	152.43 ± 6.90^{c}	83.80 ± 6^{d}	0.36 ± 0.02^{abc}	0.98
GFD-T-10%	5.07 ± 0.15^{bc}	184.36 ± 7.76^{bc}	4.09 ± 0.21^{ef}	125.50 ± 5.22^{d}	58.12 ± 8^{b}	0.34 ± 0.05^{ab}	0.98
GFD-T-20%	14.27 ± 0.33^{f}	484.51 ± 3.65^{f}	12.81 ± 0.76^{b}	258.16 ± 5.73^{b}	179.24 ± 27^{e}	0.46 ± 0.07^{c}	0.99
GFD-T-30%	29.63 ± 0.57^{g}	1012.49 ± 39.54^{g}	23.36 ± 0.47^{a}	361.54 ± 2.08^{a}	436.80 ± 45^{f}	0.28 ± 0.04^{a}	0.99

GFD, Gluten-free dough; K, kiwicha flour; Q, Quinoa flour; T, tarwi flour.

Values followed by different letters in the same column are significantly different ($P < 0.05$).

*The coefficient of determination (R^2) indicates the level of adjustment of the Power Law model with the experimental values.

ranged from 0.49 N to 12.27 N. Schober *et al.* (2005) reported that the extrusion force of gluten-free doughs made with 10 sorghum flour hybrids using 70% and 30% of corn starch varied between 3.5–10.1 N. Likewise, Moore *et al.* (2004) reported that the force of extrusion in gluten-free doughs with wheat starch, potato starch, corn starch and brown rice flour ranged from 5.49 to 11.48 N.

The firmness of gluten-free doughs, measured using back-extrusion technique, has been reported in recent research. The firmness values of the doughs made with rice flour (50%), cornflour (30%) and quinoa flour (20%) with different levels of xanthan gum (1.5%, 2.5% and 3.5%) and water (90%, 100% and 110%) ranged from 5.52 N to 13.29 N (Encina-Zelada *et al.*, 2018) and when using doughs with guar gum (2.5%, 3.0% and 3.5%) and water (90%, 100% and 110%) dough firmness varied between 9.6 N to 16.95 N (Encina-Zelada *et al.*, 2019). These values are within the firmness ranges found in the vast majority of gluten-free doughs with Andean grain flours, with the exception of doughs containing tarwi flour at 30%. It should be mentioned that the doughs prepared by Sciarini *et al.* (2010a) contain high water content, which varies between 110% to 218% (based on flour and starch). These authors point out that the excessive use of water was due to the high protein content of the soybean flour, which had the ability to absorb water, thus reducing free water in the dough system. This might have been the reason why the doughs with 20% and 30% tarwi flour showed the highest firmness values, since it has been reported, that the water absorption capacity of the tarwi flour can be more than 200% (Vidaurre-Ruiz *et al.*, 2019b).

Control dough also showed lower consistency (111.41 N.s) than the other formulations. The consistency of the doughs with 10% and 50% quinoa flour was very similar to the doughs with 10% and 50% kiwicha flour; however, the consistency of the dough with 30% kiwicha flour (212.99 N.s) was less than the dough with 30% quinoa flour (253.94 N.s). This result may be linked, as explained above, to the difference in the composition of these flours. In the case of doughs with tarwi flour, the consistency of the dough with 10% tarwi flour (184.36 N.s) was similar to the consistency of the dough with 10% quinoa flour (162.92 N.s), and 10% and 30% kiwicha flour (163.92 N.s and 212.99 N.s, respectively). However, as the level of tarwi flour increased to 20 and 30% dough consistency increased dramatically to 483.51 N.s and 1012.49 N.s, respectively. The gluten-free doughs consistency values reported by Encina-Zelada *et al.*, (2018) varied between 52.5 and 128.23 N.s. In the present research, the only dough that has consistency values in this range was the control dough (111.41 N.s). As mentioned before, this may be due to the low level of hydration (75%) that the formulations received compared to other works using water between 90 and 110% (Encina-Zelada *et al.*, 2018, 2019).

