



Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Integrated strategies for reducing acrylamide, 5-HMF, and furan in colored native and commercial potato chips: Synergistic effects of nutrient solution conductivity and pre-frying treatments

Diego García-Ríos^a, Franco Pedreschi^b, María Salomé Mariotti-Celis^c, Carolina Contreras^d, David Campos^e, Juan E. Alvaro^{a,*}, Romina Pedreschi^{a,f,**} 

^a Escuela de Agronomía, Facultad de Ciencias Agronómicas y de los Alimentos, Pontificia Universidad Católica de Valparaíso, Calle San Francisco s/n, La Palma, Quillota, Chile

^b Departamento de Ingeniería Química y Bioprocesos, Pontificia Universidad Católica de Chile, Santiago, Chile

^c Escuela de Nutrición y Dietética, Facultad de Medicina, Universidad Finis Terrae, Pedro de Valdivia 1509, Santiago, Chile

^d Instituto de Producción y Sanidad Vegetal, Facultad de Ciencias Agrarias y Alimentarias, Universidad Austral de Chile, Valdivia, 5090000, Chile

^e Instituto de Biotecnología, Universidad Nacional Agraria La Molina, Av. La Molina, La Molina, 12056, Lima, Peru

^f Millennium Institute Center for Genome Regulation (CRG), Santiago, Chile

ARTICLE INFO

Keywords:

Acrylamide
Furan
5-Hydroxymethylfurfural
Abiotic stress response
Neo-formed contaminant mitigation

ABSTRACT

Potato chips are a dietary source of potentially carcinogenic neo-formed contaminants, including acrylamide, 5-HMF, and furan. To mitigate these compounds, an agronomic strategy was implemented by increasing the electrical conductivity (EC) of the fertigation solution (1.7 and 4.0 dS m⁻¹), considering two potato cultivars (Desiree and Michuñe negra) grown under controlled conditions across two seasons. Pre-frying treatments namely ultrasound (US) leaching and asparaginase (AW) application were applied before and after cold storage (5 °C for 90 days). Seasonality and storage significantly influenced contaminant levels. Increased EC reduced cold sweetening in Desiree but had limited effect on Michuñe negra. Combined with US, acrylamide levels decreased to below 750 µg kg⁻¹ in Desiree and 1000 µg kg⁻¹ in Michuñe negra. In addition, 5-HMF was reduced by 60 % in Desiree and to undetectable levels in Michuñe negra, suggesting a synergistic effect of EC and US treatments. However, furan levels were not consistently reduced, likely due to distinct formation pathways.

1. Introduction

Potato constitutes one of the main staple food crops worldwide and it is the fourth most produced after maize, rice, and wheat (Food and Agriculture Organization of the United Nations, 2024). Our current climate change scenario is expected to increase the intensity of stressors from abiotic nature including high temperature, drought, and salinity, which are likely to occur concomitantly and threat potato productivity and availability (Dahal et al., 2019). Besides its paramount importance for food security, potato is a key raw material for the food industry since it is a source of both additives such as starch and its derivatives, and a wide variety of finished products like salty snacks.

Salinity from soil and water is a significant abiotic stressor for plants. Nevertheless, at moderate doses, it could be used as an elicitor to modify

physical properties, improve flavor and bioactive compounds, and mitigate anti-nutrients or toxic compounds (Rouphael et al., 2018). Soilless cultivation under a fertigation regime is an interesting alternative not only to produce staple foods, but also to evaluate new nutrient solutions and elicit moderate saline stress on crops (Zörb et al., 2019; Samec et al., 2021).

Crop response to moderate salinity varies by species and cultivation system. For instance, in tomatoes cultivated in a soilless system, the increase of the electrical conductivity (EC) of the nutrient solution from 2.2 dS m⁻¹ to 4.5 dS m⁻¹ favored the accumulation of L-serine, L-threonine, and L-glutamic acid, however, sugar concentrations were not altered (Rodríguez et al., 2019). Similarly, saline irrigation (up to 6.0 dS m⁻¹) had no significant effect on sweet potato sugar levels (Doganay et al., 2023). The effect of salinity on morphological, physiological and

* Corresponding author. Pontificia Universidad Católica de Valparaíso, Chile.

** Corresponding author. Escuela de Agronomía, Facultad de Ciencias Agronómicas y de los Alimentos, Pontificia Universidad Católica de Valparaíso, Calle San Francisco s/n, La Palma, Quillota, Chile.

E-mail addresses: mmariotti@uft.cl (M.S. Mariotti-Celis), juan-eugenio.alvaro@pucv.cl (J.E. Alvaro), romina.pedreschi@pucv.cl (R. Pedreschi).

<https://doi.org/10.1016/j.lwt.2025.118398>

Received 14 June 2025; Received in revised form 24 August 2025; Accepted 25 August 2025

Available online 26 August 2025

0023-6438/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

agronomical traits of potato has been extensively reported. Salinity stress via addition of NaCl had a detrimental effect on plant emergence and a significant reduction of the tuber dry matter was observed, which was related to lower starch levels and higher water-soluble carbohydrates (Ghosh et al., 2001); however, no direct measurements of starch and free sugars on tubers were reported. In general, saline water irrigation (water EC in the range of 3.4–5.9 dS m⁻¹) has shown detrimental effects on the number of tubers, yield, and individual tuber weight (Faried et al., 2022; Garg et al., 2022; van Hoorn et al., 1993). Tuber growth rate (g d⁻¹) was also severely reduced (up to 50 %) when irrigated with saline water (8.5 dS m⁻¹) compared with the control (2.26 dS m⁻¹) (Akrimi et al., 2021). In contrast, some cultivars have been reported to give better yields at higher EC (~+20 % tuber yield at 4.0 dS m⁻¹) and thus, the effect of the EC is cultivar dependent (Im et al., 2016). However, literature on salinity effects on potato tuber composition and processing quality remains limited.

Vegetable chips obtained by deep fat frying are popular snacks which have raised health concerns due to their potentially higher levels of neo-formed contaminants (NFCs): acrylamide (AA, the most studied and mainly derived from the Maillard reaction - MR), 5-hydroxymethyl furfural (5-HMF), and furan. They all have been related to the development of degenerative diseases and are considered potentially carcinogenic compounds (Barrios-Rodríguez et al., 2021; Elmore et al., 2019; Mariotti et al., 2015; Wei et al., 2018). The final concentration of those neo-formed contaminants depends on the raw material composition (sugars and free amino acids, the main substrates of the MR) and the processing conditions (temperature and time of the thermal treatment) (Elmore et al., 2015; Liyanage et al., 2021; Pedreschi et al., 2021; Raffan & Halford, 2019). Although AA has been thoroughly investigated and mitigated in commercial potato cultivars (Halford et al., 2007, 2012; Pedreschi et al., 2021; Powers et al., 2021), its presence in novel products made from native, colored potato cultivars and other vegetables is currently being examined. Recently, a study on chips made from Chilean potato native accessions shown a wide concentration range of neo-formed contaminants pointing out that new mitigation strategies should be considered on those cases (García-Ríos et al., 2024). Moreover, a native, purple-colored potato cultivar from southern Chile was cultivated under soilless, protected conditions and the chips presented a high AA content, similar to the level observed on colored potato chips commercially available in the Chilean market (García-Ríos et al., 2023).

To our knowledge, the effect of the EC of the nutrient solution as a modulator of sugar and amino acid metabolism in potato tubers and as a potential mitigator of neo-formed contaminants in potato snacks has not been previously reported. We hypothesize that modifying the EC of the nutrient solution in soilless grown potatoes modulates the accumulation of key metabolites related to the MR (simple sugars and free amino acids) in the tubers and thus could serve as a potential strategy for mitigating neo-formed contaminants. This approach during the cultivation stage could also complement the pre-frying treatments, exerting a synergistic effect. Thus, this study aims to: (i) analyze the metabolic profile of two potato genotypes (one commercial and one native colored potato) cultivated on a soilless system under two ECs of the nutrient solution with particular emphasis on the levels of MR substrates and antioxidants and (ii) determine the effect of the two EC levels combined with pre-frying treatments (ultrasound leaching of MR precursors and immersion in an asparaginases solution) on the final concentration of neo-formed contaminants (AA, 5-HMF, and furan) on potato chips obtained by deep fat frying.

2. Materials and methods

2.1. Potato material and cultivation conditions

Two potato cultivars were assessed in this study: “Desiree” (red skin/ yellow pulp) and “Michuñe negra” (purple skin/white and purple pulp) which were cultivated during two seasons (S1: winter-spring 2023 and

S2: autumn-winter 2024) in a multi-tunnel greenhouse (polyethylene cover thickness: 200 µm) equipped with a fertigation system and natural ventilation located at the Faculty of Agronomical and Food Sciences of the Pontificia Universidad Católica de Valparaíso (PUCV) (32° 53' 44.04" S and 71° 12' 25.34" O). A 55 L Projar Golden Grow Blend Medium Washed (Valencia, Spain) coir growth pot (500 × 480 mm, H × W) was employed as the unit crop in the soilless growing system. The distance between unit crops corresponded to 1.1 m and between rows to 1.8 m. The nutrient solution pH was maintained at 5.8 ± 0.1 and two electrical conductivities were assayed: 1.7 ± 0.1 dS m⁻¹ (T1) and 4.5 ± 0.1 dS m⁻¹ (T2). Plants of both cultivars were randomly distributed in the greenhouse area. A total of 50 plants were cultivated (25 per cultivar); 12 of each cultivar were submitted to T1 and the remaining 13 of each cultivar were submitted to T2. Fertigation frequency and cultural practices were carried out according to García-Ríos et al. (2023). Tubers were harvested at the decay of the vegetative part of the plants.

2.2. Postharvest storage

Harvested potatoes were stored at 12 °C for 8 days and 95 % relative humidity (RH) to cure wounds and allow cuticle formation. Then, they were stored at 5 ± 1 °C and 95–98 % RH for 3 months (90 days). Fresh potato samples (*n* = 3) each consisting of four pooled tubers were taken after curing and after the cold storage period (referred as “at harvest” (H) and “cold storage” (C) treatments, respectively). Tubers were chopped, flash frozen by immersion in liquid nitrogen, ground, freeze-dried, packed under vacuum, and stored until analysis corresponding to sections 2.4.1 to 2.4.3.

