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Valorization of *Chenopodium quinoa* residues through saponin recovery: Extraction, purification, and evaluation of antioxidant and cytotoxic activities

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ABSTRACT

Residues of *Chenopodium quinoa*, accounting for approximately 8% of the grain weight, represent an underutilized resource. In this study, saponins were extracted using hydrodynamic cavitation (HC), followed by membrane filtration, adsorption on AB-8 resin, and liquid–liquid partitioning. HC achieved an extraction yield of 66.54%, while membrane filtration increased saponin purity from 32% to 42%. Adsorption with AB-8 resin yielded a maximum purity of 65% after desorption with 70% (v/v) ethanol (CMC = 0.33 g/L), and further purification by liquid–liquid partitioning increased purity to 75%. Rutin and quercetin were identified as the predominant phenolic compounds in the purified extracts. Higher saponin purity was associated with enhanced antioxidant capacity. In addition, the extract with 65% exhibited better cytotoxic activity against MDA-MB-231, HCT-15, and A549 cancer cell lines, exhibiting low IC_{50} values and significantly reduced colony formation. These results demonstrate that quinoa residues are a valuable source of saponins with relevant biological activities and application potential.

1. Introduction

Quinoa (*Chenopodium quinoa* Willd.) is extensively cultivated across the Andean region, with its global market projected to reach USD 204.37 billion by 2030 (The Business Research Company, 2026). However, its grains contain saponins bitter and soapy-tasting compounds located in the pericarp that must be removed prior to consumption (Ahumada et al., 2016; Mora-Ocación et al., 2022). The conventional scarification process effectively eliminates these compounds but generates a yellowish by-product (5–8% w/w of the grain) rich in fiber, phenolic compounds, and saponins that currently lacks economic value (Bustos et al., 2024). Saponins are triterpene glycosides that function as natural defense metabolites in plants, consisting of hydrophobic aglycones such as oleanolic, hederagenic, and serjanic acids linked to hydrophilic sugar chains (El Hazzam et al., 2020; Otterbach et al., 2021; Taco et al., 2022).

To valorize this underutilized by-product, efficient and scalable extraction and purification strategies are required. Hydrodynamic cavitation (HC) represents a promising extraction technique that intensify and enhances the release of bioactive compounds through the implosive collapse of microbubbles, offering high efficiency, low energy consumption, and excellent scalability (Arya et al., 2023; Taco et al., 2022; Hilares et al., 2020). Although hydrodynamic cavitation has been successfully applied for the extraction of phenolic compounds (Minutolo et al., 2023; Tienaho et al., 2025), its application for this specific purpose remains scarce.

Membrane separation (MS), a physical process characterized by high efficiency and low environmental impact, has emerged as a promising alternative for the recovery and purification of bioactive compounds

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such as saponins and phenolic compounds (Baker, 2024; Li et al., 2021). Although MS has been widely applied for saponin purification, it has mostly been limited to small scales using only polymeric membranes. In contrast, the combined use of inorganic and polymeric membranes for processing has not been previously reported. This approach represents a significant step toward process scalability and potential pilot-scale implementation, providing greater robustness, operational efficiency, and suitability for continuous production (García Bustos et al., 2026).

However, to achieve higher saponin purity, additional purification steps are required. Complementary techniques such as adsorption using macroporous resins (e.g., AB-8) have demonstrated strong potential for saponin recovery from quinoa extracts (Li et al., 2025a; Liu et al., 2023; Luo et al., 2024). Likewise, organic solvent-based fractionation methods, such as liquid–liquid extraction with ethyl acetate, can further enhance saponin purity. In this process, highly polar compounds (e.g., organic acids, polysaccharides, and proteins) remain in the aqueous phase, while less polar molecules, including saponins, preferentially partition into the organic phase, leading to an increased total saponin concentration after fractionation (Chua et al., 2019).

