

Research Article

Biological, Quality, and Sensory Evaluation of Raw and Microwaved Quinoa Baked Tortilla Chips

Maribel Valenzuela-González,¹ José Luis Cárdenas-López ,¹ Armando Burgos-Hernández,¹ Manuel Viuda-Martos ,² Norma Julieta Salazar-López ,³ Alan Ruiz-Hernández ,¹ J. Abraham Domínguez-Avila ,⁴ and Maribel Robles-Sánchez ¹

¹Department of Food Research and Graduate, Universidad de Sonora, Hermosillo, Sonora, Mexico

²IPOA Research Group, Center for Agri-Food and Agro-Environmental Research and Innovation, Universidad Miguel Hernández, Orihuela, Spain

³Faculty of Medicine of Mexicali, Universidad Autónoma de Baja California, Mexicali, Baja California, Mexico

⁴SECIHTI-Center for Food and Development Research, Hermosillo, Sonora, Mexico

Correspondence should be addressed to Maribel Robles-Sánchez; maribel.roblessanchez@unison.mx

Received 13 May 2025; Revised 26 August 2025; Accepted 30 September 2025

Academic Editor: Poulami Jha

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Quinoa (*Chenopodium quinoa* Willd.) is a pseudocereal with notable bioactive properties, making it suitable for the development of functional snacks. This study is aimed at comparing the total phenolic content (TPC), total flavonoid content (TFC), individual phenolic profile, and antioxidant capacity (TEAC) of tortilla chips made from raw quinoa (RQTC) and microwave-cooked quinoa (MQTC) before and after an in vitro gastrointestinal digestion. In addition, sensory and instrumental characteristics were evaluated to assess their acceptability. The results showed that after digestion, MQTC exhibited the highest recovery index at the intestinal phase of TPC (165%), whereas this was highest during the gastric phase (154%) for RQTC. Flavonoid content was highest in the gastric phase, particularly in RQTC (141%), although MQTC stood out for its higher recovery in the intestinal phase. Antioxidant activity increased significantly throughout digestion, reaching its peak in the intestinal phase for MQTC (40 times higher than the undigested sample). UHPLC analysis revealed a differential release of phenolic compounds, with remarkable increases after the gastric phase of MQTC according to the recovery index of quercetin (3195%) > ferulic acid (567%) > *p*-coumaric acid (239%) > rutin (168%); in contrast, the recovery of phenolics in the intestinal phase was higher for *p*-coumaric acid (4538%) > ferulic acid (209%) > rutin (51%). MQTC had the highest sensory acceptability, especially regarding mouthfeel, and showed the lowest fracturability values, associated with a more brittle texture. Instrumentally, MQTC had the highest browning index, with no significant differences in lightness. These findings suggest that microwave cooking enhances the release and functionality of bioactive compounds without compromising sensory quality, positioning MQTC as a promising healthy snack option.

Keywords: consumer acceptance; functional foods; phenolic compounds; quinoa snacks

1. Introduction

There is a significant global demand for healthy, practical, and ready-to-eat snacks. These products may be formulated from different food matrices with unique biological potential and are generating great interest due to changes in the population's eating habits, which aim at countering increases in noncommunicable diet-associated diseases [1]. Healthy

snacking may help control hunger and reduce excess calorie intake; however, if it is done excessively or if the snacks contain unhealthy ingredients, obesity, diabetes, cardiovascular diseases, hypertension, and other diseases may be promoted instead [2]. Healthy snacks may include those made from a range of food sources like fruits, vegetables, cereal and legume grains, protein-rich materials, dairy, and nonconventional food sources [3].

Tortilla chips are one of the most globally popular snack products and are made mainly from nixtamalized corn [4]. Baked tortilla chips are a promising alternative to fried ones; they can be made from different base ingredients, including pseudocereals like amaranth [5], chia [6], buckwheat [7], sorghum [8], and, of particular relevance to the present work, quinoa [9]. These food matrices have significant biological potential to benefit the population, thanks to their high content of bioactive compounds like phenolics. Dietary phenolics can have a positive impact on the antioxidant activity of the consumer and can therefore play a key role in countering or preventing noncommunicable diet-associated diseases [10–14].

Quinoa (*Chenopodium quinoa* Willd.) has gained popularity as a superfood due to its nutritional and bioactive qualities [15–18]. Among its bioactive properties are immunoregulatory/anticancer [19], antidiabetic [20], antihypertensive [21], anti-inflammatory [22, 23], and gastroprotective [24]. Technologies like germination [25], extrusion [26], and fermentation [27] have been employed to enhance its bioactive potential. In particular, microwave cooking has been identified as an effective technique for improving the bioactive properties of quinoa [9, 28], making it an ideal candidate to incorporate into healthy snack products.

In addition to studies focused on quinoa-based snacks and products, several works have explored the impact of in vitro digestion on baked goods. For example, research by Muñoz-Pabon et al. [29, 30] and Pellegrini et al. [31] has evaluated how gastrointestinal digestion affects the bioactive compounds and antioxidant activity of baked products, such as bread and cookies. These studies provide evidence that the digestive processes can influence the release and bioavailability of phenolic compounds, an area of research that is also applicable to quinoa-based products. Therefore, the in vitro digestion evaluation of quinoa-based snacks in this study offers a valuable opportunity to compare their behavior to that of other baked foods.

The growing interest in healthy products has created a significant market for functional foods. Incorporating pseudocereals into such products can improve their nutritional quality and functional properties and maintain acceptable sensory characteristics for the consumer [32–35]. Under this premise, various foods have been developed from quinoa, including pastas [36], bakery products [37], and cookies [38], which may improve their bioactive potential. Quinoa flour could therefore be used to make products such as snacks, similar to corn-based snacks previously reported by other authors [39–41].

Despite the well-known nutritional benefits of quinoa, its application in snack products still faces challenges, particularly in terms of improving its bioavailability and bioactive potential. Traditional cooking methods may not optimize the phenolic compound content of quinoa; however, microwave cooking has proven to be an effective technique for enhancing its bioactivity by preserving or even increasing the concentration of bioactive compounds. Previous studies [9, 28] suggest that microwave cooking can favorably modify quinoa's structure, promoting the release of antioxidants and other beneficial compounds. This treatment offers signifi-

cant advantages over conventional methods like slow boiling or frying, which tend to reduce the concentration of available antioxidants. Therefore, incorporating microwave-treated quinoa into snack products can optimize their bioactive properties and enhance their acceptability as part of a healthy diet.

It is also known that the potential benefits of these foods can be influenced by gastrointestinal conditions. For example, it has been documented that some phenolic compounds in quinoa may undergo modifications during in vitro digestion, which can alter their bioavailability [29–31, 42, 43].

Based on this information, the aim of the present study is to (i) compare the total phenolic and flavonoid content, phenolic profile, and antioxidant activity of tortilla chips made with raw quinoa and microwave-cooked quinoa, (ii) investigate the effect of in vitro gastrointestinal digestion on phenolic compounds and changes in antioxidant activity, and (iii) evaluate the sensory and quality attributes of the tortilla chips.