2.3. Potato chip processing and pre-frying treatments

Frying experiments were conducted according to the procedure previously reported by Pedreschi and Moyano (2006) and Pedreschi et al. (2021) with slight modifications. The potato tubers were washed with tap water, cut without peeling into slices of approximately 1.5 mm thick and rinsed in distilled water to remove superficial starch. Then, two pre-frying treatments aiming to reduce the amount of MR precursors were assessed: (i) ultrasound leaching of MR precursors (Elma Schmidbauer GmbH, S10H Ultrasonic bath, Germany) with distilled water at 70 °C for 15 min at 90 W potency and 37 kHz frequency (US) as suggested by Pedreschi et al. (2021), (ii) elimination of asparagine through its conversion to aspartic acid by immersion in a commercial asparaginases solution in distilled water at 10,000 ASNU/L (Acryl-away® L, Novonesis, Denmark), 50 °C for 20 min. A control treatment by immersion of raw potato slices in distilled water at room temperature for 1 min which was performed for comparison with the US and AW treatments. The mass ratio of both distilled water in the US treatment and asparaginases solution to potato slices was 2:1. After both treatments, the slices were dried with absorbent paper and then deep-fried on 6 L of sunflower oil (Cold pressed, Natura 100 % sunflower, Argentina) in an electrical fryer (Anhui Hualing Kitchen Equipment, HDF8+8, Maanshan, China) at 180 °C ± 5 °C until a final moisture of ~1.8 %. Oil temperature was kept constant by using a potato-to-oil mass ratio of ~0.0035. Excess oil was drained, and the chips were cooled down to room temperature and stored in airtight bags at -40 °C until neo-formed contaminant determinations (AA, 5-HMF and furan).

2.4. Analytical determinations

2.4.1. Polar metabolite content and profile

Polar metabolites (amino acids, sugars, and organic acids) were extracted and derivatized with N, O-bis(trimethylsilyl)trifluoroacetamide (BSTFA) according to Fuentealba et al. (2017) using 20 mg of lyophilized sample. The derivatized extracts were stored at -20 °C until GC-MS analysis.

Samples were injected into an Agilent 7890B gas chromatographer

equipped with a PAL3 autosampler and coupled to an Agilent 5977A single quadrupole mass spectrometer (Agilent Technologies, Santa Clara, CA, USA). Separation was performed on a HP-5-MS Ultra Inert column (0.25 μm , 30 m \times 0.25 mm). Chromatographic conditions were performed as previously reported (Fuentealba et al., 2017). The chromatographic peaks were identified by comparing retention times and mass spectra with previously injected analytical standards (asparagine, fructose, glucose, and sucrose from Sigma-Aldrich, USA). Quantification of asparagine (m/z 231, 116), fructose (m/z 307, 147), glucose (m/z 319, 205), and sucrose (m/z 361, 217) were performed constructing external calibration curves with authentic standards and processed using the Mass Hunter Quantitative software (Agilent Technologies). Results were expressed as mg g^{-1} dry weight (DW). Other polar metabolites such as free amino acids other than asparagine, organic acids and sugar alcohols were also identified by comparison with previously injected standards (when available) and the NIST 14 mass spectral library. These compounds were integrated, and their relative concentrations were used for the metabolomic multivariate analysis.

2.4.2. Content of total phenolics and anthocyanins

Extraction of phenolic compounds was conducted following the method reported by Oertel et al. (2017). Total phenolics (mg gallic acid equivalents (GAE) g^{-1} DW) were determined using the Folin-Ciocalteu reagent method (Singleton & Rossi, 1965) modified for 96-well microplate reading by absorbance measure at 765 nm, while total anthocyanins were determined using the pH differential method (Giusti and Wrolstad, 2001) which was also modified for 96-well microplate measurement. The absorbance of the extract was measured at pH 1.0 and 4.5 at 520 nm and 700 nm and expressed as mg cyanidin-3-glucoside equivalents (Cy-3-GE) g^{-1} DW.

2.4.3. Starch determination

Starch was determined enzymatically according to Rodriguez et al. (2019) with some modifications. Lyophilized samples (30 mg) were washed three times with 1.8 mL of ultrapure water to remove soluble sugars. The remaining pellet was incubated at 100 $^{\circ}\text{C}$ for 10 min and cooled down to room temperature. Next, 600 μL of 0.2 mol L^{-1} sodium acetate (pH 5.5), 120 μL (70 units mL^{-1}) of amyloglucosidase from *Aspergillus niger* (Sigma-Aldrich, St. Louis, USA) and 120 μL (7 units mL^{-1}) of α -amylase from *Aspergillus oryzae* (Sigma-Aldrich, St. Louis, USA) were added to the samples and incubated at 37 $^{\circ}\text{C}$ for 16 h. Samples were centrifuged at 15,000 g for 5 min and reducing sugars were quantified on the supernatant by the method of Miller (1959) with 3,5-dinitrosalicylic acid (DNS). Absorbance was measured at 540 nm (Multiskan™ SkyHigh, Thermo Scientific, USA) in samples, blank solution, and a positive control (starch 0.01 g mL^{-1}). A standard curve of glucose was built to determine the amount of reducing sugars after the enzymatic hydrolysis. Starch content was determined by multiplying the glucose concentration by 0.9 (factor to convert glucose to anhydrous glucose) and expressed as mg starch g^{-1} DW.

2.4.4. Acrylamide determination

Acrylamide content of potato chips was quantified by GC-MS according to the method reported by Pedreschi et al. (2021). Two grams of homogenized sample with 40 μL isotope labelled AA (AA-d3, 20 mg L^{-1}) and 10 mL of methanol were added in a centrifuge tube and mixed by homogenization in a vortex for 30 s. Extraction was performed on an ultrasound bath at 60 $^{\circ}\text{C}$ for 20 min. After, the extract was centrifugated at -4°C and 4800 g for 10 min. A 5 mL supernatant aliquot was cleaned up using a C18 reverse phase cartridge (Biotage, ISOLUTE® Multimode 300 mg, UK). Then, 5 mL of methanol was passed through the cartridge and the extract obtained was mixed with 10 mL of n-hexane, sonicated for 5 min, and thereafter centrifuged at -10°C and 4800 g for 10 min. The methanolic phase (lower) was recovered and evaporated to dryness at 40 $^{\circ}\text{C}$. The dry extract was reconstituted in 1 mL of methanol and passed through a 0.22 μm PTFE filter before analysis (Millipore,

Millipore, Germany). AA (m/z 70) and AA-d3 (m/z 73) were detected in SIM mode and negative polarity. A standard calibration curve was constructed using AA and results were expressed as μg of AA kg^{-1} fried chips.

2.4.5. Furan determination

The furan content was determined by headspace gas chromatography coupled with a mass spectrometry detector in electron ionization mode. Sample preparation was carried out according to the methodology reported in Mariotti-Celis et al. (2017). Briefly, 0.5 g of homogenized sample was diluted with 5.5 mL of 5 mol L^{-1} NaCl in a 10 mL headspace vial (Agilent Technologies, Santa Clara, CA, USA). Then, d4-furan (200 $\mu\text{L mL}^{-1}$) was added as internal standard to mitigate the evaporation of furan in the sample and the vials were sealed. Afterwards, the vials were incubated at 60 $^{\circ}\text{C}$ for 20 min at 50 RPM and then injected.

Furan (m/z 68 and m/z 39) and d4-furan (m/z 72 and m/z 42) were detected in SIM mode. The standard addition method was used for quantification and the results were expressed as ng furan g^{-1} fried chips.

2.5. 5-Hydroxymethyl furfural determination

The 5-HMF quantification was carried out by HPLC-DAD according to the method reported by Toker et al. (2013) with some modifications. One gram of potato chips homogenized sample was mixed with 20 mL of distilled water, 1.5 mL of Carrez I, and 1.5 mL of Carrez II. Then, the mixture was centrifugated at 4800 g for 15 min. Next, the supernatant was collected and filtered with a 0.22 μm syringe filter before injection.

Chromatographic separation was performed on an HPLC system with a diode array detector (Dionex UltiMate 3000, Thermo Scientific, Waltham, MA, USA) and an Acclaim™ 120 C18 column. The mobile phase consisted of 95 % acetic acid solution (at 1 % in water) and 5 % acetonitrile. Elution was isocratic at a flow rate of 1 mL min^{-1} . The injection volume was 20 μL . The detection wavelength was 284 nm and results were expressed as μg 5-HMF kg^{-1} fried chips.

2.6. Statistical analysis

Results were expressed as the mean of the measurements with the standard deviation ($n = 3$). A three-way ANOVA was conducted with cultivation season (S1 and S2), electrical conductivity (1.7 and 4.0 dS m^{-1}) and postharvest storage (at harvest and after 3-month cold storage) for each cultivar using the Statgraphics Centurion XV statistic software (Manugistic Inc., Rockville, MD, USA). Tukey's HSD test ($p < 0.05$) was employed to determine the differences between treatments. Metabolomic and neo contaminant data were analyzed by partial least squares regression (PLS-R), with metabolites as the predictor variables and neoformed contaminants (acrylamide, furan and 5-HMF) as the response variables. All variables (predictors and response variables) were mean centered and weighted by their standard deviation. Important variables (VIP) were selected using the Jack-Knifing feature and their weighted correlation coefficients were calculated. Multivariate analyses were realized using Unscrambler® X version 10.4 (CAMO Software, Oslo, Norway).

3. Results and discussion

3.1. Effect of cultivation season, electrical conductivity and cold storage on Maillard reaction precursors and neo contaminant levels of potato chips

The main MR precursors (reducing sugars, free asparagine), starch and sucrose of both cultivars are shown in Tables 1 and 2. In Michuñe negra potato, the cultivation season and storage condition were statistically significant in the accumulation of reducing sugars and asparagine (Supplementary Table 1). The interaction between the cultivation season and the storage condition was influential on the starch, glucose and

Table 1

Effect of the cultivation season, electrical conductivity of the nutrient solution and postharvest storage on starch, reducing sugars, sucrose and asparagine (mg g^{-1} dry weight) contents of Michuñe negra potatoes.