The crude extract contains saponins and phenolic compounds with potential antioxidant activity, attributed to their capacity to neutralize free radicals and prevent oxidative damage (Omeiri et al., 2025; Saeid et al., 2024; Yang et al., 2025). Saponins have significant anti-inflammatory and antioxidant activities, which help mitigate oxidative stress and reduce systemic inflammation (Fordos et al., 2025). Several studies have also demonstrated its antihypertensive, antitumor, antimicrobial, and anticancer properties, highlighting its potential for pharmaceutical applications. For instance, saponin extracts from *Chenopodium quinoa* have been evaluated for their effects on human colon cancer HT-29 cells (Shang et al., 2024) and other cancer cell lines, including A549, SH-SY5Y, HepG2, and HeLa (Carpio-Paucar et al., 2023), showing significant antitumor activity (Tan et al., 2022). Moreover, crude saponin extracts exhibited antimicrobial activity against foodborne pathogenic bacteria (Dong et al., 2020).

Therefore, further studies assessing the antioxidant and cytotoxic activities of these extracts in new cell lines are warranted. As quinoa processing by-products are often discarded leading to resource waste and environmental pollution the results of this study could contribute to the sustainable development and comprehensive utilization of quinoa resources.

This study explores the valorization of quinoa scarification by-products through hydrodynamic cavitation-assisted extraction of saponins, followed by sequential membrane filtration (microfiltration: MF, ultrafiltration: UF and nanofiltration: NF). Further purification was achieved using macroporous resin (AB-8) adsorption and liquid–liquid partition, aiming to obtain a high-purity saponin extract with enhanced antioxidant and cytotoxic activities.

2. Material and methods

2.1. Quinoa powder and characterization

Quinoa powder residue generated in the mechanical pearling process of grains was kindly donated by a local industry in Arequipa-Peru. After reception, the powder was sieved using a sieve of 0.145 μm and the fine particles were analyzed and used in all experiments. The crude powder was analyzed according to the Peruvian Technical Standard (NTP, for its acronym in Spanish), which included crude protein (NTP 205.006:2018), fat (NTP 205.006:2018), ash (NTP 205.004, 2017), crude and dietary fiber (NTP 205.003, 2016) and moisture (NTP 205.002:1979). For carbohydrates, the formula by difference was used: 100 - (% protein + % fat + % fiber + % ash). All results were expressed on a dry weight (DW) basis. Additionally, the elemental composition (CHNS) was determined, and result was expressed as weight percent of oven-dried material and measured using a FLASHSMART elemental analyzer (Thermo Scientific, USA).

2.2. Extraction of saponin by hydrodynamic cavitation

Saponins were extracted from quinoa residue powder using a hydrodynamic cavitation (HC) system. The setup consisted of a centrifugal pump (1.4 CV) that forced the solution through an orifice plate, inducing cavitation. The cavitation device combined an orifice plate and a Venturi tube and was constructed based on the design reported by Flores Alarcón et al. (2022). Temperature during extraction was monitored and controlled in 30 °C via a cooling coil located in the recirculation tank, connected to a refrigerated bath. The effects of ethanol concentration in the solvent (0, 40 and 80%) on saponin extraction (g/L) were evaluated. Liquid samples were collected at specific intervals for saponin quantification.

Total saponin content was determined using the colorimetric method described by Hiai et al. (1976). Briefly, 0.5 mL of sample was mixed with 0.5 mL of 8% (w/v) vanillin solution and 1.5 mL of 70% (v/v) sulfuric acid prepared in ethanol. The reaction mixture was incubated at 60 °C for 10 min, cooled to room temperature, and the absorbance was measured at 531 nm using a Thermo Scientific Genesys 150 UV–Vis spectrophotometer. Quantification was carried out using an oleanolic acid calibration curve, and the results were expressed as grams of oleanolic acid equivalents per liter (g OAE/L).