The cohesiveness of the control dough (2.27 N) was lower than the other formulations. The doughs with 10% quinoa were similar to the doughs with 10% kiwicha. In both cases, as the flour level increased, cohesiveness increased; however, the cohesiveness of the dough with 30% kiwicha flour (4.96 N) was much lower than the cohesiveness of the dough with quinoa flour at 30% (6.44 N). The cohesiveness of the dough with 10% tarwi flour (4.09 N) was similar to the doughs with quinoa flour and 10% kiwicha (3.73 N - 3.54 N); however, as the level of tarwi increased in the dough, cohesiveness increased to 12.81 N for the dough with 20% tarwi flour and 23.36 N for the dough with 30% tarwi flour. As reported by Encina-Zelada *et al.* (2018), the minimum and maximum cohesivity values of the gluten-free doughs composed of rice flour, cornflour and quinoa flour vary between 3.92–8.36 N when mixed with different concentrations of xanthan gum and water. Higher cohesiveness values (12.95 N) have been reported when this same dough has been mixed with 3.5% guar gum (Encina-Zelada *et al.*, 2019). Most of the cohesiveness values determined in this study were in the range reported in other studies, with the exception of the dough with 30% tarwi flour, which was the most cohesive (23.36 N).

The viscosity index of the control dough (67.47 N.s) was lower than the other formulations. In the case of dough with quinoa flour, the viscosity index of the doughs with 30 and 50% was similar (148.73–161.92 N.s), corresponding with the viscosity index of dough with kiwicha flour at 50 % (152.43 N.s). The dough with 30% kiwicha flour had a similar viscosity index than the dough with 10% tarwi flour (126.33–125.50 N.s). The highest viscosity index value was obtained in the dough with 30% tarwi flour (361.54 N.s). The textural behaviour of gluten-free doughs was influenced by the composition of the flours and the proportion of the ingredients used. Likewise, it could have been influenced by the physical characteristics of the flours, such as the particle size. In the present investigation, quinoa and kiwicha were ground using a smaller screen size than tarwi, because tarwi grain contains a high-fat content (21.6%), which did not allow to use too small sieve sizes. Although this flour characteristic was not addressed in the present study, it could have contributed to the textural properties of gluten-free doughs. In future studies, this factor would need to be addressed.

According to Encina-Zelada *et al.* (2018, 2019), the physical quality of gluten-free breads is closely related to the textural properties of the dough. These authors demonstrated that at a higher concentration of gum (guar gum or xanthan gum 3.5%) with a low level of hydration (90%) breads with low specific volume and harder crumbs are produced. Therefore, according to the results obtained in the present investigation it should be expected that doughs with 10% or 30% quinoa or kiwicha or 10% tarwi flour can result in gluten-free breads of good quality. However, it is advisable to consider the amount of water and gums, in order to achieve appropriate textural properties, obtain gluten-free breads with Andean grain flours with satisfying specific volume.

Flow properties of gluten-free doughs made with Andean grain flours

Table 1 shows the flow properties of gluten-free doughs made with different concentrations of quinoa (10%, 30% and 50%), kiwicha (10%, 30% and 50%) and tarwi flour (10%, 20% and 30%), as well as control dough flow properties. The flow behaviour index (n) of the dough was in the range of 0.28–0.42, showing a pseudoplastic behaviour. Similar values of n (0.29–0.5) have been reported by Tunç & Kahyaoglu (2016), in gluten-free doughs based on rice flour, with different substitutions with defatted hazelnut flour (5%, 10% and 15%) and different gums such as locust bean gum, guar gum and 0.25% xanthan gum. Higher values of n (0.43 - 0.70) have also been reported by Sabanis & Tzia (2011), in gluten-free doughs based on corn starch and rice flour with different concentrations of xanthan gum, HPMC, guar gum and carrageenan (1%, 1.5% and 2%) and different levels of hydration (75–105%). High values of n are more frequent in doughs of gluten-free cakes (0.585–0.629) (Aydogdu *et al.*, 2017, 2018). The value of flow behaviour index (n) found confirms with the statement by Demirkesen *et al.* (2010) and Ronda *et al.* (2017), who pointed out that gluten-free doughs generally follow a pseudoplastic behaviour when subjected to constant shear stress tests.