Content (mg g^{-1} DW)	Season winter-spring 2023 (S1)				Season autumn-winter 2024 (S2)			
	1.7 dS m^{-1}		4.0 dS m^{-1}		1.7 dS m^{-1}		4.0 dS m^{-1}	
	Harvest	90-d cold storage	Harvest	90-d cold storage	Harvest	90-d cold storage	Harvest	90-d cold storage
Starch	233.4 \pm 16.2 ^c	236.4 \pm 25.9 ^c	263.1 \pm 7.2 ^c	257.4 \pm 42.7 ^c	494.2 \pm 42.7 ^a	392.7 \pm 30.2 ^b	465.1 \pm 36.3 ^{ab}	390.1 \pm 46.9 ^b
Fructose	5.6 \pm 0.9 ^{ab}	7.4 \pm 1.0 ^{ab}	4.9 \pm 0.1 ^{abc}	8.2 \pm 3.3 ^a	1.4 \pm 0.1 ^c	6.7 \pm 1.6 ^{ab}	1.3 \pm 0.0 ^c	4.2 \pm 0.5 ^{bc}
Glucose	8.47 \pm 1.99 ^{ab}	6.8 \pm 1.56 ^{bc}	6.4 \pm 1.21 ^{bc}	8.13 \pm 3.01 ^{ab}	1.87 \pm 0.28 ^{cd}	11.9 \pm 2.53 ^a	1.27 \pm 0.2 ^d	7.71 \pm 1.15 ^{ab}
Sucrose	6.23 \pm 0.96 ^{abc}	5.23 \pm 0.74 ^{bc}	5.90 \pm 0.56 ^{abc}	5.37 \pm 0.55 ^{abc}	5.19 \pm 0.61 ^{bc}	6.79 \pm 0.51 ^{ab}	4.90 \pm 0.61 ^c	7.03 \pm 0.30 ^a
Asparagine	8.4 \pm 2.26 ^b	7.90 \pm 1.04 ^b	7.93 \pm 1.12 ^b	9.37 \pm 3.99 ^b	16.2 \pm 4.45 ^{ab}	18.5 \pm 3.4 ^a	20.2 \pm 2.28 ^a	24.60 \pm 3.94 ^a

Data are presented as means \pm SD ($n = 3$). Different letters within the same row indicate significant differences (Tukey HSD $p < 0.05$).

Table 2

Effect of the cultivation season, electrical conductivity of the nutrient solution and postharvest storage on starch, reducing sugars, sucrose and asparagine (mg g^{-1} dry weight) contents of Desiree potatoes.

Content (mg g^{-1} DW)	Season winter-spring 2023 (S1)				Season autumn-winter 2024 (S2)			
	1.7 dS m^{-1}		4.0 dS m^{-1}		1.7 dS m^{-1}		4.0 dS m^{-1}	
	Harvest	90-d cold storage	Harvest	90-d cold storage	Harvest	90-d cold storage	Harvest	90-d cold storage
Starch	357 \pm 88.2 ^{bc}	204 \pm 20.6 ^d	234 \pm 22.1 ^d	258 \pm 14.2 ^{cd}	498 \pm 26.5 ^a	442 \pm 42.8 ^{ab}	508 \pm 46.5 ^a	427 \pm 30.9 ^{ab}
Fructose	4.33 \pm 0.42 ^{bc}	12 \pm 0.66 ^a	5.57 \pm 1.65 ^b	8.43 \pm 0.40 ^{ab}	1.12 \pm 0.04 ^c	10.7 \pm 3.75 ^a	1.12 \pm 0.02 ^c	5.91 \pm 0.13 ^b
Glucose	4.70 \pm 0.79 ^{cde}	16.20 \pm 2.99 ^a	5.57 \pm 1.36 ^{cde}	7.53 \pm 0.30 ^{bc}	1.44 \pm 0.24 ^{de}	12.40 \pm 3.85 ^{ab}	1.04 \pm 0.05 ^e	6.39 \pm 0.46 ^{cd}
Sucrose	4.57 \pm 0.49 ^{ab}	4.20 \pm 0.85 ^{ab}	5.17 \pm 0.31 ^a	4.20 \pm 0.66 ^{ab}	3.07 \pm 0.08 ^b	5.63 \pm 1.44 ^a	3.72 \pm 0.31 ^{ab}	4.58 \pm 0.07 ^{ab}
Asparagine	4.30 \pm 0.17	5.10 \pm 1.05	4.63 \pm 0.83	5.23 \pm 0.06	5.05 \pm 0.69	5.79 \pm 1.15	6.22 \pm 2.47	6.73 \pm 1.42

Data are presented as means \pm SD ($n = 3$). Different letters within the same row indicate significant differences (Tukey HSD $p < 0.05$).

sucrose levels. Higher levels of fructose and glucose after the 90-day cold storage were observed during the autumn-winter season (S2) than during the winter-spring season (S1). In S2, a lower average concentration of reducing sugars after cold storage was measured in tubers cultivated with 4.0 dS m^{-1} although it was not significantly lower ($p > 0.05$) than in the 1.7 dS m^{-1} fertigation treatment (Table 1). The asparagine content was not influenced by the storage condition, in agreement with previous studies in these potato cultivars under similar cold storage temperatures and times (Elmore et al., 2015; García-Ríos et al., 2023). In addition, the influence of the EC was statistically significant ($p < 0.05$) for this amino acid (Supplementary Table 1). Similarly, in Desiree potato, seasonality and storage condition were statistically significant factors ($p < 0.05$) for the levels of reducing sugars and starch (Table 2, Supplementary Table 2). However, for this cultivar the electrical conductivity of the nutrient solution and its interaction with the storage condition were statistically significant on the fructose and glucose levels. As shown in Table 2, greater levels of these reducing sugars at harvest were present in S1 than in S2, though a lower increase of these sugars after the cold storage period was observed in potatoes cultivated at 4.0 dS m^{-1} in both cultivation seasons. These results suggest that, for Desiree cultivar, a moderate increase in the EC during the tuber growth could be a strategy to lower the magnitude of the cold induced sweetening (CIS). Postharvest carbohydrate metabolism is crucial for potatoes destined to the chip industry and the prolonged cold storage is a basic technology to ensure their availability, delay sprouting and spoilage. Abiotic stressors such as heat, when manifested during tuber development and maturation have been shown to abolish the CIS tolerance in CIS-resistant cultivars (Zommick et al., 2014). Thus, a cultivar-dependent carbohydrate metabolism regulating effect could be induced by moderate saline stress.

Regarding neo contaminant accumulation on the potato chips, there were significant differences ($p < 0.05$) for both cultivars among the cultivation seasons studied as shown in Fig. 1A–B, 1C–D and 1E–F, respectively. During the winter-spring season (S1), the increase in EC from 1.7 dS m^{-1} to 4.0 dS m^{-1} favored a reduction in the average AA content from 1045 $\mu\text{g kg}^{-1}$ to 750 $\mu\text{g kg}^{-1}$ (–28.2 %) in chips obtained at

harvest and from 2383 $\mu\text{g kg}^{-1}$ to 1892 $\mu\text{g kg}^{-1}$ (–20.6 %) in Michuñe negra chips obtained after the 90-day cold storage period. Likewise, a significant decrease in AA levels was observed in chips obtained from the Desiree cultivar when fertigated with 4.0 dS m^{-1} , which went from 528 $\mu\text{g kg}^{-1}$ to 337 $\mu\text{g kg}^{-1}$ at harvest (–36.2 %) and from 2113 $\mu\text{g kg}^{-1}$ to 1930 $\mu\text{g kg}^{-1}$ (–8.7 %) after the cold storage period. In contrast, during the autumn-winter season (S2) there were no significant differences ($p > 0.05$) in the AA level in chips obtained at harvest for both cultivars and electrical conductivities. In chips obtained after the 90-day cold storage period; however, a decrease from 3750 $\mu\text{g kg}^{-1}$ to 2890 $\mu\text{g kg}^{-1}$ (–22.9 %) was observed in Michuñe negra-based chips and an increase from 2171 $\mu\text{g kg}^{-1}$ to 3031 $\mu\text{g kg}^{-1}$ (+39.6 %) occurred in Desiree-based chips. The higher average amounts of AA during the autumn-winter season (S2) relative to S1 even at harvest, could be attributed to the higher amount of asparagine accumulated during that season (about 2–2.5 times higher). This result is consistent with the previous results for cultivars with lower reducing sugars but high asparagine levels, which tend to produce higher AA levels compared to cultivars with similar levels of both reducing sugars and asparagine or higher reducing sugars and lower asparagine (Liyanage et al., 2021).

With respect to 5-HMF, its occurrence differed abruptly among cultivation seasons in both varieties studied (Fig. 1C and D). For Michuñe negra-based chips, in the winter-spring season (S1), the 5-HMF content at harvest went from 815 $\mu\text{g kg}^{-1}$ for potatoes cultivated at 1.7 dS m^{-1} to non-quantifiable levels for potatoes cultivated at 4.0 dS m^{-1} . Conversely, after cold storage, the content of 5-HMF went from non-quantifiable to 109 $\mu\text{g kg}^{-1}$ as the EC value increased (Fig. 1C). Desiree-based chips showed non-quantifiable 5-HMF levels at harvest for both EC values; however, they increased to 4104 $\mu\text{g kg}^{-1}$ and 709 $\mu\text{g kg}^{-1}$ for 1.7 and 4.0 dS m^{-1} , respectively after cold storage (Fig. 1D). Meanwhile, during the autumn-winter season (S2), 5-HMF content at harvest for Michuñe negra-based chips went from 758 $\mu\text{g kg}^{-1}$ to 1219 $\mu\text{g kg}^{-1}$ as the EC value increased (+60.8 % higher). After cold storage, however, the 5-HMF content in chips from high EC potatoes was non-quantifiable while for low EC, it was 1387 $\mu\text{g kg}^{-1}$ (Fig. 1C). Lastly, for Desiree-based chips in the autumn-winter season (S2), the 5-HMF