2.3. Purification by membrane process, adsorption, and liquid-liquid partition

The supernatant obtained after sedimentation was subjected to membrane filtration to concentrate the saponin content in the retentate. A ceramic cross-flow filtration module purchased from Inopor® (Scheßlitz, Germany) was modified to allow the use of both inorganic and polymeric membranes throughout the filtration processes. The module was operated under the following conditions: pressure range 10–15 bar, flow rate 6–7 L·min^{-1}, temperature range 25–30 °C, and a pump rated at 400 V AC, 50 Hz. Tubular ceramic ultrafiltration membranes (Al_2O_3, 250 mm length, 7 mm internal diameter) with pore sizes of 10 and 800 nm were purchased from Inopor® and operating conditions was 10 bar, 25 °C, and a flow rate of 6–7 L·min^{-1}, while a polymeric PES membrane (30 cm length, 4.57 cm external diameter) with a molecular weight cut-off (MWCO) of 500–800 Da were obtained from Synder Filtration (USA) and operation condition was 15 bar, 25 °C, and the same flow rate. The retentate obtained from the nanofiltration (NF) process was recovered and spray-dried using a Pilotech YC-500 (China) under the following conditions: temperature of 170 °C and feed flow rate of 1.5 L/h. This step yielded a saponin-rich powder (SRP), which was subsequently subjected to further purification through macroporous resin (AB-8) adsorption followed by liquid–liquid partitioning.

The SRP was subjected to an adsorption process using AB-8 macroporous resin. The resin was conditioned following the methodology described by Chen et al. (2023). For the adsorption kinetics, 10 g of resin (dry weight) were added to 250 mL of an SRP solution at 10 g/L, and the saponin and phenolic compound concentrations were monitored every two hours over a 24-hour period. The static adsorption capacity of saponin and total phenolic compounds were calculated using the following formula:

$$Q_e(mg/g) = \frac{(C_0 - C_e)V_i}{W} \quad (1)$$

Where C_0 is the initial concentration (mg/L), Ce is the concentration at time t (mg/L), V is the volume (L), m is the mass of resin (g). In order to understand the mechanism involved in the adsorption process, the values were fitted using an adsorption kinetic model:

Pseudo-first order kinetic model:

$$Ln\ (Q_e - Q_t) = LnQ_e - k_1 t \quad (2)$$

Pseudo-second-order kinetic model:

$$\frac{1}{Q_t} = \frac{1}{k_2 Q_e^2} + \frac{t}{Q_e} \quad (3)$$

Intraparticle diffusion kinetic model:

$$Q_t = k_3 t^{0.5} + C \quad (4)$$

where k_1, k_2, and k_3 are the rate constants of the pseudo-first-order model, pseudo-second-order model and intraparticle diffusion model for the adsorption process, respectively, and the constant C (mg/g) represents the boundary layer diffusion effect. Q_e (mg/g) and Q_t (mg/g) are the adsorption capacity values at equilibrium and at various time periods.

To assess desorption capacity, the resin was subjected to sequential washes with 10%, 30%, 50%, 70%, 90% and 100% ethanol every 12 h, after which the saponin concentration and purity were quantified (Chen et al., 2023).

Finally, 50 g of powder was resuspended in 1000 mL of water and mixed with 70 g of resin, allowing the mixture to stand for 24 h under agitation at 180 rpm. After adsorption, the residual liquid was removed, and the resin was sequentially washed with ethanol solutions of increasing concentrations (20%, 40%, 60%, and 80% v/v), each step lasting 24 h. The final extract, obtained from the 80% ethanol wash, was dried to yield a product with a high saponin content.

The SRP was further subjected to liquid–liquid extraction using ethyl acetate as the organic solvent, following the procedure reported by Li et al. (2003). Briefly, 10 g of SRP were dissolved in 100 mL of a 10% (v/v) methanolic solution prepared in distilled water and mixed with 100 mL of ethyl acetate under vigorous agitation. The mixture was allowed to stand until the complete phase separation was achieved. The extraction was repeated until the organic phase became clear and colorless. The combined organic phases were then concentrated by rotary evaporation to remove the ethyl acetate. Subsequently, saponins were recovered from the remaining residue using methanol and dried in an oven at 60 °C.

2.4. Surface tension and critical micelle concentration (CMC)

The surface tension (γ, mN/m) of partially purified saponin extract was measured across concentrations ranging from 0.005 to 5 g/L. Measurements were performed using 30 mL of solution at 25 °C with a KRÜSS Scientific K20 force tensiometer (Krüss, USA) equipped with a standard Wilhelmy plate. Each solution was allowed to equilibrate for 3 min in the measurement vessel before recording the surface tension. The critical micelle concentration (CMC) was determined by identifying the intersection of the pre-micellar and post-micellar linear regions in a plot of surface tension versus the logarithm of saponin concentration (Rai et al., 2023; Randriamamonjy et al., 2022). All measurements were carried out in triplicate to ensure reproducibility.