2. Materials and Methods

2.1. Sample Collection and Preparation. Commercially available quinoa (*Chenopodium quinoa* Willd.) was obtained from a local market (COSTCO Wholesale, Hermosillo, Sonora, Mexico). Whole white organic saponin-free quinoa was used, according to the specifications shown on the product label. Cooked quinoa was obtained through a microwave treatment described by Valenzuela González et al. [9]. The quinoa was baked in a conventional microwave oven (LG Electronic Appliances, Model MS2047GR, Tianjin, China, with a maximum power of 1650 W, equivalent to 100% power) for 14 min. The sample was then rapidly cooled in an ice bath and placed on aluminum trays to dry at a temperature of 45°C–55°C. The dry sample was ground (Laboratory Mill, Model 3100, operated at 230 V/60 Hz) to a particle size of <0.5 mm and stored at –20°C.

2.2. Tortilla Chip Preparation. Quinoa tortilla chips were prepared using 100 g of raw or microwaved whole-grain quinoa flour, mixed with olive oil (3 mL) and water (50 mL). The mix was manually kneaded for 5 min to form a dough and then rested for 30 min at room temperature. Small balls of dough (2 g) were formed and flattened using a large electric press (PE10-G, Máquinas González, Monterrey, Mexico).

Tortilla chips were preheated for 30 s in an electric press, placed on baking racks, baked for 10 min at 160°C, and cooled to room temperature. The final thicknesses of the chips were 0.95 and 40 mm in diameter. They were labeled RQTCs (raw quinoa tortilla chips) and MQTCs (microwaved quinoa tortilla chips) and stored at 4°C before being analyzed. Traditional corn tortilla chips (CTCs) were prepared as a commercial comparative reference, following the previously mentioned procedure.

2.3. Phenolic Compound Extraction. A methanolic extraction of phenolic compounds was carried out in accordance with the procedure described by Salazar Lopez et al. [44]. In a

15-mL conical tube, 1 g of sample was weighed and mixed with 15 mL of 80% methanol. The mixture was sonicated at room temperature for 60 min. The sample was then centrifuged at $150\times g$ for 15 min, and the supernatant was separated. The precipitate was subjected to the same procedure, and the supernatants were collected, pooled together, and filtered through Whatman No. 1 filter paper. Supernatants were evaporated in a rotary evaporator (BUCHI Labortechnik AG R-100, Flawil, Switzerland) and resuspended in 10 mL of 50% methanol (final concentration of 0.1 g/mL). This extract was stored in amber tubes at -20°C until further analysis.

2.4. Total Phenolic Compounds (TPCs). A microplate-adapted Folin–Ciocalteu method was used to measure TPCs. Thirty microliters of each extract was placed in a microplate well, to which 120 μL of 7.0% sodium carbonate solution and 150 μL of Folin–Ciocalteu reagent (diluted 1:9 with deionized water) were added. The mixture was incubated at room temperature for 60 min, and its absorbance was read in a microplate reader (FLUOstar Omega, BMG Labtech Inc., Ortenberg, Germany) at a wavelength of 765 nm. TPC content was calculated using a gallic acid standard curve, and the results were expressed as micrograms of gallic acid equivalents per gram of sample ($\mu\text{g GAE/g}$).

2.5. Total Flavonoid Content (TFC). Total flavonoids were quantified with the aluminum chloride method, following the procedure described by Robles Sanchez et al. [45] and adapted for microplate. The assay consisted of placing 30 μL of sample from each of the extracts in microplate wells, adding 9 μL of NaNO_2 and then 120 μL of H_2O . The mixtures were incubated for 5 min, 9 μL of AlCl_3 was added, and the mixture was incubated once again for 5 min. Sixty microliters of NaOH and 72 μL of H_2O were then added and mixed. Absorbance was then immediately read at 415 nm in a microplate reader (FLUOstar Omega, BMG Labtech Inc., Ortenberg, Germany). The flavonoid content was calculated using a quercetin standard curve, and the results were expressed as micrograms of quercetin equivalents per gram of sample ($\mu\text{g QE/g}$).

2.6. Antioxidant Activity. Antioxidant activity was quantified according to the Trolox equivalent antioxidant capacity (TEAC) assay, which is based on the ability of an antioxidant to stabilize the cationic radical 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) ($\text{ABTS}^{\bullet+}$); the reduction of this radical induces a color change that can be measured at 734 nm. For this, a stable ABTS stock solution was prepared by mixing 5 mL of an aqueous ABTS solution (7 mM) with 0.088 mL of potassium persulfate (148 mM) and incubated in the dark at room temperature for 16 h. The $\text{ABTS}^{\bullet+}$ working solution was prepared before use by diluting the stock solution in ethanol (1:88 v/v), and its absorbance was adjusted to 0.70 ± 0.02 at 734 nm. Two hundred and eighty microliters of the working solution was mixed with 20 μL of each extract in a microplate well and allowed to react for 5 min. The results were expressed as micromoles of Tro-

lox equivalents per gram of sample ($\mu\text{mol TE/g}$), according to a Trolox calibration curve [46].

2.7. Phenolic Profile by Ultrahigh Performance Liquid Chromatography (UHPLC). Phenolic compounds were quantified following the methodology described by Lee et al. [47] with minor modifications. Briefly, components were separated using an Agilent Binary LC system coupled to a diode array detector (DAD) (Agilent Technologies, 1290 Infinity, Santa Clara, California, United States). Three phenolic acids and four flavonoids were separated with a Zorbax Eclipse Plus C18 (2.1×50 mm, $1.8 \mu\text{m}$) at 30°C . A binary phase solvent system was used, using 0.1% formic acid in water (Solvent A) and 0.1% formic acid in acetonitrile (Solvent B). The solvent gradient was as follows: 97%–93% A, 0–3 min; 93%–90% A, 3–5 min; 90%–88% A, 5–8 min; 88%–85% A, 8–10 min; 85% A, 10–15 min; 85%–45% A, 15–18 min; 45%–10% A, 18–20 min; and 10%–97% A, 20–23 min. The flow rate was 0.4 mL/min, and the injection volume was 10 μL . The phenolic compounds were identified according to their spectra at the following wavelengths: gallic acid at 280 nm, *p*-coumaric and ferulic acids at 320 nm, and rutin, myricetin, quercetin, and kaempferol at 360 nm. Compound identification was made by comparing retention times and UV spectra of samples with those of pure reference standards. The results were expressed as microgram phenolic compound per gram ($\mu\text{g/g}$).