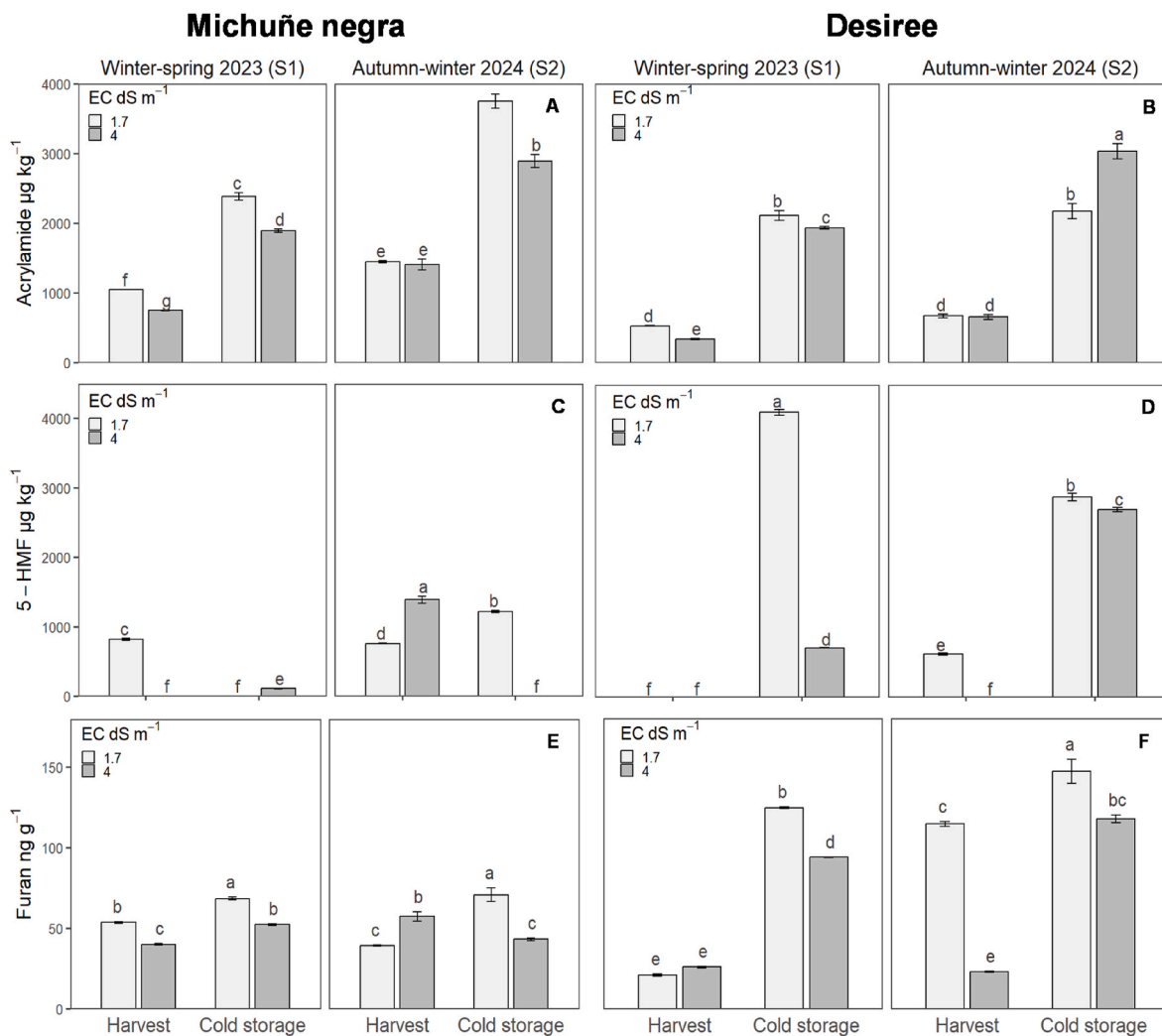


Fig. 1. Neo-formed contaminant contents of potato chips made from Michuñe negra and Desiree cultivars at two different cultivation seasons. Different letters above the bars indicate significant differences (Tukey HSD $p < 0.05$).

content at harvest and low EC was $620 \mu\text{g kg}^{-1}$ and non-quantifiable in chips from potatoes cultivated at high EC. After cold storage though, a significant increase in 5-HMF content was observed with values of $2882 \mu\text{g kg}^{-1}$ and $2700 \mu\text{g kg}^{-1}$ for EC values of 1.7 and 4.0 dS m^{-1} , respectively (Fig. 1D).

During the winter-spring season (S1), the increase in the EC of the nutrient solution resulted in a lower amount of furan in chips. As shown in Fig. 1E, furan content went from 53.6 ng g^{-1} to 39.9 ng g^{-1} (-25.6%) at harvest and from 68.4 ng g^{-1} to 52.2 ng g^{-1} (-23.7%) after cold storage in Michuñe negra-based chips. Desiree-based chips showed no significant differences ($p > 0.05$) in their amount of furan for both EC values at harvest (Fig. 1F); however, the EC increase to 4.0 dS m^{-1} led to a 25% decrease of furan in chips obtained after cold storage (from 125 ng g^{-1} to 93.8 ng g^{-1}). Interestingly, in the next season S2 for Michuñe negra-based chips the amount of furan increased from 39.2 ng g^{-1} to 57.4 ng g^{-1} ($+46.4\%$) as the EC was increased in chips obtained at harvest. Meanwhile, a 39.1% reduction was observed after cold storage, from 70.8 ng g^{-1} to 43.1 ng g^{-1} when the EC was increased. For Desiree-based chips, a sharp decrease in the amount of furan was observed at harvest (-80%) whereas a milder decrease occurred after cold storage (-19.7%). It is worth noting that furan content after cold storage was significantly higher in the Desiree cultivar than in the Michuñe negra cultivar, which may be related to the relatively higher amount of reducing sugars after cold storage observed in that variety (Tables 1 and 2). Although it is studied in a lesser extent, furan

constitutes a relevant neo contaminant in potato chips as reported in the existing literature (García-Ríos et al., 2024; Mariotti et al., 2015; Mariotti-Celis et al., 2017). In contrast to acrylamide, which is mainly formed through the MR, furan formation in foods is the result of the thermal-induced degradation and rearrangement of sugars and free amino acids as well as the oxidation of polyunsaturated fatty acids catalyzed by the high temperatures, all of these reactions may take place simultaneously during the deep-fat frying of potato chips (Mariotti et al., 2015). Furan could also form from the thermal degradation of polyunsaturated fatty acids and ascorbic acid (Schöpf & Oellig, 2024) and due to its lipophilic nature could accumulate in the oil phase of the potato chips.

3.2. The harvest season and cold storage play a significant role in neo-formed contaminant potential formation: multivariate analysis shows the relevance of other MR substrates than reducing sugars and asparagine

Neo-formed contaminant levels in potato chips, across different cultivars and treatments, could not be fully explained by only reducing sugars and asparagine, a finding consistent with previous research (Elmore et al., 2015; Muttucumaru et al., 2014). To address this, we performed a multivariate analysis using Partial Least Squares-Regression (PLS-R), incorporating other metabolites such as free amino acids (excluding asparagine), organic acids, sugar alcohols, and polyphenolic compounds, that might contribute to neo-contaminant

formation (Fig. 2). The PLS-R model, correlating fresh potato metabolites with fried chip neo-formed contaminants, revealed significant influences beyond varietal differences. Cultivation season played a crucial role, particularly in the autumn-winter season (S2), where it distinctly separated cultivars. The impact of postharvest cold storage was also more pronounced in S2. Interestingly, the effect of electrical conductivity (EC) was not resolvable with this technique due to the major influence of seasonality and cold storage on tuber composition. PLS-R calibration statistics (Fig. S5) showed good correlation for acrylamide ($R^2 = 0.843$, RMSE = 386.94) and furan ($R^2 = 0.805$, RMSE = 16.97) while a lower correlation was found for 5-HMF ($R^2 = 0.739$, RMSE = 617.39). Cross-validation analysis revealed that the PLS-R model showed a better predictive power for acrylamide than for 5-HMF and furan for which the calculated Q^2 dropped (Fig. S5). The explained variance for the response variables (Y) by the model VIP analysis (by Jack-Knifing approach) identified nine key variables (six amino acids, one organic acid, one sugar alcohol, and total anthocyanin content, Supplementary Table 3, Fig. S6) strongly correlated with acrylamide formation. Specifically, acidic amino acids (aspartic and glutamic) and malic acid showed a strong positive correlation with AA. This aligns with previous studies linking 5-HMF as an AA predictor (Pedreschi et al., 2021) and noting that glutamic and aspartic acids, along with acidic conditions, favor 5-HMF formation from sugars (Huang et al., 2022; Kavousi et al., 2015). Conversely, basic amino acids like lysine, arginine, and histidine have been shown to reduce 5-HMF concentration in model systems (Kavousi et al., 2015). These findings underscore the importance of considering a broader range of substrates beyond just reducing sugars and asparagine, and their complex interactions. Free amino acids, for instance, can compete for carbonyl groups of reducing sugars, leading to other MR products (Muttucumaru et al., 2014). While amino acid blanching solutions have been used for mitigation (Liyanage et al., 2021), their effect might also involve direct AA elimination rather than just MR competition. Therefore, an effective strategy to mitigate AA and 5-HMF formation could involve not only reducing asparagine but also decreasing the levels of specific amino acids and organic acids that

promote 5-HMF formation.

3.3. Effect of pre-frying treatments on neo-formed contaminant levels of potato chips

Given the AA levels observed in potato chips after the period of cold storage observed in the winter-spring season - S1 - (which occurred in both varieties alike) exceeding the EU benchmark value of $750 \mu\text{g kg}^{-1}$ for potato chips from commercial uncolored potato tubers herein used as the reference value, two previously reported mitigation strategies at the processing level were assayed to further reduce the neo-formed contaminants in potato chips obtained from the autumn-winter season tubers (S2). Both ultrasound leaching of MR precursors and asparagine elimination by asparaginases aim to reduce the AA content which is so far the most studied and relevant NFC. The levels of the main MR precursors and secondary metabolites after the pre-frying treatments are shown in Tables 3 and 4 for Michuñe negra and Desiree cultivars, respectively.