With respect to the mathematical model, the experimental data were correctly adjusted to the power law model (R^2: 0.94–0.99) (Fig. 1). The Herschel-Bulkley and Bingham model had also been tested to model the flow behaviour of gluten-free doughs with quinoa flour, although with less success in adjusting the experimental data (Turkut *et al.*, 2016).

The consistency coefficient (K) of the control dough (31.38 $Pa.s^n$) was similar to the consistency recorded in the dough with 10% kiwicha flour (32.56 $Pa.s^n$). This could be related to the lipid content of kiwicha flour, since it has been shown that the inclusion of oil in the system decreases the consistency of the dough (Moreira *et al.*, 2012; Mancebo *et al.*, 2017). The consistency of all doughs increased as Andean grain flours were incorporated, the most significant increase was evidenced in the dough with tarwi flour at 20% and 30% (maximum consistency 436.80 $Pa.s^n$). This is obviously related to the increase of proteins in the dough, which have the ability to absorb cold water and decrease the fluidity of the dough, additionally it could have been influenced by the fibre content in the system (Sabanis *et al.*, 2009). It has been reported that quinoa bran, which is rich in dietary fibre, has a high capacity for water absorption and negatively affects the final volume of gluten-free bread, producing compact crumbs (Föste *et al.*, 2014). Likewise, it has been reported that quinoa and kiwicha contain a higher proportion of insoluble fibre than soluble fibre (Repo-Carrasco-Valencia *et al.*, 2019) and that insoluble fibre is responsible for increasing the retention capacity of water (Kurek *et al.*, 2018). Therefore, it was expected that the more insoluble fibre present in the dough, the