2.8. In Vitro Gastrointestinal Digestion. The in vitro gastrointestinal digestion model used was adapted from Salazar Lopez et al. [48] and was performed in triplicate for each sample. It is important to note that this study had no implications for human experimentation, was not of a clinical or epidemiological nature, and all tests complied with ethical guidelines [49]. Three laboratory staff members participated as volunteers; in a healthy state and fasting, they chewed 1 g of each of the samples (RQTC, MQTC, and CTC) for 15 s, and each chewed sample was individually poured into a 50-mL conical tube. They rinsed their mouths twice with 5 mL of water for 60 s, where the liquid was poured into the respective tubes. The tubes remained at 37°C for 3 min to obtain the digest of the oral phase. Subsequently, to move on to the gastric phase, the samples were mixed with 5 mL of 0.2 M HCl–KCl buffer solution, and its pH was adjusted to 1.5. Next, 667 μL of a pepsin solution (300 mg/mL Cat. P7000 powder ≥ 250 units/mg solid, Sigma-Aldrich, St. Louis, Missouri, United States) was added to reach a final enzyme concentration of 2000 U/mL, and the tubes were incubated for 1 h at 37°C in a water bath with constant orbital rotation of 100 rpm (Precision Scientific Mod. 66800, Winchester, Virginia, United States). After the incubation period, three tubes were removed from each of the samples and placed in an ice bath. The remaining samples continued with the intestinal digestion phase. For this phase, 9.0 mL of phosphate buffer (0.1 M, pH 7.5) was added to each tube, and the pH was adjusted to 7.5. Next, 1 mL of pancreatin solution (17 mg/mL Cat. P1750 4 $\times$ USP specifications, Sigma-Aldrich) was added to reach a final enzyme concentration of 100 U/mL (trypsin activity), and bile salts

(80 mg Cat. B8756, Sigma-Aldrich) were also added; the mixture was incubated for 6 h at 37°C in a water bath with constant orbital rotation of 100 rpm to obtain the intestinal digest. After incubation, the oral, gastric, and intestinal samples were frozen at −20°C and resuspended in 50% methanol for subsequent analysis. Blanks followed the same protocol but without samples.

2.9. Recovery Index (RI%) of Phenolic Compounds and Antioxidant Activity. The RI% of TPC, TFC, individual phenolics, and antioxidant activity was calculated for all digestion phases according to Equation (1):

$$RI(\%) = \left(\frac{A}{B} \right) \times 100 \quad (1)$$

where A is TPC, TFC, individual phenolics, and antioxidant activity variables quantified in each sample at each digestion phase and B is the same variable in the samples before the in vitro gastrointestinal digestion.

2.10. Sensory Evaluation/Consumer Test. An open invitation was made to the general student population of the University of Sonora; they were explained the types of foods to be evaluated, requirements for their participation, and the possibility of withdrawing from the study at any time if they so decided. No compensation of any kind was offered. Oral informed consent was obtained from all participants. No personal or identifying information was collected, thereby protecting the rights and privacy of all participants in accordance with the Declaration of Helsinki.

Ninety-three participants agreed to evaluate our samples. Three tortilla chip samples were presented to participants on plastic trays labeled with randomized three-digit codes. Water was used to rinse their mouths before tasting each sample. They were asked to rate each chip in terms of color, aroma, texture, flavor/taste, and overall acceptability by assigning a score based on a 7-point hedonic scale ("I dislike it a lot" as 1 and "I like it a lot" as 7), with 4 as the neutral point. The evaluation was carried out in one session (approximately 10 min), and each participant tasted the samples only once. They also responded to an acceptance/rejection test of the product by answering "yes" if they would consume the product or "no" if they would not consume the product.

2.11. Fracturability Analysis. The fracturability of all samples (RQTC, MQTC, and CTC) was analyzed on a TA.XTPlus Texture Analyzer (Stable Micro Systems, Surrey, United Kingdom), in compression mode with a 25 kg load cell. The test was conducted at 27°C with pretest, test, and post-test speeds of 1.0, 1.0, and 10.0 mm/s, respectively, and a trigger force of 5 g. A spherical probe of 8 mm diameter was used, with samples placed on an HDP/CFS (crisp fracture support rig) with a corresponding platform cylindrical holding of 16 mm diameter. Each measurement was performed in triplicate, and results were expressed in N.

2.12. Color. Instrumental color was analyzed for all samples (RQTC, MQTC, and CTC) using a colorimeter (Konica

Minolta Model CR-10, Osaka, Japan). It was measured on both sides of each sample (average calculated) in triplicate for lightness (L^*), redness/greenness (a^*), and yellowness/blueness (b^*). The browning index (BI) was also determined, using Equations (2) and (3):

$$BI = 100 \times \frac{(x - 0.31)}{0.17}, \quad (2)$$

$$\text{where } x = \frac{a^* + 1.75 \times L^*}{5.645 \times L^* + a^* - 3.012 \times b^*}. \quad (3)$$

2.13. Statistical Analysis. The data obtained were analyzed using an analysis of variance (ANOVA), using Tukey–Kramer HSD test for differentiation of means with a level of significance of $p \leq 0.05$, and using the statistical package JMP 5.0.1 (SAS Institute, Cary, North Carolina, United States).

3. Results and Discussion

CTCs are the most consumed snacks after potato chips [50]. Their composition may include, in addition to corn flour, different ingredients that modify their flavor or improve their nutritional and functional quality, such as cassava or pomegranate peel, as previously reported [51, 52]. In this sense, quinoa flour could be a promising ingredient to formulate baked tortilla chips, as a healthy alternative to fried snacks. The food matrix and food processing methods influence the recovery of bioactive compounds [53], in addition to multiple other physicochemical parameters. This has been reported in corn [54], rice [55], wheat [56], and quinoa foods [57, 58]. However, studies are limited in products made from microwave-cooked quinoa flour; thus, tortilla chips with microwave-treated quinoa flour were analyzed in the present study.

3.1. RI% of Phenolic Compounds and Antioxidant Activity of Tortilla Chips. Changes in the TPC, TFC, and antioxidant activity were found between digested and undigested samples, as well as between each digestion phase; results are shown in Figure 1.

Regarding TPC, it was observed that RQTC (733.54 μg GAE/g) was 1.45 and 1.49 times higher compared to MQTC and CTC (505.61 and 490.54 μg GAE/g, respectively), which were significantly different.

After the simulated digestion, a decrease in TPC was observed during the oral phase, with reductions of 10%, 12%, and 15% in the MQTC, CTC, and RQTC samples, respectively. During the gastric phase, TPC concentrations increased notably, whereas in the intestinal phase, a decrease was observed. In this final stage, the MQTC sample showed the highest TPC concentration, approximately 15% higher than RQTC and 30% higher than CTC (Figure 1a).

According to these findings, the higher TPC content observed in the tortilla chips made with RQTC may be attributed to less thermal exposure of phenolic compounds, which remain in their free or extractable forms. In its raw state, quinoa retains a significant fraction of phenolic compounds (nondegraded), mainly phenolic acids and various flavonoids, which can be easily solubilized in aqueous