Ultrasonic treatment (US) of the potato slices before frying significantly reduced AA content at both storage conditions, except for Desiree-based chips where the reduction was not statistically significant (Fig. 3A and B). The greatest AA reduction (53.7%–67.6%) occurred in chips produced after cold storage. A similar trend was observed for 5-HMF reduction from 63% up to non-detectable levels (Fig. 3C and D). Conversely, furan levels in general were not successfully reduced by US, and for some cases even an increase was observed (Fig. 3E and F). Zhang et al. (2021) found that ultrasonic treatment of potato slices before frying reduced penetrated surface oil (PSO), however, the structural oil (STO) increased because of the modifications generated by cavitation in the potato slice structure, causing a higher absorption of oil during frying. The increase in the proportion of structural oil in US treated potatoes could explain the observed increase in the furan content. The AA and 5-HMF mitigation achieved with US in this study was lower than the obtained in previous studies which attained reductions of 88% (Antunes-Rohling et al., 2018), and 95% (Pedreschi et al., 2021). A

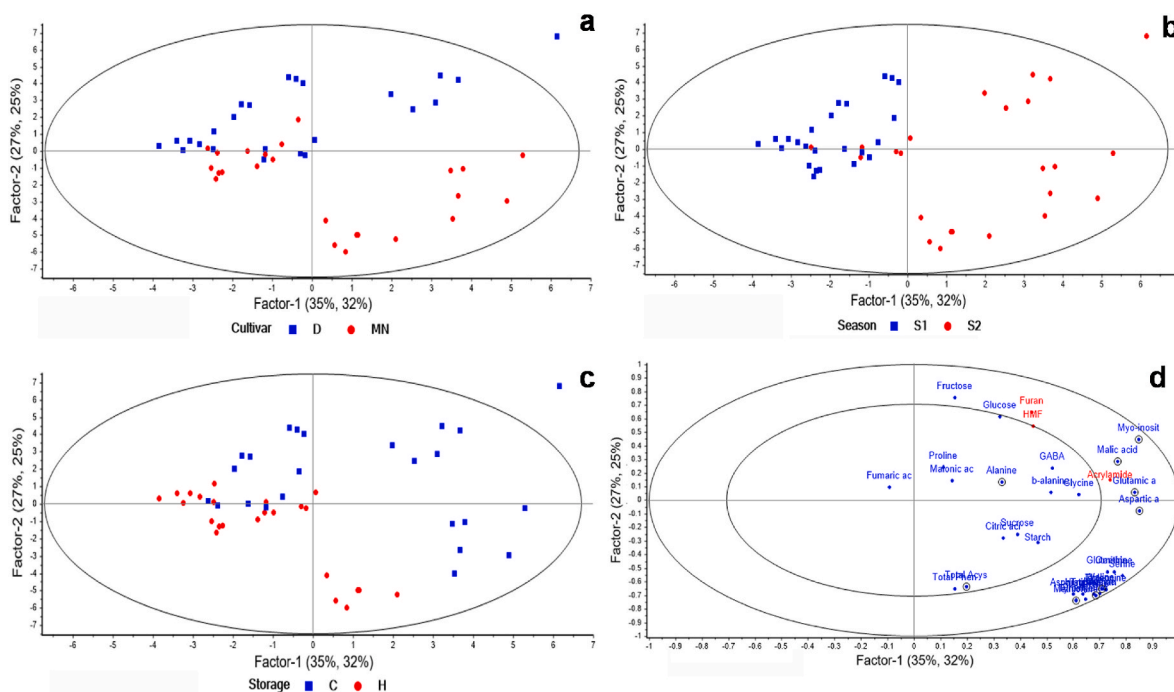


Fig. 2. Partial least squares-regression (PLS-R) scores plot of samples from the two cultivars (a), two cultivation seasons (b), at harvest and after the 90-day month cold storage (c) grown under two EC regimes (1.7 and 4.0 dS m^{-1}). PLS-R correlation loading plot (d) where X variables correspond to the metabolites (blue dots) and Y (red dots) to neo-formed contaminants. Legend from left-to-right and top-to-bottom: D (Desiree), MN (Michuñe negra), S1 (Winter-spring 2023 season), S2 (Autumn-winter 2024 season), C (90-day cold storage), H (Harvest).

Table 3Main Maillard reaction precursors and secondary metabolites levels (mg g⁻¹ DW) in potato slices after the pre-frying treatments from the cultivar Michuñe negra.

Main MR precursors (mg g ⁻¹ DW)	Electrical conductivity (dS m ⁻¹)	Harvest			90-day cold storage		
		Control	Asparaginase	Ultrasound	Control	Asparaginase	Ultrasound
Fructose	1.7	1.42 ± 0.05 ^c	1.71 ± 0.39 ^c	1.12 ± 0.05 ^c	6.71 ± 1.61 ^a	4.19 ± 0.68 ^b	1.69 ± 0.15 ^c
	4.0	1.27 ± 0.04 ^c	1.77 ± 0.42 ^c	1.12 ± 0.03 ^c	4.19 ± 0.52 ^b	2.32 ± 0.54 ^c	1.25 ± 0.07 ^c
Glucose	1.7	1.87 ± 0.28 ^c	0.62 ± 0.03 ^c	0.54 ± 0.02 ^c	11.9 ± 2.53 ^a	0.84 ± 0.09 ^c	0.83 ± 0.03 ^c
	4.0	1.27 ± 0.20 ^c	0.57 ± 0.13 ^c	0.48 ± 0.01 ^c	7.71 ± 1.15 ^b	0.75 ± 0.12 ^c	0.61 ± 0.04 ^c
Sucrose	1.7	5.19 ± 0.61 ^b	0.54 ± 0.12 ^c	0.71 ± 0.02 ^c	6.79 ± 0.51 ^a	0.26 ± 0.01 ^c	0.31 ± 0.02 ^c
	4.0	4.90 ± 0.61 ^b	0.63 ± 0.22 ^c	0.83 ± 0.13 ^c	7.03 ± 0.29 ^a	0.51 ± 0.27 ^c	0.54 ± 0.08 ^c
Asparagine	1.7	16.2 ± 4.45 ^b	0.88 ± 0.11 ^c	0.95 ± 0.19 ^c	18.5 ± 3.40 ^{ab}	0.97 ± 0.11 ^c	0.66 ± 0.06 ^c
	4.0	20.2 ± 2.28 ^{ab}	0.66 ± 0.07 ^c	1.04 ± 0.22 ^c	24.6 ± 3.94 ^a	1.24 ± 0.07 ^c	0.84 ± 0.22 ^c
Secondary metabolites (mg g⁻¹ DW)							
Total phenolics ^a	1.7	3.52 ± 0.55 ^a	2.60 ± 0.48 ^a	1.32 ± 0.17 ^b	3.34 ± 0.10 ^a	2.58 ± 0.22 ^a	1.07 ± 0.18 ^b
	4.0	3.23 ± 0.81 ^a	2.56 ± 0.24 ^a	1.16 ± 0.20 ^b	3.24 ± 0.21 ^a	2.63 ± 0.25 ^a	1.20 ± 0.21 ^b
Total anthocyanins ^b	1.7	0.85 ± 0.20 ^{abc}	0.56 ± 0.03 ^{cd}	0.17 ± 0.02 ^d	1.04 ± 0.04 ^{ab}	0.92 ± 0.20 ^{abc}	0.21 ± 0.01 ^d
	4.0	0.91 ± 0.43 ^{abc}	0.62 ± 0.05 ^{bcd}	0.18 ± 0.07 ^d	1.10 ± 0.08 ^a	0.91 ± 0.09 ^{abc}	0.24 ± 0.02 ^d

Data are presented as means ± SD (n = 3). Different letters within the same row indicate significant differences (Tukey HSD *p* < 0.05).

(a) Total phenolics are expressed as equivalent gallic acid.

(b) Total anthocyanins are expressed as equivalent cyanidin-3-*O*-glucoside.**Table 4**Main Maillard reaction precursors and secondary metabolites levels (mg g⁻¹ DW) in potato slices after the pre-frying treatments from the cultivar Desiree.

Main MR precursors (mg g ⁻¹ DW)	Electrical conductivity (dS m ⁻¹)	Harvest			90-day cold storage		
		Control	Asparaginase	Ultrasound	Control	Asparaginase	Ultrasound
Fructose	1.7	1.12 ± 0.04 ^d	1.16 ± 0.03 ^d	1.05 ± 0.07 ^d	10.70 ± 3.75 ^a	4.56 ± 0.29 ^{bc}	2.26 ± 0.32 ^{cd}
	4.0	1.12 ± 0.02 ^d	1.06 ± 0.06 ^d	0.97 ± 0.03 ^d	5.91 ± 0.13 ^b	4.46 ± 0.37 ^{bc}	1.80 ± 0.24 ^{cd}
Glucose	1.7	1.44 ± 0.24 ^c	0.53 ± 0.05 ^c	0.50 ± 0.01 ^c	12.4 ± 3.85 ^a	0.61 ± 0.05 ^c	0.66 ± 0.02 ^c
	4.0	1.04 ± 0.05 ^c	0.47 ± 0.01 ^c	0.46 ± 0.01 ^c	6.39 ± 0.46 ^b	0.63 ± 0.07 ^c	0.58 ± 0.04 ^c
Sucrose	1.7	3.07 ± 0.08 ^c	0.64 ± 0.06 ^d	0.67 ± 0.01 ^d	5.63 ± 1.44 ^a	0.19 ± 0.05 ^d	0.25 ± 0.03 ^d
	4.0	3.72 ± 0.31 ^{bc}	0.81 ± 0.05 ^d	0.78 ± 0.09 ^d	4.58 ± 0.07 ^{ab}	0.23 ± 0.04 ^d	0.39 ± 0.05 ^d
Asparagine	1.7	5.05 ± 0.69 ^a	0.66 ± 0.03 ^b	0.65 ± 0.02 ^b	5.78 ± 1.15 ^a	0.60 ± 0.12 ^b	0.56 ± 0.02 ^b
	4.0	6.22 ± 2.47 ^a	0.59 ± 0.04 ^b	0.64 ± 0.03 ^b	6.73 ± 1.42 ^a	0.58 ± 0.12 ^b	0.55 ± 0.04 ^b
Secondary metabolites (mg g⁻¹ DW)							
Total phenolics ^a	1.7	2.07 ± 0.34 ^a	1.29 ± 0.27 ^{bcd}	0.73 ± 0.10 ^e	1.82 ± 0.20 ^{ab}	1.14 ± 0.12 ^{cde}	0.61 ± 0.09 ^e
	4.0	1.46 ± 0.15 ^{bc}	0.88 ± 0.10 ^{de}	0.64 ± 0.07 ^e	1.46 ± 0.25 ^{bc}	1.44 ± 0.22 ^{bc}	0.67 ± 0.03 ^e

Data are presented as means ± SD (n = 3). Different letters within the same row indicate significant differences (Tukey HSD *p* < 0.05).

(a) Total phenolics are expressed as equivalent gallic acid.

lower reduction percentage (34 %) was obtained by applying ultrasound directly during the frying process (Ostermeier et al., 2021). While US reduced MR-derived contaminants by leaching free reducing sugars and amino acids, its effectiveness highly depends on experimental conditions like temperature, time, frequency, amplitude and power (Saini et al., 2023). In this study, soundwave amplitude was fixed at 100 %, and the relatively low ultrasonic power (90 W) used might have impacted the results. Research suggests lower ultrasonic power could be more effective at lower amplitudes, while higher power works better at full amplitude (Bruno et al., 2024), indicating that adjustable power and frequency settings are crucial for improved mitigation.