2.5. Total phenolic content and profile in different extract

The total phenolic content (TPC) of the different extracts (post-membrane filtration, post-adsorption, and post-liquid–liquid partition) was determined using the Folin–Ciocalteu assay, following the methodology described by Huamán-Castilla et al. (2024). Gallic acid (GAE) was used as the standard at concentrations ranging from 0 to 0.04 mg mL^{-1}. For the analysis, 3.75 mL of distilled water, 0.5 mL of sample extract, and 0.25 mL of Folin–Ciocalteu reagent (1 N) were mixed. Subsequently, 0.5 mL of sodium carbonate solution (10% w/v) was added to the reaction mixture. The mixture was kept in the dark at room temperature for 1 h, and absorbance was measured at 765 nm using a UV–Vis spectrophotometer (Genesys 150, Thermo Fisher Scientific, San Jose, CA, USA). Results were expressed as milligrams of gallic acid equivalents (mg GAE) per gram of dry sample.

Specific phenolic compounds were quantified on a Vanquish Flex UHPLC system (Thermo Scientific, Germany) coupled to an Orbitrap mass spectrometer with a HESI-II source (Thermo Scientific, USA). Extracts were purified using Sep-Pak C18 cartridges (Waters) prior to injection of 1 μL onto a Poroshell EC—C18 column (2.1 × 150 mm, 1.9 μm). The mobile phase consisted of solvent A (water with 0.1% formic acid) and solvent B (acetonitrile with 0.1% formic acid), using a gradient of 95:5 (A:B) for 15 min, 60:40 for 18 min, and returning to 95:5 for 20 min, at 0.2 mL/min and 30 °C. Calibration curves were constructed with standard solutions, and results were expressed as mg of phenolic compound/100 g dry sample.

2.6. Antioxidant activity by ORAC of extract of saponins

Oxygen radical scavenging capacity (ORAC) assay analyses of the obtained samples were performed using a microplate reader (Synergy/HTX, Biotek Instruments Inc., Winooski, VT, USA) according to the methodology described by Chirinos et al. (2008). 2,2′-Azo-bis(2-amidinopropane) dihydrochloride (AAPH) was used as the peroxyl radical generator, Trolox as the standard, and fluorescein as the fluorescent probe. Prior to analysis, 55 nM fluorescein and 153 mM AAPH solutions were prepared in 75 mM PBS buffer (pH 7.4). Briefly, 25 μL of sample (blank, Trolox standard, or diluted extract) were mixed with 250 μL of fluorescein in a black 96-well microplate. The mixture was incubated for 10 min at 37 °C before the automated injection of 25 μL of AAPH in the plate reader. Fluorescence was measured at 485 nm (excitation) and 520 nm (emission) every minute for 50 min. Final ORAC values were calculated based on the area under the curve and expressed as μmol Trolox equivalents (TE) per gram of dry sample.

2.7. Cytotoxic activity of saponin extracts in cancer cells

The MCF-7 human breast adenocarcinoma, MDA-MB-231 human triple-negative breast carcinoma, HCT-15 human colorectal adenocarcinoma and A549 human lung carcinoma cell lines were obtained from American Type Culture Collection (ATCC) and cultured in Dulbecco's Modified Eagle's Medium (Sigma-Aldrich) supplemented with 10% fetal bovine serum and 1% of a penicillin–streptomycin solution (Merck). Cells were incubated at 37 °C, 5% CO_2 until optimal confluency (> 80%) was reached for subsequent use.

Cytotoxic activity

The cytotoxic activity of the saponin-rich powder (SRP) with purities of 42% (post-membrane), 65% (post-adsorption), and 75% (post-liquid–liquid extraction) was evaluated in vitro using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay. Stock solutions of SRP at each purity level were prepared in 30% (v/v) dimethyl sulfoxide (DMSO). However, the final concentration of DMSO in the cell culture medium was <1% due to the subsequent serial dilutions. Cells were seeded in 96-well plates at a density of 3×10^4 cells per well and incubated for 24 h. After incubation, SRP solutions at 42%, 65%, and 75% purity were added in two-fold serial dilutions starting from an initial concentration of 1000 $\mu g \cdot mL^{-1}$. The plates were then incubated at 37 °C in a humidified atmosphere containing 5% CO_2.