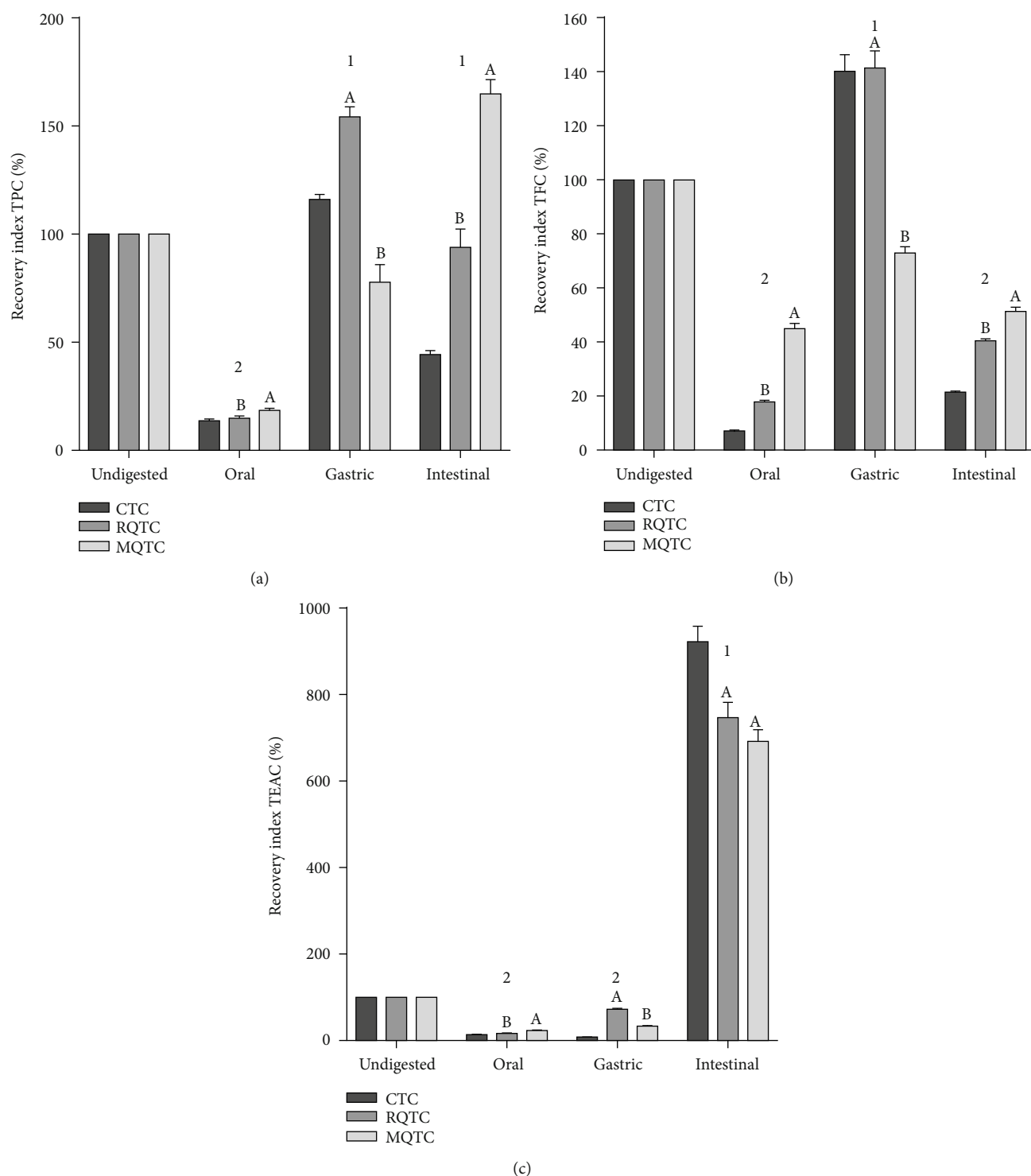


FIGURE 1: (a) Total phenolic compound (TPC), (b) total flavonoid content (TFC), and (c) antioxidant capacity (TEAC) of traditional corn tortilla chips (CTCs), raw quinoa tortilla chips (RQTCs), and microwaved quinoa tortilla chips (MQTCs) (undigested and digested samples). Values are shown as the mean $\pm$ standard error (SE) ($n = 3$). Different uppercase letters indicate a significant difference between samples; different numbers (1 and 2) indicate a significant difference between digestion phases ($p \leq 0.05$), according to an ANOVA and Tukey–Kramer HSD test. The CTC samples were not included in the statistical analysis; they were considered similar to commercial chips and used solely as a reference for comparison with a commercial product.

solutions [59]. In this regard, microwave treatment can induce the restructuring of hydrogen bonds and a reduction in viscosity by promoting the rotation of dipolar molecules

(such as water or -OH groups from phenolic compounds), which may disrupt the hydrogen bond network. This molecular rotation leads to the weakening of hydrogen bonds,

decreasing viscosity, and increasing diffusion. In the context of cooked quinoa, this process may facilitate the loss of phenolic compounds through oxidation or transformation, increasing not only their mobility but also their susceptibility to interactions with other molecules, such as proteins or gelatinized starches [60].

It should also be noticed that double thermal processing (microwave cooking followed by baking) may induce early Maillard reactions, in which phenolic compounds act as nucleophiles in condensation reactions with reducing carbonyl compounds. This not only reduces their quantification by redox-based methods like Folin–Ciocalteu but may also lead to the formation of high-molecular-weight polymeric products that are not extractable [61, 62].

Dynamic changes in TPC concentration were observed throughout the gastrointestinal digestion process, affecting the RI of TPC. When comparing the RI of the gastric phase of the different tortilla chips, RQTC samples showed higher values than MQTC. In contrast, the RI of TPC in MQTC increased significantly, as compared to its RQTC counterpart (Figure 2a).

Changes in TPC concentration during digestion are explained by multiple chemical phenomena that affect the release, stability, and detectability of phenolics. In the initial phases, free phenolics or those weakly bound to the food matrix are released through physical disruption and aqueous solubilization, facilitated by noncovalent interactions such as hydrogen bonds and van der Waals forces [63]. During the simulated gastric phase, a general increase in TPC was observed in all samples, which may be attributed to several chemical and structural mechanisms. The acidic environment, along with the proteolytic action of pepsin, promotes protein denaturation and partial breakdown of the food matrix, enabling the release of phenolic compounds that were previously trapped or weakly bound through hydrogen bonding and hydrophobic interactions [64]. In the intestinal phase, a decrease in TPC was observed, possibly due to interactions with lipids, soluble fibers, or denatured proteins [65, 66]. Moreover, the ionization state of polyphenols, influenced by pH variations, alters their redox status and stability [67].

Regarding TFC (Figure 1b), MQTC and RQTC samples showed a similar flavonoid concentration ($p > 0.05$). During the simulated gastrointestinal digestion, in the gastric phase, the highest flavonoid concentrations were recorded in the order RQTC > CTC > MQTC, with significant differences among RQTC and MQTC samples. In contrast, the MQTC sample showed the higher flavonoid concentration in the intestinal phase, which was approximately 1.2-fold higher than RQTC and twice as high as CTC.

Regarding the gastric RI of TFC, the RQTC sample showed a higher percentage (>100%) than MQTC, while the intestinal RI of all three types of tortilla chips showed a lower percentage (<100%). However, MQTC showed significantly higher RI compared to RQTC and CTC (Figure 2b).

The data suggest that thermal treatments, including microwave irradiation, promote the release of flavonoids from the food matrix. However, the cooking process applied to the tortilla chips may negatively affect the stability and

biological functionality of free or newly released flavonoids in the MQTC sample [68].

During digestion, the different composition of the food matrix may have influenced the concentration of flavonoids. For instance, MQTC may have had a structure more susceptible to enzymatic hydrolysis in the intestine, facilitating greater flavonoid release, while RQTC and CTC may have better retained flavonoids in the gastric phase due to interactions with proteins or fibers; however, this could have limited their subsequent intestinal release, thus affecting their recovery [69]. The chemical form of flavonoids may also play a role; if MQTC contained more aglycones or easily hydrolyzable glycosides, they could be easier to absorb in a biological system, whereas RQTC/CTC might contain more stable conjugates whose potential absorption would differ [70].