Enzymatic treatment with an asparaginase solution has been proposed as a promising strategy for reducing AA levels in heat processed foods, especially in the bakery industry in which the critical precursor for AA formation is asparagine since it is converted to aspartic acid by the asparaginases (Mudaliar et al., 2025). Under the experimental conditions of this study, AA reduction by the application of this enzyme was not as effective as the ultrasound treatment with lower percentages of reduction and in some cases even a higher amount of AA was obtained (Fig. 3A and B). This result was unexpected given the significant reduction of asparagine and glucose that was achieved by the asparaginase treatment. Hence, the discrepancy between precursor levels and AA content on potato chips was consistent with previous results reported by Pedreschi et al. (2011). These authors found that commercial asparaginases increased their effectiveness when used in combination with blanching since it increases the permeability of the cell wall, allowing the penetration of the enzyme. In this study, potato slices were

immersed in the asparaginases solution directly, a treatment that is just as effective as blanching in hot water at 85 °C (Pedreschi et al., 2011). Thus, here we confirm that immersion in asparaginases solution as a treatment to reduce acrylamide should be used in conjunction with another treatment such as ultrasound or electric pulses to increase its effectiveness. Moreover, due to their irregular shape, Michuñe negra potato slices were processed “as is” and differences in chip diameter were greater than those obtained from Desiree potatoes and could have influenced both the effect of the pretreatments and the frying process itself. Another factor to consider is the origin of the enzyme and dose. Recently, novel sources of asparaginase, mostly microbial, are being prospected as alternatives for AA reduction (Shi et al., 2017; Mudaliar et al., 2025). Likewise, the reductions of 5-HMF and furan under this treatment were inferior to those obtained with the ultrasound treatment. Since the formation of these NFCs is more dependent on the reactions of reducing sugars rather than the MR, US treatment appears as a more effective pre-frying treatment to mitigate them. However, the impact of ultrasound leaching of MR precursors in the sensorial properties of the final product needs to be assessed.

As in section 3.1.1, a PLS-R analysis was performed since, despite reducing both sugars and asparagine levels in a similar magnitude as the ultrasound treatment, the enzymatic treatment with asparaginase was not as effective as ultrasound in reducing the AA and other neo-formed contaminant levels, a discrepancy also reported by Pedreschi et al. (2011). These results could be attributed to the fact that the main limiting precursors for AA formation in fried potatoes and chips are reducing sugars rather than asparagine (Knight et al., 2021; Liyanage

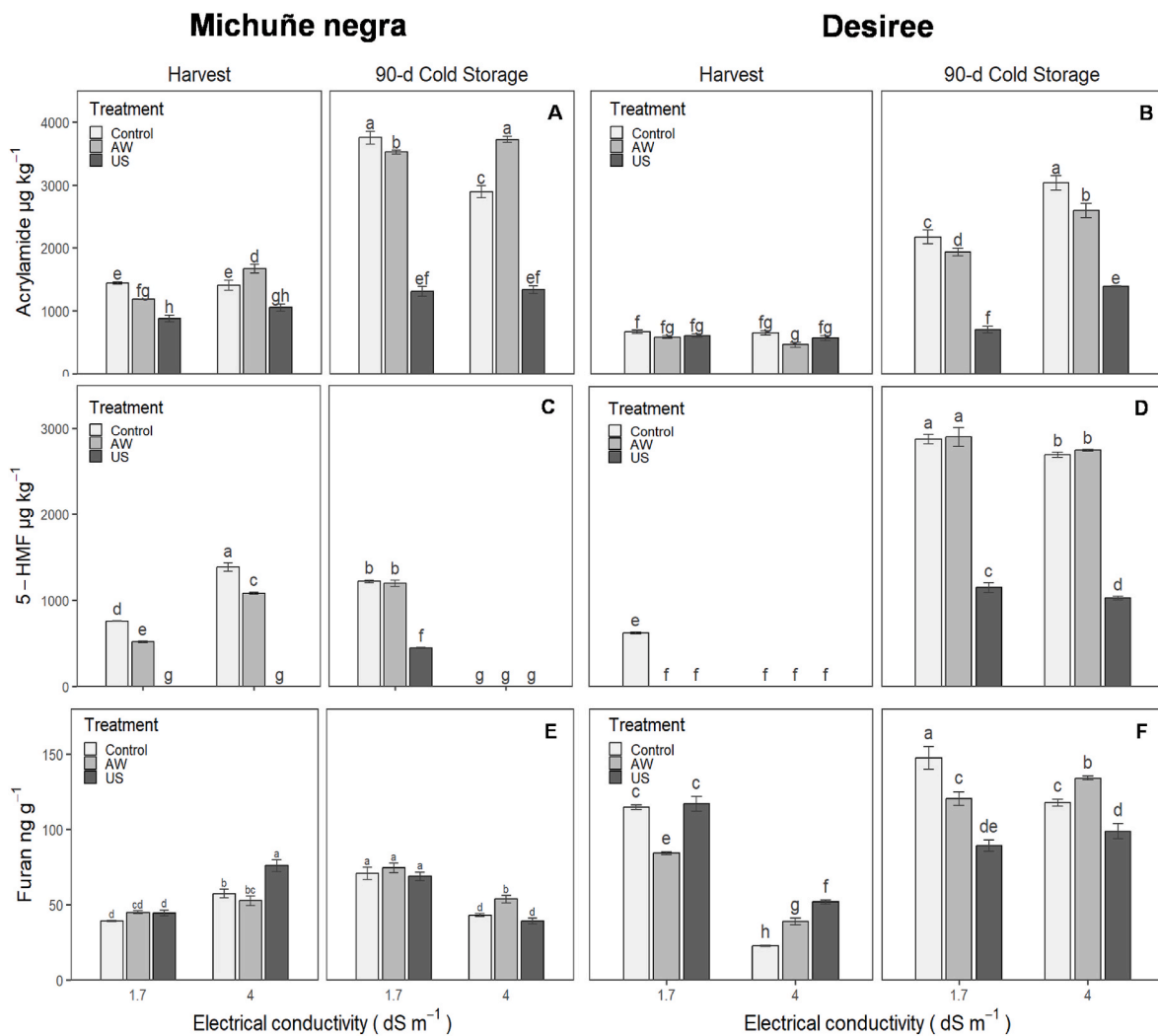


Fig. 3. Effect of pre-frying treatments on neo-formed contaminant contents of potato chips made from Michuñe negra and Desiree (Season autumn-winter 2024). Different letters above the bars indicate significant differences (Tukey HSD $p < 0.05$). Legend: AW (Asparaginase), US (Ultrasound).

et al., 2021; Pedreschi et al., 2021). Furthermore, given the experimental conditions under which the asparaginases were applied, it could be inferred that the mitigating effect could also be due to the leaching of the MR precursors rather than an effective asparaginase activity. The score plots display that factor 1 separated the control samples from the pre-frying treatments for both varieties (Fig. 4a and b). Meanwhile, the correlation loadings plot revealed similar predictor metabolites for the neo-formed contaminants as the analysis performed in section 3.1.1. The PLS-R calibration statistics displayed a high correlation for acrylamide ($R^2 = 0.9033$, RMSE = 324.40), followed by furan ($R^2 = 0.7365$, RMSE = 17.59), and 5-HMF ($R^2 = 0.7160$, RMSE = 529.47). Similar to the analysis for the experiment relating harvest seasons, postharvest storage and fertigation EC (Section 3.2), the PLS-R model displayed a better predictive power for acrylamide whereas 5-HMF and furan presented lower Q^2 values after cross-validation (Fig. S7). Of the 12 selected metabolites by VIP analysis (marked black circles in Fig. 4c–Supplementary Table 4, Fig. S8), five coincided with the obtained in the previous analysis (Glutamic acid, malic acid, methionine, myo-inositol, and total anthocyanins). In addition, total anthocyanin content showed to be positively correlated with AA formation (Fig. 4c). Previous studies have dealt with the formation of AA in colored potatoes and other colored tubers, however, none of them have related it with anthocyanins, thus the attempt to include these pigments in this study. Potato cultivars with red or purple flesh color formed more AA after frying than yellow ones

(Orsák et al., 2022); however, the authors pointed that the colored potatoes studied also tend to have a higher amount of reducing sugars and asparagine. Similar results were obtained by Kalita et al. (2013), after analyzing 20 potato cultivars/selections with different skin/flesh colors, colored potatoes tend to have higher amounts of chlorogenic acids which correlated negatively with AA ($r = -0.3590$). In contrast to our findings, a recent study found a non-significant relationship between anthocyanins and AA formation in bakery products from wheat lines with different anthocyanin contents (Kotíková et al., 2025). Although exogenous application of phenolic antioxidants has been applied as an AA mitigation strategy, its effectiveness depends on the type of antioxidant (Kumari et al., 2022), the effect of endogenous phenolics in neo-formed contaminant formation seems to be minor.

4. Conclusions

Increasing the nutrient solution electrical conductivity shows promise for modulating the content of reducing sugars and free amino acids in soilless-grown potatoes, though its effectiveness is highly dependent on the cultivar and growing season. This approach could help mitigate some neo-formed contaminants (like acrylamide and 5-HMF) in potato chips, particularly by reducing cold-induced sweetening in cultivars like Desiree. However, pre-frying treatments remain crucial for further reducing contaminants. Ultrasound (US) leaching proved most