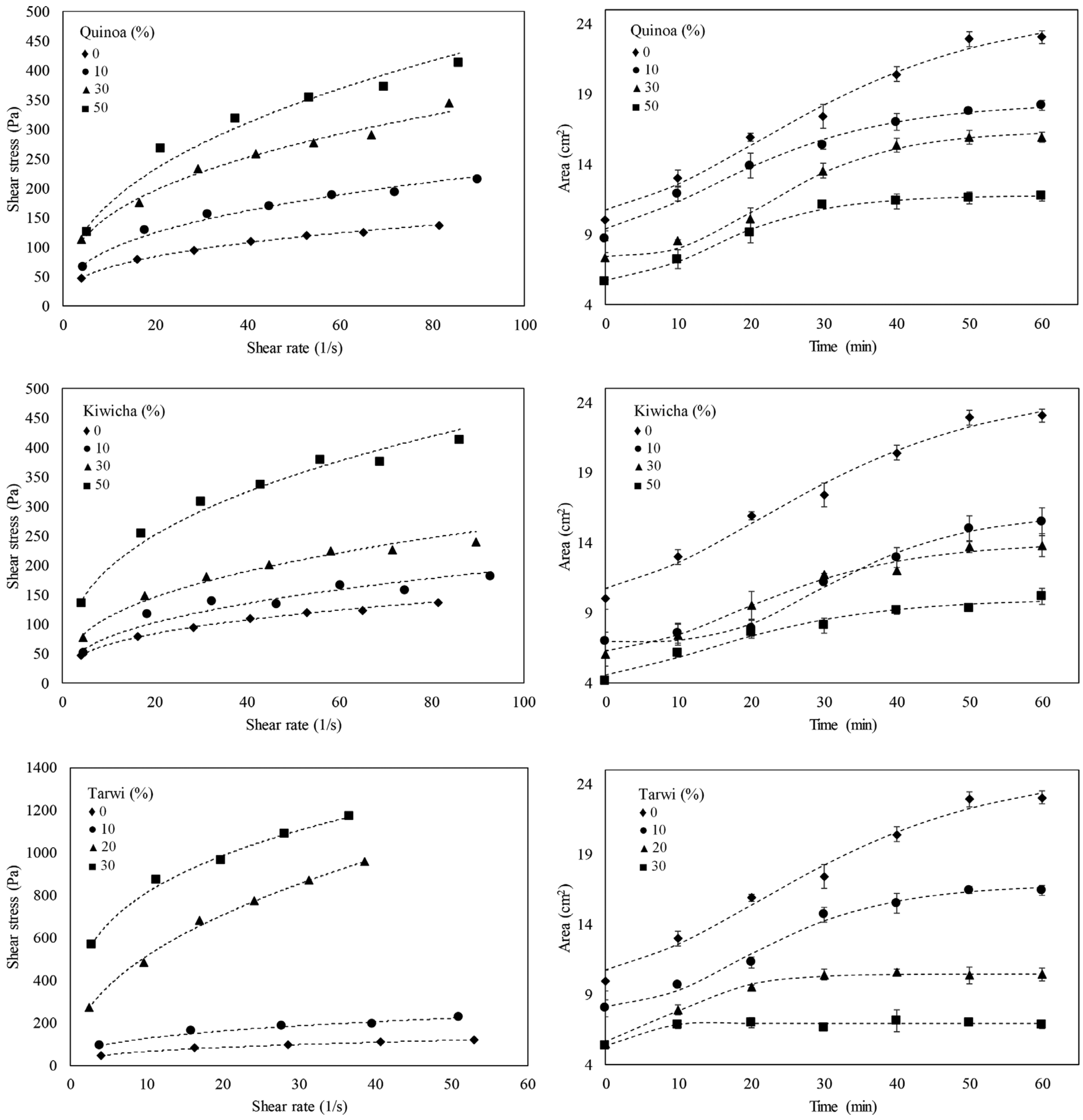

Figure 1 Rheograms and growth curves during the leavening process of gluten-free doughs made with Andean grains in different concentrations.

more consistency would increase. The dough with tarwi flour (10%) had a similar consistency (58.12 Pa.s^n) than the dough with 30% kiwicha (47.24 Pa.s^n). This is related to the high oil content of tarwi flour (21.6%). As the content of lupines flour in the doughs increased, their consistency increased as well. The inclusion of lupine protein in gluten-free breads has been investigated recently, highlighting its good techno-functional properties (water absorption capacity and emulsion), which produced breads with soft crumbs and good distribution of alveoli in the bread (Horstmann *et al.*, 2017). It has also been reported that the inclusion of lupine protein concentrate (59% protein) in 10% gluten-free breads based on corn starch flour and potato starch provided breads with good specific volume (Ziobro *et al.*, 2013).

According to Fig. 1, where the flow curves are shown, maximum shear rate of 100 s^{-1} were experienced. Similar shear rate have been experienced by Tunç & Kahyaoglu (2016), who evaluated the flow properties of gluten-free doughs based on rice flour, with different substitutions with defatted hazelnut flour (5%, 10% and 15%) and different gums such as carob, guar and xanthan. Lower shear rate (up to 50 s^{-1}) have also been experienced in the evaluation of the flow properties of gluten-free doughs, as in the work done by Turkut *et al.* (2016), who evaluated the flow properties of gluten-free dough with rice flour, potato starch, quinoa flour, buckwheat flour and xanthan gum. Likewise, high shear rate (200 s^{-1}) have also been reported, as in the work of Sabanis *et al.,* (2009), who evaluated the flow properties of gluten-free doughs based on corn starch, rice flour and hydroxypropyl methyl cellulose (HPMC) with different fibre levels (3%, 6% and 9%) of wheat, corn, oats and barley. The wide variety of shear rates experienced in the investigations basically depends on the consistency of the doughs. Future works should be carried out to analyse the thermo-mechanical properties of gluten-free doughs made from Andean grain flours using Mixolab, in order to determine water absorption capacity, protein weakening, and starch behaviour during heating and cooling period (Duta & Culetu, 2015; Ding *et al.*, 2018).