Regarding antioxidant activity measured by TEAC (Figure 1c), no significant differences were observed between undigested samples ($p > 0.05$). Significant differences were found between oral and gastric digests of RQTC and MQTC, with the former showing higher values than the latter. An increase in antioxidant activity was noted throughout the digestion process, with the intestinal phase showing the highest levels ($p \leq 0.05$); no significant differences were found between the RQTC and MQTC samples.

When comparing the antioxidant RI% (Figure 2c), very high values were observed in the intestinal phase across all samples, with no significant differences between RQTC and MQTC.

The exponential increase in antioxidant activity observed in the intestinal phase—contrasting with the relatively constant or moderate levels of total phenolics or flavonoids—suggests that compounds with higher radical-scavenging capacity are generated during digestion, even if not in higher concentrations. This may result from the transformation of conjugated phenolic compounds or glycosides into more reactive aglycones, as well as the formation of more potent secondary metabolites such as quinones, simple phenolic acids, or degradation products of polymeric flavonoids [71, 72]. These molecules may exhibit significantly greater efficiency in electron-transfer mechanisms, closely related to the number and position of phenolic hydroxyl group substitutions [73, 74]. Furthermore, the progressive release of these compounds during digestion and the structural modifications induced by enzymatic action and pH conditions may enhance their chemical reactivity, amplifying their antioxidant effect, even if total concentration does not increase proportionally [75].

The reported evidence indicates notable levels of total phenolics and flavonoids [76, 77], supporting quinoa's potential as a functional ingredient, given the biological relevance of these compounds due to their antioxidant, anti-inflammatory, and neuroprotective properties [78]. In agreement with these findings, the results of the present study highlight the functional value of quinoa, both in its application in processed products and after a simulated digestion.

3.2. Phenolic Acids and Flavonoids. In order to evaluate the stability of individual phenolic compounds during the *in vitro* gastrointestinal digestion, the phenolic profile was

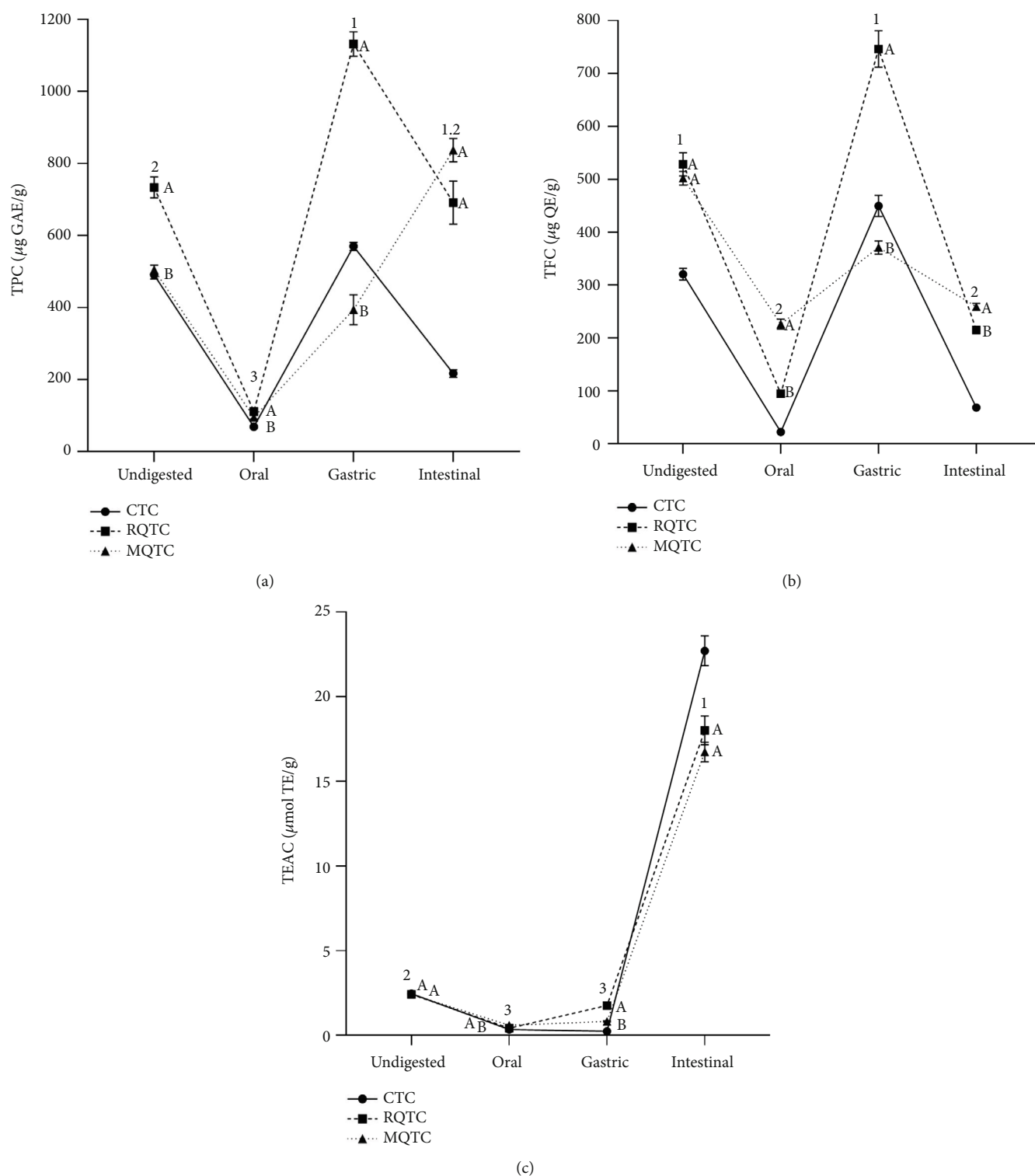


FIGURE 2: Recovery index (RI%) of (a) total phenolic compound (TPC), (b) total flavonoid content (TFC), and (c) antioxidant capacity (TEAC) of traditional corn tortilla chips (CTCs), raw quinoa tortilla chips (RQTCs), and microwaved quinoa tortilla chips (MQTCs). Values are shown as the mean ± standard error (SE) ($n = 3$). Different uppercase letters indicate a significant difference between samples; different numbers (1, 2, and 3) indicate a significant difference between digestion phases ($p \leq 0.05$), according to an ANOVA and Tukey–Kramer HSD test. The CTC samples were not included in the statistical analysis; they were considered similar to commercial chips and used solely as a reference for comparison with a commercial product.

evaluated by UHPLC-DAD; results are shown in Table 1. It is apparent that the profile is comprised of seven compounds, three phenolic acids (gallic, *p*-coumaric, and ferulic acids), and four flavonols (rutin, myricetin, quercetin, and kaempferol). These compounds were identified and quantified in the samples before and after in vitro digestion, as well as their RI.

The results show marked variability in the presence and transformation of individual phenolic compounds before and after in vitro digestion. Before digestion, the RQTC sample exhibited the highest concentration of gallic acid ($152.61 \pm 1.38 \mu\text{g/g}$). In contrast, rutin was most abundant in MQTC ($10.85 \pm 1.02 \mu\text{g/g}$), and quercetin was primarily detected in CTC.

After digestion, a differential release of phenolic compounds was observed at each stage. In the oral phase, a relative increase in certain compounds was recorded, such as gallic acid in MQTC ($82.92 \mu\text{g/g}$, equivalent to 324% of the original value) and quercetin in CTC (163%), suggesting a rapid release of soluble compounds at the beginning of the digestive process.