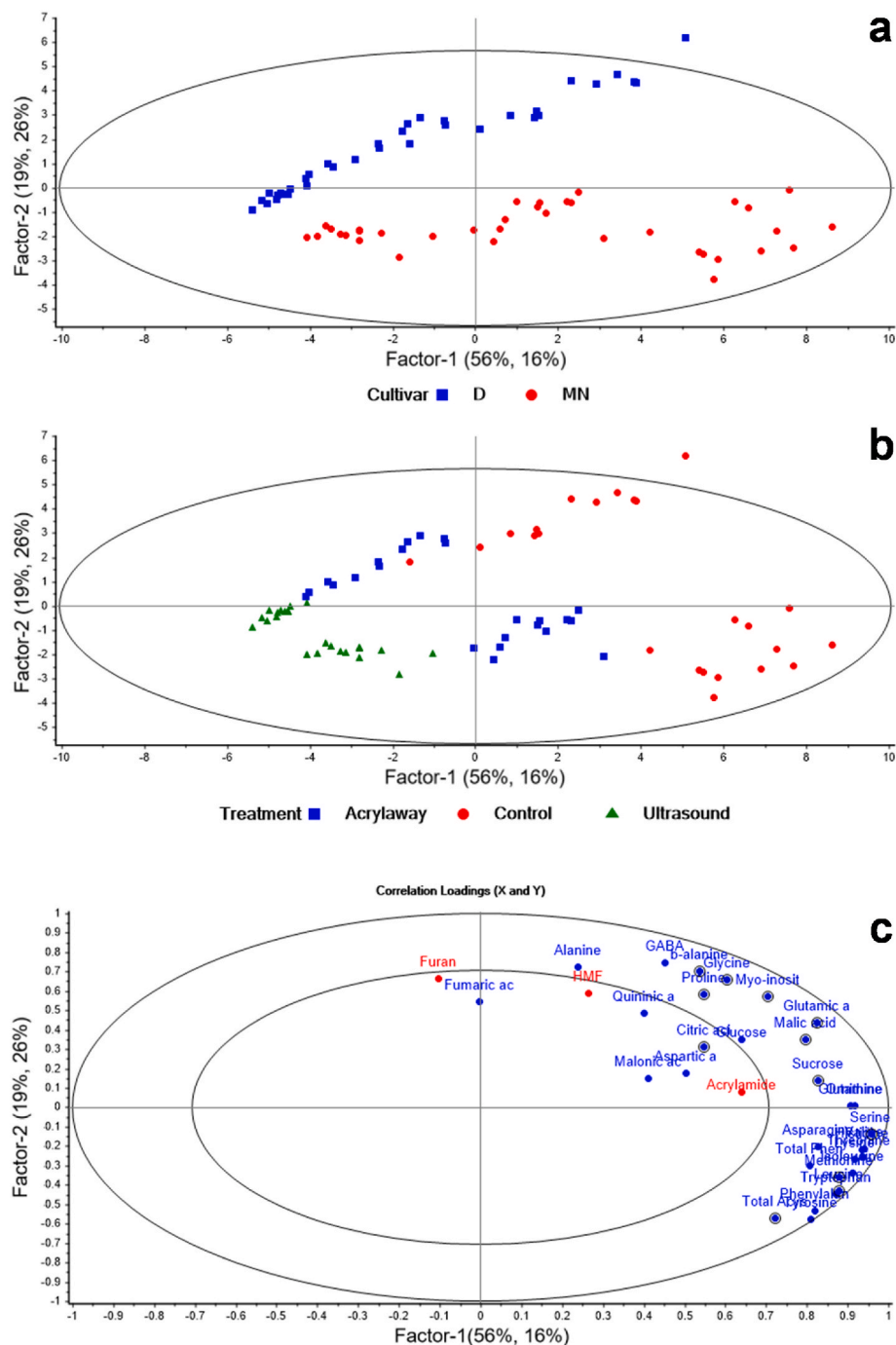


Fig. 4. Partial least squares-regression (PLS-R) scores plot of samples from the two varieties (a) and subjected to different pre-frying treatments (b). Samples corresponding to the autumn-winter 2024 season (S2). PLS-R correlation loading plot (c) where X variables correspond to the metabolites (blue dots) and Y (red dots) to neo-formed contaminants. Legend: D (Desiree), MN (Michuñe negra).

effective for acrylamide mitigation achieving up to 68 % reduction in Desiree chips and 65 % in Michuñe negra chips. US also reduced 5-HMF to non-quantifiable levels, but furan mitigation was inconsistent across pre-frying treatments. The complex chemistry of frying suggests a more holistic approach, considering other metabolites that participate in the MR are needed, as indicated by PLS-R analysis. Further research should also investigate how abiotic stressors (e.g., salinity, heat, radiation) at different growth stages influence the composition and post-harvest quality of colored potatoes, and their resulting neo-contaminant levels after processing.

CRediT authorship contribution statement

Diego García-Ríos: Writing – original draft, Investigation, Formal analysis, Data curation. **Franco Pedreschi:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Conceptualization. **María Salomé Mariotti-Celis:** Writing – review & editing, Supervision, Formal analysis. **Carolina Contreras:** Writing – review & editing, Resources. **David Campos:** Writing – review & editing, Supervision. **Juan E. Alvaro:** Supervision, Methodology, Funding acquisition, Conceptualization. **Romina Pedreschi:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization.

Funding

This work was supported by ANID – Millennium Science Initiative Program – ICN2021_044, Fondecyt Regular N°1240031, Centenario VINCI-PUCV N°039.308/2024, and DI Equipamiento Mediano 039.452/2024, PUCV. Diego García-Ríos thanks ANID-Subdirección de Capital Humano/Doctorado Nacional/2022-21220912.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors thank the technical assistance of Excequel Ponce, Juan Pablo Gómez, Juan Vidal, and Sebastián Veas.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lwt.2025.118398>.

Data availability

Data will be made available on request.

References

- Akrimi, R., Hajlaoui, H., Batelli, G., Ruggiero, A., Badri, M., Grillo, S., & Mhamdi, M. (2021). Electromagnetic water enhanced metabolism and agro-physiological responses of potato (*Solanum tuberosum* L.) under saline conditions. *Journal of Agronomy and Crop Science*, 207(1), 44–58. <https://doi.org/10.1111/jac.12449>
- Antunes-Rohling, A., Ciudad-Hidalgo, S., Mir-Bel, J., Raso, J., Cebrián, G., & Álvarez, I. (2018). Ultrasound as a pretreatment to reduce acrylamide formation in fried potatoes. *Innovative Food Science & Emerging Technologies*, 49, 158–169. <https://doi.org/10.1016/j.ifset.2018.08.010>
- Barrios-Rodríguez, Y. F., Pedreschi, F., Rosowski, J., Gómez, J. P., Figari, N., Castillo, O., & Mariotti Celis, M. S. (2021). Is the dietary acrylamide exposure in Chile a public health problem? *Food Additives & Contaminants: Part A*, 38(7), 1126–1135. <https://doi.org/10.1080/19440049.2021.1914867>
- Bruno, F., Ledbetter, M., Davies, B., Riedinger, L., Blidi, S., Sturrock, K., McNamara, G., Montague, G., & Fiore, A. (2024). Effect of ultrasound and additives treatment as mitigation strategies to reduce acrylamide formation in potato chips on industrial scale. *Lebensmittel-Wissenschaft und -Technologie: Food Science and Technology*, 197, Article 115876. <https://doi.org/10.1016/j.lwt.2024.115876>
- Dahal, K., Li, X.-Q., Tai, H., Creelman, A., & Bizimungu, B. (2019). Improving potato stress tolerance and tuber yield under a climate change scenario – A current overview. *Frontiers in Plant Science*, 10. <https://doi.org/10.3389/fpls.2019.00563>
- Doganay, K. H., Kurunc, A., & Dincer, C. (2023). Salinity stress effects on the growth yield and quality performance of two sweet potato varieties. *ACS Agricultural Science & Technology*, 3(6), 508–516. <https://doi.org/10.1021/acscagtech.3c00069>
- Elmore, J. S., Briddon, A., Dodson, A. T., Muttucumaru, N., Halford, N. G., & Mottram, D. S. (2015). Acrylamide in potato crisps prepared from 20 UK-grown varieties: Effects of variety and tuber storage time. *Food Chemistry*, 182, 1–8. <https://doi.org/10.1016/j.foodchem.2015.02.103>
- Elmore, J. S., Xu, F., Maveddat, A., Kapetanou, R., Qi, H., & Oruna-Concha, M.-J. (2019). Acrylamide content of vegetable chips. In *Food-borne toxicants: Formation, analysis, and toxicology* (pp. 15–26). ACS Publications.
- Fariéd, H. N., Ayyub, C. M., Wattoo, F. M., Bashir, M., Razaq, K., Akhtar, G., Hussain, A., Ullah, S., Wattoo, J. I., Amin, M., Munir, S., Shaheen, M. R., Ahmed, N., & Khan, W. (2022). Assessing salt tolerance induction in potato by salicylic acid using morpho-physio-biochemical, ionic, and yield indices. *Potato Research*, 65(3), 677–691. <https://doi.org/10.1007/s11540-021-09539-4>
- Food and Agriculture Organization of the United Nations. (2024). FAOSTAT: Rome. Available <http://www.fao.org/faostat/en/#data/QC>.
- Fuentealba, C., Hernandez, I., Saa, S., Toledo, L., Burdiles, P., Chirinos, R., Campos, D., Brown, P., & Pedreschi, R. (2017). Colour and in vitro quality attributes of walnuts from different growing conditions correlate with key precursors of primary and secondary metabolites. *Food Chemistry*, 232, 664–672. <https://doi.org/10.1016/j.foodchem.2017.04.029>
- García-Ríos, D., Alvaro, J. E., Zuñiga, M. E., Campos, D., Aguilar-Galvez, A., Mariotti-Celis, M. S., Pedreschi, F., & Pedreschi, R. (2023). Targeted primary and secondary metabolite analysis of colored potato "Michune Negra" grown in soilless culture and during prolonged cold storage: Implications in acrylamide formation during frying. *Agronomy*, 13(5), 1209. <https://doi.org/10.3390/agronomy13051209>
- García-Ríos, D., Hernández, I., Alvaro, J. E., Pedreschi, F., Campos, D., Behn, A., & Pedreschi, R. (2024). Analysis of Maillard reaction precursors and secondary metabolites in Chilean potatoes and neofomed contaminants during frying. *Food Chemistry*, 460, Article 140478. <https://doi.org/10.1016/j.foodchem.2024.140478>
- Garg, N., Choudhary, O. P., Thaman, S., Sharma, V., Singh, H., Vashista, M., Sekhon, K. S., Sharda, R., & Dhaliwal, M. S. (2022). Effects of irrigation water quality and NPK-fertilization levels on plant growth, yield and tuber size of potatoes in a sandy loam alluvial soil of semi-arid region of Indian Punjab. *Agricultural Water Management*, 266, Article 107604. <https://doi.org/10.1016/j.agwat.2022.107604>
- Ghosh, S. C., Asanuma, K.-i., Kusutani, A., & Toyota, M. (2001). Effect of salt stress on some chemical components and yield of potato. *Soil Science & Plant Nutrition*, 47(3), 467–475. <https://doi.org/10.1080/00380768.2001.10408411>
- Giusti, M. M., & Wrolstad, R. E. (2001). Characterization and measurement of anthocyanins by UV-visible spectroscopy. *Current Protocols in Food Analytical Chemistry*, 1. F1. 2.1-F1. 2.13.
- Halford, N. G., Curtis, T. Y., Muttucumaru, N., Postles, J., Elmore, J. S., & Mottram, D. S. (2012). The acrylamide problem: A plant and agronomic science issue. *Journal of Experimental Botany*, 63(8), 2841–2851. <https://doi.org/10.1093/jxb/ers011>
- Halford, N. G., Muttucumaru, N., Curtis, T. Y., & Parry, M. A. J. (2007). Genetic and agronomic approaches to decreasing acrylamide precursors in crop plants. *Food Additives & Contaminants Part A-Chemistry Analysis Control Exposure & Risk Assessment*, 24, 26–36. <https://doi.org/10.1080/02652030701403093>
- Huang, Y., Lu, J., Li, M., Li, C., Wang, Y., Shen, M., Chen, Y., Nie, S., Zeng, M., Chen, J., & Xie, M. (2022). Effect of acidity regulators on acrylamide and 5-hydroxymethylfurfural formation in French fries: The dual role of pH and acid radical ion. *Food Chemistry*, 371, Article 131154. <https://doi.org/10.1016/j.foodchem.2021.131154>
- Im, J. S., Cho, J. H., Cho, K. S., Chang, D. C., Jin, Y. I., Yu, H. S., & Kim, W. Y. (2016). Effect of salinity stress on growth, yield, and proline accumulation of cultivated potatoes (*Solanum tuberosum* L.). *Horticultural Science and Technology*, 34(6), 818–829. <https://doi.org/10.12972/kjst.20160086>
- Kalita, D., Holm, D., & Jayanty, S. (2013). Role of polyphenols in acrylamide formation in the fried products of potato tubers with colored flesh. *Food Research International*, 54(1), 753–759. <https://doi.org/10.1016/j.foodres.2013.08.023>
- Kavousi, P., Mirhosseini, H., Ghazali, H., & Ariffin, A. A. (2015). Formation and reduction of 5-hydroxymethylfurfural at frying temperature in model system as a function of amino acid and sugar composition. *Food Chemistry*, 182, 164–170. <https://doi.org/10.1016/j.foodchem.2015.02.135>
- Knight, M., McWilliam, S., Peck, S., Koutsidis, G., Chope, G., Puddephat, I., & Wedzicha, B. (2021). Kinetic modelling of acrylamide formation during the frying of potato chips. *Food Chemistry*, 352(7), Article 129305. <https://doi.org/10.1016/j.foodchem.2021.129305>
- Kotíková, Z., Burešová, B., Cejpková, K., Paznocht, L., Brnka, M., & Martinek, P. (2025). Do anthocyanins affect acrylamide formation in wholemeal bakery products? A study on near-isogenic wheat lines. *Food Control*, 168, Article 110892. <https://doi.org/10.1016/j.foodcont.2024.110892>
- Kumari, A., Bhattacharya, B., Agarwal, Paul, V., & Chakkaeavarthi, S. (2022). Integrated approach towards acrylamide reduction in potato-based snacks: A critical review. *Food Research International*, 156, Article 111172. <https://doi.org/10.1016/j.foodres.2022.111172>
- Lianage, D. W. K., Yevtushenko, D. P., Kunschuh, M., Bizimungu, B., & Lu, Z. X. (2021). Processing strategies to decrease acrylamide formation, reducing sugars and free asparagine content in potato chips from three commercial cultivars. *Food Control*, 119(9), Article 107452. <https://doi.org/10.1016/j.foodcont.2020.107452>
- Mariotti, M., Cortés, P., Fromberg, A., Bysted, A., Pedreschi, F., & Granby, K. (2015). Heat toxicant contaminant mitigation in potato chips. *LWT - Food Science and Technology*, 60(2, Part 1), 860–866. <https://doi.org/10.1016/j.lwt.2014.09.023>
- Mariotti-Celis, M. S., Cortés, P., Dueik, V., Bouchon, P., & Pedreschi, F. (2017). Application of vacuum frying as a furan and acrylamide mitigation technology in potato chips. *Food and Bioprocess Technology*, 10(11), 2092–2099. <https://doi.org/10.1007/s11947-017-1981-5>
- Miller, G. L. (1959). The use of dinitrosalicylic acid reagent for determination of reducing sugar. *Analytical Chemistry*, 31, 426–428.
- Mudaliar, S., Kumar, V., & Verma, P. (2025). Bioprospecting of microbial L-asparaginase: Sustainable production from waste and its application for acrylamide reduction in food industry. *Process Safety and Environmental Protection*, 195, Article 106737. <https://doi.org/10.1016/j.psep.2024.12.118>
- Muttucumaru, N., Powers, S. J., Elmore, J. S., Briddon, A., Mottram, D. S., & Halford, N. G. (2014). Evidence for the complex relationship between free amino acid and sugar concentrations and acrylamide-forming potential in potato. *Annals of Applied Biology*, 164, 286–300. <https://doi.org/10.1111/aab.12101>
- Oertel, A., Matros, A., Hartmann, A., Arapitsas, P., Dehmer, K. J., Martens, S., & Mock, H. P. (2017). Metabolite profiling of red and blue potatoes revealed cultivar and tissue specific patterns for anthocyanins and other polyphenols. *Planta*, 246(2), 281–297. <https://doi.org/10.1007/s00425-017-2718-4>
- Orsák, M., Kotíková, Z., Podhorecká, K., Lachman, J., & Kasal, P. (2022). Acrylamide formation in red-, purple- and yellow-fleshed potatoes by frying and baking. *Journal of Food Composition and Analysis*, 110, Article 104529. <https://doi.org/10.1016/j.jfca.2022.104529>
- Ostermeier, R., Hill, K., Dingis, A., Töpfl, S., & Jäger, H. (2021). Influence of pulsed electric field (PEF) and ultrasound treatment on the frying behavior and quality of potato chips. *Innovative Food Science & Emerging Technologies*, 67, Article 102553. <https://doi.org/10.1016/j.ifset.2020.102553>
- Pedreschi, F., Ferrera, A., Bunger, A., Alvarez, F., Huaman-Castilla, N. L., & Mariotti-Celis, M. S. (2021). Ultrasonic-assisted leaching of glucose and fructose as an alternative mitigation technology of acrylamide and 5-hydroxymethylfurfural in