Kinetics of dough growth during the leavening process

The growth of gluten-free doughs with Andean grain flours was correctly modelled using the Gompertz equation (R^2: 0.87–0.99) (Fig. 1). The kinetic parameters of dough growth during the leavening process are shown in Table 2. According to parameter C (cm^2), which represents the difference between the maximum and minimum area obtained, the control dough grew much more than the others formulations (15.22 cm^2), while doughs with quinoa flour (10% and 30%), doughs with kiwicha flour (10% and 30%) and dough with tarwi flour (10%) achieved moderate growth (between 7.91–9.73 cm^2). Reduced dough growth was observed with 50% quinoa, 50% kiwicha and 20% tarwi (between 4.97–6.12 cm^2), while the dough with 30% tarwi flour was the least growing (1.58 cm^2).

With respect to the maximum growth rate ($V_{\max}$) of the doughs, it was observed that as the Andean grain flour was incorporated, the speed increased. The minimum growth rate was evidenced in the control dough (0.05 min^{-1}), while the maximum value was obtained in the dough with 30% tarwi flour (2.92 min^{-1}). The time to achieve maximum dough growth (X, min) decreased as the percentage of Andean grain flour increased. This time was in the range of 20.97–29.17 min for the control dough, quinoa dough at 10% and for the dough with 10% kiwicha. For the doughs with quinoa flour (30% and 50%), kiwicha flour (30, 50%) and tarwi flour (10%), the time needed to achieve maximum growth was between 12.97–17.87 min, while for the doughs with 20% and 30% tarwi flour the lowest times were evident (7.39–8.26 min). These results showed that the fermentation time of 30 min was sufficient for all doughs, it could even be shorter for doughs with a higher percentage of Andean grain flours (Fig. 2). In Fig. 1, the maximum growth time of the doughs is appreciated, when the curve becomes asymptote. Knowing the appropriate fermentation time of gluten-free doughs would help in optimising process times. The control of this parameter is important because if it is not controlled it could cause weakening of the structure and its collapse during baking (Cappa *et al.*, 2016; Vidaurre-Ruiz *et al.*, 2019a).

Table 2 Kinetic parameters of gluten-free doughs made with different concentrations of quinoa, kiwicha and tarwi flour

	Kinetic parameters during dough growing				
Formulation	A_o	C (cm^2)	$V_{\max}$ (min^{-1})	X (min)	R^2*
GFD-Control	10.02 ± 0.7^{g}	15.22 ± 1^{e}	0.05 ± 0.01^{a}	21.03 ± 3^{d}	0.99
GFD-Q-10%	8.69 ± 0.1^{fg}	9.73 ± 1^{d}	0.07 ± 0.01^{a}	20.97 ± 1^{d}	0.99
GFD-Q-30%	7.38 ± 0.3^{def}	8.95 ± 1^{d}	0.12 ± 0.05^{a}	13.73 ± 2^{bc}	0.99
GFD-Q-50%	5.66 ± 0.1^{bc}	6.12 ± 0.3^{bc}	0.11 ± 0.02^{a}	13.49 ± 2^{abc}	0.99
GFD-K-10%	6.99 ± 0.6^{cde}	9.50 ± 2^{d}	0.09 ± 0.04^{a}	29.17 ± 3^{e}	0.99
GFD-K-30%	6.06 ± 0.8^{bcd}	7.91 ± 1^{cd}	0.08 ± 0.01^{a}	17.82 ± 3^{cd}	0.99
GFD-K-50%	4.13 ± 0.1^{a}	5.89 ± 1^{bc}	0.07 ± 0.01^{a}	12.97 ± 1^{abc}	0.98
GFD-T-10%	8.04 ± 0.6^{df}	8.91 ± 1^{d}	0.09 ± 0.03^{a}	18.17 ± 1^{cd}	0.99
GFD-T-20%	5.51 ± 0.3^{b}	4.97 ± 0.3^{b}	0.16 ± 0.01^{a}	8.26 ± 1^{ab}	0.99
GFD-T-30%	5.37 ± 0.2^{ab}	1.58 ± 0.3^{a}	2.92 ± 1.27^{b}	7.39 ± 3^{a}	0.87

The values followed by different letters in the same column are significantly different ($P < 0.05$).

*The coefficient of determination (R^2) indicates the level of adjustment of the Gompertz model with the experimental values.