The greatest relative increases were observed during the gastric phase. In MQTC, quercetin reached $157.86 \mu\text{g/g}$ (3195%), while RQTC showed significantly elevated concentrations of rutin ($16.47 \mu\text{g/g}$), myricetin ($2.77 \mu\text{g/g}$), and kaempferol ($67.29 \mu\text{g/g}$), indicating that this stage favors the release of matrix-bound phenolic compounds or those transformed from precursors.

In the intestinal phase, the release pattern changed drastically. MQTC maintained a high concentration of *p*-coumaric acid ($52.19 \mu\text{g/g}$) and RI of 4538%, while other compounds like rutin and quercetin significantly decreased or were not detected. This could be attributed to degradation processes or structural transformations under simulated intestinal conditions (higher pH and enzymatic activity).

Taken together, these data suggest that the different thermal treatments applied to the tortilla chips influence both the initial phenolic profile and its release and transformation during digestion. In particular, the MQTC treatment showed greater efficiency in the release of total and specific phenolic compounds, especially in the gastric phase, which may be related to a food matrix more susceptible to enzymatic or thermal breakdown [60].

The results show high variability in the concentration and transformation of individual phenolic compounds throughout in vitro digestion, influenced by the chemical nature of each compound and the type of thermal treatment applied to the quinoa chips [61, 62]. Before digestion, the RQTC sample exhibited a markedly higher concentration of gallic acid, a free phenolic acid that may be associated with the soluble fractions of quinoa or physically retained within the matrix [79]. Its abundance suggests greater preservation due to a less aggressive thermal treatment or lower susceptibility to prior oxidative reactions [80]. In contrast, MQTC showed a high concentration of rutin, a flavonoid relatively stable to heat, suggesting that the microwave treatment favored its release by breaking cellular structures and noncovalent bonds without inducing degradation [81].

During the oral phase, a rapid release of soluble compounds such as gallic acid and quercetin was observed, likely due to matrix hydration and the mechanical and enzymatic action of saliva, which facilitates the dissociation of weak interactions with macromolecular components [82]. In the gastric phase, characterized by an acidic pH and the presence of pepsin, an intensified release of flavonoids was noted, particularly in MQTC, where quercetin reached an increase of 3195%. This increase suggests the acid hydrolysis of glycosylated compounds like rutin, releasing the aglycone quercetin [83]. Similarly, RQTC exhibited elevated levels of rutin, myricetin, and kaempferol, indicating that protein and polysaccharide denaturation under acidic conditions may have facilitated the breakdown of physical complexes or the release from partially intact cellular structures [81].

In the intestinal phase, characterized by an alkaline pH and the action of pancreatic enzymes, flavonoids such as quercetin and rutin decreased significantly or were not detected. This may be explained by their structural instability under basic pH conditions, where they can undergo oxidation, C-ring opening, and degradation into nonquantifiable compounds [84, 85]. Additionally, the formation of complexes with metal ions, bile salts, or digestive proteins may reduce their solubility or interfere with chromatographic detection [86, 87]. In contrast, *p*-coumaric acid, a relatively more stable hydroxycinnamic acid, exhibited significant release at this stage (up to 4538% in MQTC), which could be related to alkaline hydrolysis of phenolic esters bound to cell wall components such as arabinoxylans or proteins [75].

Altogether, these results suggest that the release and transformation of quinoa phenolic compounds are strongly influenced by their chemical structure (e.g., glycosylation, pH stability, and type of matrix binding) and by structural modifications of the food matrix induced by thermal treatment. In particular, microwave treatment (MQTC) appears to promote both early release and gastric transformation of phenolic compounds, positioning it as a favorable technological strategy to enhance the recovery of these bioactive molecules.

In this context, the detection of flavonoids such as quercetin and kaempferol in the gastric digests of both RQTC and MQTC represents a functionally relevant finding. Quercetin, for instance, has demonstrated gastroprotective effects by reducing inflammation and oxidative stress, as well as by modulating apoptosis and acid secretion in biological models [88]. Kaempferol has been described as a regulator of gastric barrier integrity and the TRPV1 pathway, in addition to its ability to inhibit gastric acid secretion [89]. Although the stability of these compounds may be compromised under intestinal conditions, their release in the gastric phase suggests a potential immediate local effect. Moreover, the glycosylation of some flavonoids, such as rutin, may confer a degree of protection against intestinal degradation, allowing them to reach the colon for further biotransformation by the microbiota [90]. Therefore, targeted analysis of these compounds in specific digestive phases helps not only to characterize their potential bioaccessibility but also to

TABLE 1: Phenolic acids and flavonoids (micrograms per gram), recovery index (%) of traditional corn tortilla chips (CTCs), raw quinoa tortilla chips (RQTCs), and microwaved quinoa tortilla chips (MQTCs) before and after the different phases of an in vitro gastrointestinal digestion.

Sample	Gallic acid	<i>p</i> -Coumaric acid	Ferulic acid	Rutin	Myricetin	Quercetin	Kaempferol
Before digestion							
CTC	25.07 ± 0.64	2.93 ± 0.15	-	1.70 ± 0.08	-	8.21 ± 0.88	3.03 ± 0.05
RQTC	152.61 ± 1.38 ^a	1.30 ± 0.02 ^a	-	-	4.28 ± 0.03	-	-
MQTC	25.52 ± 0.53 ^b	1.15 ± 0.00 ^a	1.06 ± 0.01	10.85 ± 1.02	-	4.94 ± 0.12	-
After digestion							
CTC (oral)	-	3.18 ± 1.16 (108%)	20.73 ± 1.47	-	-	13.46 ± 0.42 (163%)	-
CTC (gastric)	-	1.08 ± 0.08 (36%)	-	-	-	33.13 ± 0.00 (403%)	4.31 ± 0.01 (142%)
CTC (intestinal)	-	-	10.42 ± 0.82	-	-	-	-
RQTC (oral)	99.21 ± 5.34 ^{aA} (65%)	1.94 ± 0.10 ^{aB} (149%)	2.02 ± 0.11 ^{aC}	24.00 ± 0.01 ^A	1.68 ± 0.01 ^B (39%)	5.60 ± 0.01 ^B	2.11 ± 0.00 ^B
RQTC (gastric)	-	8.38 ± 0.06 ^{aA} (644%)	10.76 ± 0.79 ^{aA}	16.47 ± 0.46 ^{aB}	2.77 ± 0.02 ^{bA} (64%)	209.66 ± 12.46 ^{aA}	67.29 ± 2.55 ^{aA}
RQTC (intestinal)	4.75 ± 0.19 ^B (3%)	-	5.52 ± 0.02 ^{aB}	-	-	-	-
MQTC (oral)	82.92 ± 5.45 ^a (324%)	2.08 ± 0.16 ^{aB} (180%)	1.85 ± 0.14 ^{aB} (174%)	-	-	-	-
MQTC (gastric)	-	2.75 ± 0.14 ^{bB} (239%)	6.02 ± 0.17 ^{bA} (567%)	18.23 ± 0.35 ^{aA} (168%)	3.44 ± 0.19 ^a	157.86 ± 3.80 ^b (3195%)	68.71 ± 1.89 ^a
MQTC (intestinal)	-	52.19 ± 7.81 ^A (4538%)	2.22 ± 0.05 ^{bB} (209%)	5.63 ± 0.24 ^B (51%)	-	-	-

Note: Values are shown as micrograms per gram and expressed as the mean ± standard error (SE) (*n* = 3); recovery index is expressed as percentage in parentheses, where possible to calculate. Different lowercase letters indicate a significant difference between samples; different uppercase letters indicate a significant difference between digestion phases (*p* ≤ 0.05), according to an ANOVA and Tukey–Kramer HSD test. A dash (-) indicates compounds that were not detected. The CTC samples were not included in the statistical analysis; they were considered similar to commercial chips and used solely as a reference for comparison with a commercial product.