- potato chips. *Innovative Food Science & Emerging Technologies*, 73(8), Article 102752. <https://doi.org/10.1016/j.ifset.2021.102752>
- Pedreschi, F., Mariotti, S., Granby, K., & Risum, J. (2011). Acrylamide reduction in potato chips by using commercial asparaginase in combination with conventional blanching. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology*, 44(6), 1473–1476. <https://doi.org/10.1016/j.lwt.2011.02.004>
- Pedreschi, F., & Moyano, P. C. (2006). Kinetics of oil uptake during frying of potato slices: Effect of pre-treatments. *LWT - Food Science and Technology*, 39(3), 285–291. <https://doi.org/10.1016/j.lwt.2005.01.010>
- Powers, S. J., Mottram, D. S., Curtis, A., & Halford, N. G. (2021). Progress on reducing acrylamide levels in potato crisps in Europe, 2002 to 2019. *Food Additives & Contaminants Part A-Chemistry Analysis Control Exposure & Risk Assessment*, 38(5), 782–806. <https://doi.org/10.1080/19440049.2020.1871083>
- Raffan, S., & Halford, N. G. (2019). Acrylamide in food: Progress in and prospects for genetic and agronomic solutions. *Annals of Applied Biology*, 175(3), 259–281. <https://doi.org/10.1111/aab.12536>
- Rodríguez, F., Pedreschi, R., Fuentealba, C., de Kartzow, A., Olaeta, J. A., & Alvaro, J. E. (2019). The increase in electrical conductivity of nutrient solution enhances compositional and sensory properties of tomato fruit cv. Patron. *Scientia Horticulturae*, 244, 388–398. <https://doi.org/10.1016/j.scienta.2018.09.059>
- Rouphael, Y., Petropoulos, S. A., Cardarelli, M., & Colla, G. (2018). Salinity as eustressor for enhancing quality of vegetables. *Scientia Horticulturae*, 234, 361–369. <https://doi.org/10.1016/j.scienta.2018.02.048>
- Saini, R., Kaur, S., Aggarwal, P., Dhiman, A., & Suthar, P. (2023). Conventional and emerging innovative processing technologies for quality processing of potato and potato-based products: A review. *Food Control*, 153, Article 109933. <https://doi.org/10.1016/j.foodcont.2023.109933>
- Šamec, D., Linić, I., & Salopek-Sondi, B. (2021). Salinity stress as an elicitor for phytochemicals and minerals accumulation in selected leafy vegetables of Brassicaceae. *Agronomy*, 11(2), 361. <https://doi.org/10.3390/agronomy11020361>
- Schöpf, A., & Oellig, C. (2024). Formation of furan and furan derivatives in carotenoid-containing model systems and in vegetable puree. *ACS Food Science & Technology*, 4(3), 668–678. <https://doi.org/10.1021/acscfoodscitech.3c00584>
- Shi, R., Liu, Y., Mu, Q., Jiang, Z., & Yang, S. (2017). Biochemical characterization of a novel l-asparaginase from *Paenibacillus barengoltzii* being suitable for acrylamide reduction in potato chips and mooncakes. *International Journal of Biological Macromolecules*, 96, 93–99. <https://doi.org/10.1016/j.ijbiomac.2016.11.115>
- Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture*, 16(3), 144–158.
- Toker, O. S., Dogan, M., Ersöz, N. B., & Yılmaz, M. T. (2013). Optimization of the content of 5-hydroxymethylfurfural (HMF) formed in some molasses types: HPLC-DAD analysis to determine effect of different storage time and temperature levels. *Industrial Crops and Products*, 50, 137–144. <https://doi.org/10.1016/j.indcrop.2013.05.030>
- van Hoorn, J. W., Katerji, N., Hamdy, A., & Mastrorilli, M. (1993). Effect of saline water on soil salinity and on water stress, growth, and yield of wheat and potatoes. *Agricultural Water Management*, 23(3), 247–265. [https://doi.org/10.1016/0378-3774\(93\)90032-6](https://doi.org/10.1016/0378-3774(93)90032-6)
- Wei, Q., Liu, T., & Sun, D.-W. (2018). Advanced glycation end-products (AGEs) in foods and their detecting techniques and methods: A review. *Trends in Food Science & Technology*, 82, 32–45. <https://doi.org/10.1016/j.tifs.2018.09.020>
- Zhang, J., Xie, T., & Fan, L. (2021). Improving the quality and reducing oil absorption of fried potato chips by ultrasound pretreatment. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology*, 148, Article 111763. <https://doi.org/10.1016/j.lwt.2021.111763>
- Zommick, D. H., Knowles, L. O., Pavek, M. J., & Knowles, N. R. (2014). In-season heat stress compromises postharvest quality and low-temperature sweetening resistance in potato (*Solanum tuberosum* L.). *Planta*, 239, 1243–1263. <https://doi.org/10.1007/s00425-014-2048-8>
- Zörb, C., Geilfus, C.-M., & Dietz, K.-J. (2019). Salinity and crop yield. *Plant Biology*, 21(S1), 31–38. <https://doi.org/10.1111/plb.12884>