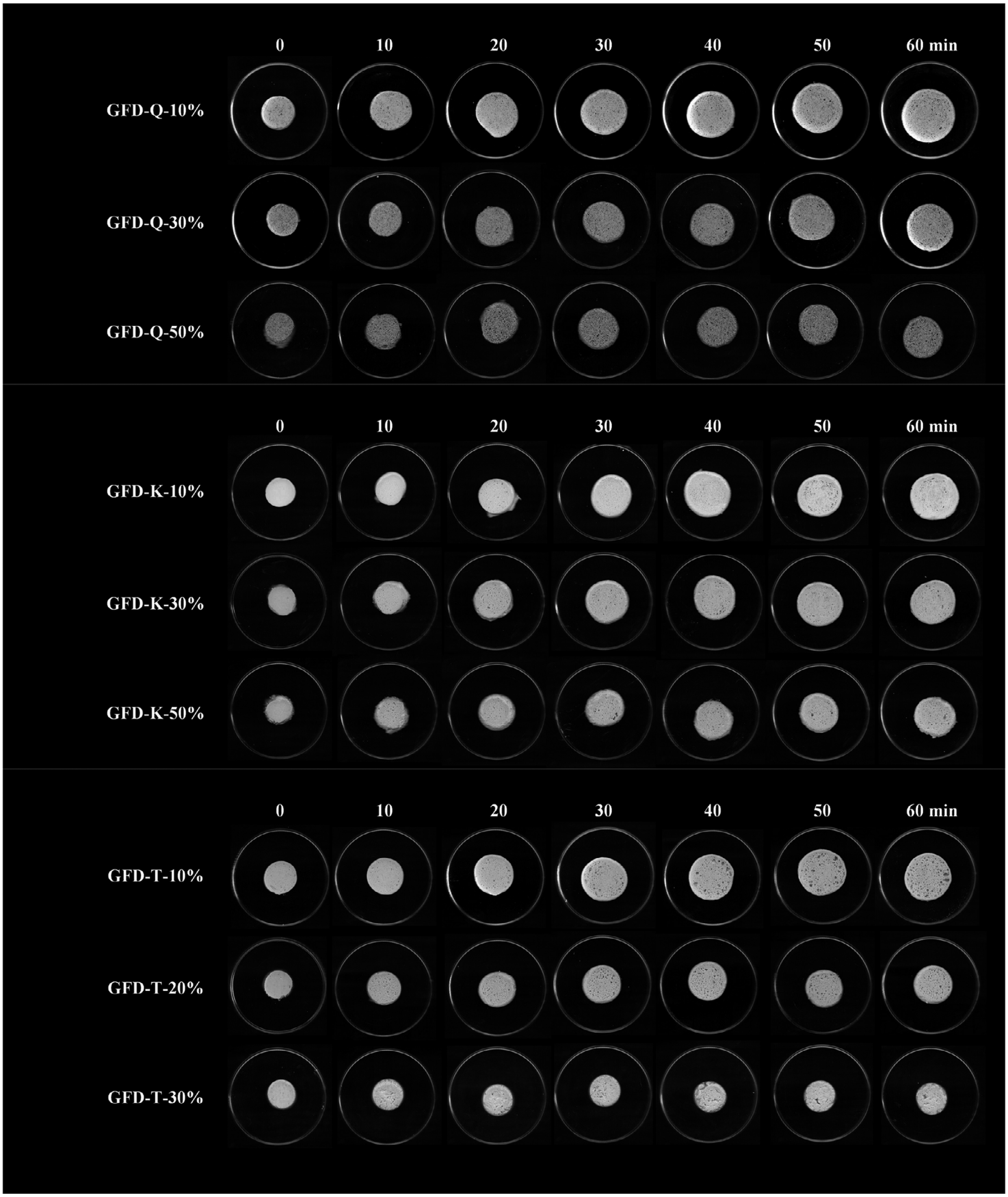

Figure 2 Growth of gluten-free doughs (GFD) with different concentrations of Andean grain flours. Quinoa (Q). Kiwicha (K), Tarwi (T).