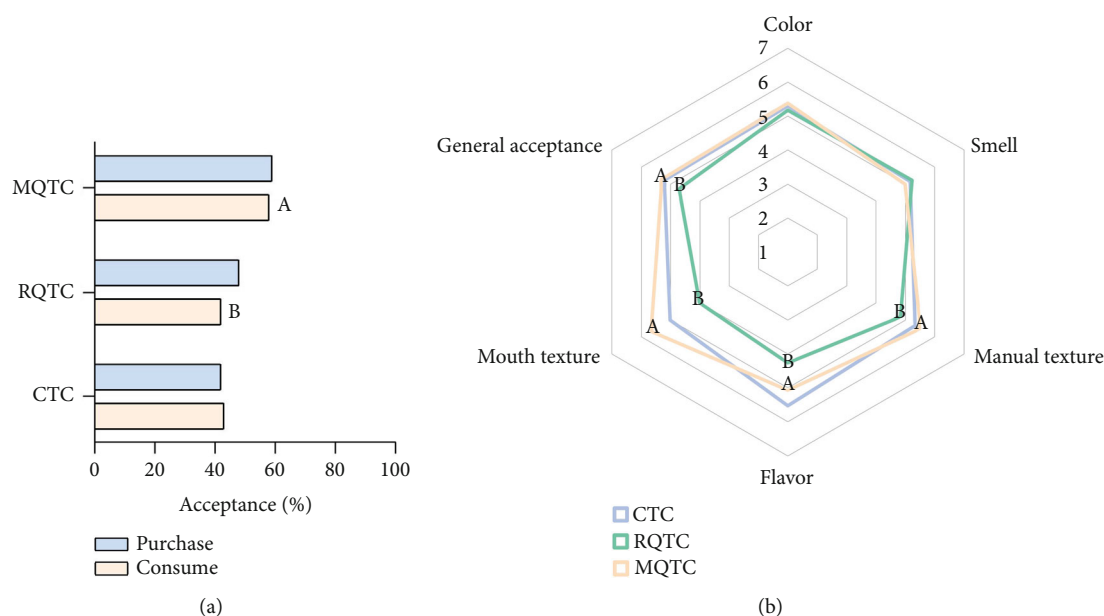


FIGURE 3: (a) Sensory analysis and (b) consumption and purchase test of traditional corn tortilla chips (CTCs), raw quinoa tortilla chips (RQTCs), and microwaved quinoa tortilla chips (MQTCs). Different uppercase letters indicate a significant difference between samples ($p \leq 0.05$). The Student t -test was used to calculate the mean in the sensory analysis, and the Wilcoxon test was used to analyze consumption and purchase. The CTC samples were not included in the statistical analysis; they were considered similar to commercial chips and used solely as a reference for comparison with a commercial product.

establish their localized bioactive potential, with implications for the design of functional foods aimed at gastrointestinal health.

3.3. Sensory Evaluation. In the current landscape of healthy eating, consumers demand products that not only fulfill basic nutritional functions but also provide additional health benefits. This trend has driven the development of functional foods, defined as those that, beyond their nutritional value, exert a positive effect on specific physiological functions, contributing to overall well-being and reducing the risk of disease [91, 92]. In this context, quinoa-based tortilla chips represent a promising alternative, as they incorporate ingredients naturally rich in bioactive compounds. However, the market acceptance of a functional food depends not only on its nutritional or physiological value but also on its sensory attributes, such as flavor, texture, color, and aroma, which directly influence consumer-purchasing decisions [93]. Particular characteristics like crispness and golden color in baked or fried products are highly valued by young, health-conscious consumers who prioritize foods with a “naturally functional” profile [94, 95]. Therefore, evaluating the sensory performance of thermally processed tortilla chips not only assesses their consumer acceptability but also helps determine their viability as a delivery vehicle for bioactive compounds in real-world consumption scenarios.

Figure 3 shows the results of the sensory evaluation, as well as the consumers' consumption and purchase intention. Most values ranged between 4 and 5 on the hedonic scale, with none of the evaluated attributes reaching the highest score of 7. The CTC and MQTC samples received similar scores for flavor, hand texture, and overall acceptability, with

the mouthfeel of the MQTC sample being significantly higher compared to the others. Regarding RQTC, its manual texture, flavor, mouth texture, and general acceptance were close to 4 and significantly lower than the other two samples. No differences were apparent for the color and smell of any sample. Consumer acceptance was higher in MQTC, followed by RQTC and CTC.

The color of the tortilla chips was accepted with a value of 6 points on the hedonic scale, indicating that this parameter was pleasing to the consumers. There is current interest in consuming products with beneficial effects on health, but without sacrificing the organoleptic properties of the products. Therefore, a sensory evaluation enriches the analysis of a product to know its consumption and acceptability [41]. In products made from 100% quinoa, good acceptability has been seen both in organoleptic properties and in their potential acceptance and consumption [28], as well as in snack products to which different percentages are added [96, 97].

3.4. Fracturability and Instrumental Color. The high acceptance of color in the tortilla chips, as reflected on the hedonic scale, highlights the importance of sensory evaluation in validating key attributes of food products. However, to complement these findings and ensure consistent quality, instrumental analysis using tools like colorimeters provides objective measurements of properties like color, minimizing subjective bias [98]. In this context, the instrumental assessment of fracturability and color parameters revealed significant differences among treatments. Raw quinoa samples (RQTC) exhibited the highest mechanical resistance (10.72 N), indicative of a more rigid and crunchy texture,

TABLE 2: Fracturability and instrumental color of traditional corn tortilla chips (CTCs), raw quinoa tortilla chips (RQTCs), and microwaved quinoa tortilla chips (MQTCs).

Sample	Fracturability (N)	<i>L</i> *	<i>a</i> *	<i>b</i> *	BI
CTC 	7.75 ± 0.23	62.73 ± 0.53	2.66 ± 0.23	21.53 ± 0.20	44.25 ± 1.16
RQTC 	10.72 ± 0.49 ^a	58.60 ± 1.19 ^a	6.30 ± 2.22 ^a	26.73 ± 0.83 ^b	67.28 ± 5.33 ^a
MQTC 	5.41 ± 0.29 ^b	61.30 ± 1.96 ^a	8.00 ± 1.15 ^a	29.90 ± 0.25 ^a	74.81 ± 4.11 ^a

Note: Values are shown as the mean ± standard error ($n = 3$). Values with different letters between treatments are significantly different ($p \leq 0.05$), according to an ANOVA and Tukey–Kramer HSD test. *L* *: lightness; *a* *: redness; *c* *: yellowness. The CTC samples were not included in the statistical analysis; they were considered similar to commercial chips and used solely as a reference for comparison with a commercial product. Abbreviation: BI, browning index.

although with the potential drawback of being perceived as excessively hard. Conversely, cooked quinoa samples subjected to microwave processing (MQTC) showed the lowest fracturability (5.41 N), resulting in more fragile chips with reduced perceived crunchiness. Corn samples (CTC), with an intermediate value (7.75 N), displayed a balance between firmness and ease of mastication, suggesting a texture that is structurally stable, yet sensorially acceptable (Table 2).

In terms of color, although no significant differences were detected in brightness (*L* *), both MQTC and RQTC exhibited significantly higher *a* * and *b* * values, reflecting more intense reddish and yellowish tones that are commonly associated with Maillard reactions and caramelization. These variations were further corroborated by the BI, in which both quinoa-based chips had higher values than CTC, with the most pronounced effect observed in MQTC (74.81). Taken together, the integration of sensory and instrumental data indicates that the incorporation of quinoa, particularly when subjected to thermal pretreatment, enhances browning and alters texture, resulting in more visually appealing products, albeit with contrasting effects on crispness.

The fracturability of the evaluated chips ranged from 5.41 to 10.72 N, evidencing significant variations in their mechanical strength, which can be explained by fracture mechanisms associated with changes to the starch–protein matrix and its transformation during processing. High fracture values, such as those recorded in RQTC (10.72 N), reflect a more rigid and cohesive microstructure capable of withstanding greater loads before crack initiation. This behavior is linked to starch gelatinization and protein denaturation, which promote cross-link formation and more efficient stress transfer, thereby delaying crack propagation and increasing the energy required for fracture [99]. In contrast, the lowest value (5.41 N) was observed in MQTC, which

suggests a more fragile matrix resulting from thermal treatment and/or expansion that produces large pores and thin cell walls. These structural defects act as stress concentrators that reduce resilience [100, 101]. The intermediate value of CTC (7.75 N) reflects a balance between stiffness and fragility, where moderate structural density enables more controlled crack propagation [102].

These results confirm that fracturability is strongly associated with microstructural changes induced by processing. A rigid and cohesive texture, as observed in RQTC, is linked to more compact and homogeneous cell walls that reinforce macromolecular interactions [103–105]. Conversely, the brittleness of microwaved chips can be attributed to rapid water loss and expansion, which produce high porosity and structural defects that diminish the material's capacity to absorb energy [104, 105]. This behavior has been related to the specific effects of microwave processing on grain morphology and the destruction of the cryptomeric structure, processes that alter internal cohesion and regulate pore formation [106–108]. Fracturability is determined overall by the interplay between water loss, starch gelatinization, retrogradation, and porosity, confirming that microstructure is a critical factor governing the final texture [103, 105, 106, 109].

From a mechanical perspective, instrumental values can be associated with fundamental properties like Young's modulus, fracture toughness, and the elastic limit. High fracturability values are indicative of a greater elastic modulus and a stronger internal network, capable of absorbing and redistributing stresses before rupture [110, 111]. Sensory perception of this condition corresponds to a firm and crunchy texture with high resistance to the first bite [112]. At the opposite extreme, low fracturability values reflect structures with low elastic limits, thin cell walls, and high porosity, which facilitate crack propagation under relatively small

loads and may be perceived as soft or stale textures [112, 113]. The intermediate value observed in CTC represents balanced mechanical behavior, with a moderate elastic modulus that preserves the characteristic crunchiness of snacks [111, 114].

In addition to physical phenomena, the phenolic compounds present in quinoa also influence mechanical strength. These metabolites contain hydroxyl groups capable of forming hydrogen bonds and other noncovalent interactions with starch and protein molecules, thereby reinforcing matrix cohesion and enhancing fracture resistance [115, 116]. However, when present at high concentrations or distributed heterogeneously, phenolics may interfere with starch gelatinization or form complexes with proteins, leading to structurally weak regions that compromise the plasticity of the network [117]. Maintaining an appropriate balance in both the amount and distribution of phenolic compounds during processing is therefore critical to obtaining a crispy yet not excessively rigid texture, in agreement with observations reported in other products such as potato chips [118].

Processing conditions also exerted a marked influence on the results; for example, RQTC, with its higher mechanical resistance, showed a process of progressive starch gelatinization and structural reinforcement mediated by protein-phenolic interactions [119]. In contrast, MQTC exhibited fragility attributable to the intense and rapid heat transfer that promoted dehydration and the formation of large pores, conditions that compromise matrix integrity [106, 120]. The CTC samples displayed intermediate behavior, suggesting more stable viscoelastic properties. Initial hydration was also critical; moderate water levels promoted cohesion, whereas accelerated water loss during microwaving favored structural defects and more intense browning, as evidenced by the higher a^* , b^* , and BI values in MQTC [119, 121, 122].

Finally, integrating consumer perception provides a mechanistic understanding of how processing and formulation modulate product acceptability. Fracturability was confirmed as a reliable predictor of crunchiness; high values like those in RQTC were associated with an intense crunchy experience, whereas very low values like those of MQTC resulted in a soft and less appealing texture [111, 113, 123]. The BI further reinforced this relationship; moderate browning of RQTC (BI = 67.28) enhanced visual appeal and was linked to pleasant toasted notes, while higher browning of MQTC (BI = 74.81) may contribute to sensory defects like bitterness and higher brittleness [106, 122, 124, 125]. The CTC samples, with intermediate values for both fracturability and color, provided a balanced combination of acceptable texture and mechanical stability. Overall, these findings confirm that sensory quality does not rely on a single attribute but rather emerges from the convergence of mechanical resistance and surface browning, whose balance ultimately defines consumer preference.

4. Conclusion

The present study reports the use of quinoa, both raw (RQTC) and microwaved (MQTC), to prepare tortilla chips; their bioactive content (phenolics and flavonoids) and anti-

oxidant activity were compared before and after the different phases of an in vitro gastrointestinal digestion, along with consumer acceptability and instrumental parameters. Before gastrointestinal digestion, RQTC samples had higher concentrations of phenolics and flavonoids (the latter was similar to MQTC), although no differences in antioxidant capacity were found between samples. The RI% of TPC and TFC in the gastric digestion phase was higher in RQTC than in MQTC. In contrast, MQTC had higher values after the intestinal digestion phase. Overall, flavonoids showed greater recovery percentages during the gastric phase, whereas antioxidant activity was highest following the intestinal phase. Notably, *p*-coumaric acid and quercetin demonstrated the highest recovery (4538% and 3195%, respectively), both in MQTC samples. Instrumental and sensory evaluations confirmed that both quinoa-based samples possessed favorable sensory attributes and consumer acceptability. These findings support the feasibility of using quinoa to develop healthy tortilla chip snacks without compromising organoleptic quality.

Importantly, the promising bioactive potential and consumer acceptance observed for MQTC suggest a strong commercial applicability in the development of functional snack products. This approach may contribute to the formulation of nutritionally enhanced foods targeting health-conscious consumers and could support public health strategies aimed at promoting antioxidant-rich diets. Further in vivo studies are warranted to explore the physiological effects and long-term benefits of these products.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

No funding was received for this manuscript.

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