Table 3 Correlation matrix (*r*) between rheological and textural properties of the doughs with the kinetic parameters of dough growth during leavening process

	Textural properties				**Rheological properties**	
Kinetic parameters	**Firmness**	**Consistency**	**Cohesiveness**	**Viscosity Index**	**Flow behaviour index (*n*)**	**Consistency index (K)**
C (cm^2)	−0.81*	−0.8*	−0.82*	−0.85*	0.11	−0.73*
V_{max} (min^{-1})	0.86*	0.85*	0.82*	0.77*	−0.52	0.87*
X (min)	−0.64*	−0.66*	−0.69*	−0.72*	0.04	−0.63*

*Level of significance ($P < 0.05$).

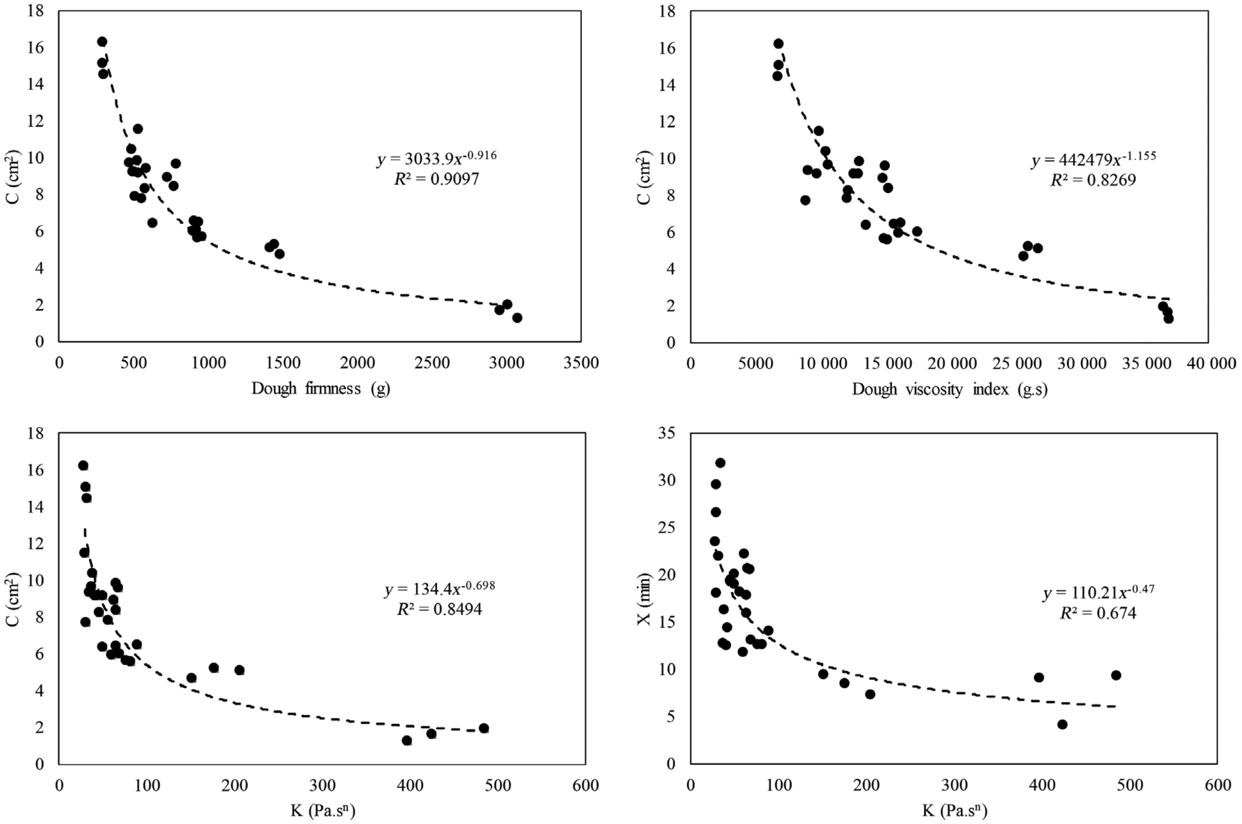

Figure 3 Power law relation between the kinetic parameters of dough growth during the leavening process with firmness, the viscosity index and consistency index of gluten-free doughs made with Andean grain flours.

Correlation between the growth of the doughs and their textural and rheological properties

The kinetic parameters of dough growth during the leavening process were significantly correlated ($P < 0.05$) with all textural properties and with the dough consistency coefficient (Table 3). It was found that the doughs grew to a greater extent when the firmness, consistency, viscosity index (textural properties), and consistency (rheological property) of the dough were lower. On the contrary, it was found that higher maximum growth rates of the dough (V_{max}) were achieved when the firmness, consistency (textural), viscosity index and consistency (rheological) of the dough were higher. It was also found that the maximum dough growth was negatively correlated with the textural and rheological parameters of the dough. A better correlation kinetic growth parameters (C and X) with the textural properties (firmness and viscosity index) and rheological properties (K) was found using power law models (Figure 3). With these models, it can be seen that the growth of the dough during the leavening process is greatly influenced by the firmness (N), viscosity index (N.s) and rheological consistency (Pa.s^n) of the dough. According to Pruska-Kędzior *et al.* (2008), the consistency index of gluten-free doughs (K) is closely related to CO_2 retention parameters and would serve to control the fermentation behaviour of the dough. Therefore, the equations found could also be used to predict the growth behaviour of gluten-free doughs, with Andean grain flours, during the leavening process.

It has been reported that the consistency of the dough (K) had a significant effect on the specific volume of bread (Sabanis *et al.*, 2009; Sciarini *et al.*, 2010a), where less consistent doughs do not have the ability to retain the CO_2 produced during fermentation or the air incorporated during the shaking and therefore breads with low specific volume would be produced (Sabanis *et al.*, 2009). However, it is known that very consistent doughs do not guarantee their growth during the leavening process (Sciarini *et al.*, 2010b). According to Ziobro *et al.* (2016), it is difficult to predict the exact influence of the rheological properties on the characteristics of the product, but its evaluation during the whole bakery process could give us an idea of the influence on the quality of the finished product. Based on the results obtained, it could be stated that the incorporation of 10 and 20% of quinoa and kiwicha flour, as well as 10% of tarwi flour (in the investigated recipe), would generate enough dough consistency to produce breads with good specific volume. In future work, the consistency of gluten-free dough with high content of Andean grain flours could be modified by assessing the level of hydration of the dough, as well as the type and level of hydrocolloids.

Conclusions

In this research, the rheological and textural properties of gluten-free doughs made with different proportions of Andean grain flours were evaluated. It was found that the textural parameters of the doughs such as firmness, consistency, cohesiveness and viscosity index increased as the percentage of substitution with quinoa, kiwicha and tarwi flour in the formulation increased. The same effect was observed for the consistency index (K) of the doughs. The moderate content of lipids in Andean grains contributed to reducing the rheological and textural properties of quinoa and kiwicha doughs, but in the case of tarwi doughs, the high protein content with high water absorption capacity caused a decrease in dough fluidity. The kinetics of leavening during the leavening process was modelled using the Gompertz equation. It was shown that the growth of the doughs and the fermentation time was influenced by their textural and rheological properties. Doughs containing 10 and 20% of quinoa flour or kiwicha flour, or 10% of tarwi flour developed adequately during fermentation.

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Author contribution

Julio Vidaurre-Ruiz: Conceptualization (equal); Data curation (equal); Investigation (equal); Methodology (equal); Writing-original draft (equal); Writing-review & editing (equal). **Francisco Salas-Valerio:** Funding acquisition (equal); Methodology (equal); Project administration (equal); Resources (equal); Writing-review & editing (equal). **Regine Schoenlechner:** Software (equal); Supervision (equal); Writing-original draft (equal); Writing-review & editing (equal). **Ritva Repo-Carrasco-Valencia:** Conceptualization (equal); Data curation (equal); Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing-review & editing (equal).

Ethical approval

Ethics approval was not required for this research.

Conflict of interest

Authors have no interest of conflict to declare.

Data availability statement

All data of this study are presented within this study.

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