After 24 h, the culture medium and extracts were removed, and MTT reagent was added to each well. The plates were incubated under the same conditions for 4 h. Subsequently, the MTT solution was discarded, and the resulting formazan crystals were solubilized in DMSO and left to react for 10 min. Absorbance was measured at 575 nm using a Varioskan™ LUX Multimode Microplate Reader (Thermo Fisher Scientific).

The cytotoxic activity was expressed as the logarithm of the concentration (μg/mL), and the half-maximal inhibitory concentration (IC_{50}) was determined from the dose–response curves by comparing treated and untreated cells.

Clonogenic assay

Following the determination of the IC_{50}, a clonogenic assay was performed to evaluate the long-term cytotoxic effects of the SRP samples. This assay measures the reproductive viability and proliferative capacity of single cells after exposure to the different SRP purity levels.

The four cell lines were cultured in separate wells to include a negative control (untreated), a positive control (treated with doxorubicin), and SRP treatments of varying purity, each seeded at an initial concentration of 500 cells per mL. Following treatment, the cells are cultured for 1–3 weeks, with regular medium changes, to allow surviving cells to form colonies. The colonies are then fixed. For staining, 0.5% (w/v) crystal violet was used. The culture medium was removed, cells were washed with physiological saline, and 3 mL of crystal violet solution were added to each well. Plates were agitated at 100 rpm for one hour. After incubation, the dye was discarded, stained colonies were counted, and data were analyzed using one-way ANOVA.

3. Result and discussion

3.1. Composition of quinoa residues powder

Quinoa grains (Fig. 1A) possess an outer layer rich in saponins. To remove this layer, the grains undergo a mechanical scarification process followed by washing, resulting in saponin-free grains as shown in Fig. 1B The generated residue corresponds to approximately 8% of the total grain weight. Considering Peru's quinoa production in 2024 (around 144,600 tons), this by-product is abundantly available. However, this residue is currently underutilized in Peru and other countries due to its bitter taste caused by saponins. Therefore, removing the remaining saponins is essential to valorize this by-product, enabling its use in alternative applications such as bioprocesses.

The quinoa saponin residues were primarily composed of carbohydrates (57.52%) and ash (20.21%) (Table 1). As shown in the table, the saponin content in the residue obtained from the yellow-colored Marangani variety was approximately 25% (w/w). This value is comparable to those reported by Zhou et al. (2023), who found average saponin contents of 23% and 20% in quinoa bran cultivated in the Shanxi and Gansu provinces of China, respectively. These values are considerably higher than those reported by Lim et al. (2020), who observed 8.34% in quinoa bran and 1.60% in quinoa pericarp. In that study, the quinoa variety was not specified but corresponded to quinoa cultivated in Hongcheon, Korea, which is likely a low-saponin type. The higher saponin content observed in our sample is mainly attributed to varietal characteristics and growing conditions, as the Marangani variety was cultivated at elevations above 3800 m above sea level. When comparing the saponin content of the quinoa hull with that of the whole grain, the hull exhibits a much higher concentration; the whole grain contains up to approximately 5% of saponins, as reported by Ruiz et al. (2017). Therefore, the hull can be regarded as a concentrated source of saponins and a promising material for valorization.

Table 1
Proximate physicochemical composition of *Chenopodium quinoa* residue powder.

Compositional analysis	%
Carbohydrate	57.52 ± 0.01
Protein	7.50 ± 0.03
Fat	1.70 ± 0.12
Ash	20.21 ± 0.09
Moisture	5.77 ± 0.23
Saponin	25 ± 0.32
Total phenolic compounds (mg GAE/g)	10.72 ± 0.01
Elemental analysis	**%**
N	1.40 ± 0.06
C	44.49 ± 0.25
H	6.05 ± 0.03
S	0.14 ± 0.01

Regarding the protein content, the residue contained 7.5%, which is comparable to the 8.39% reported for quinoa bran produced in Gansu, China (Zhou et al., 2023). The relatively high ash content may be attributed to the accumulation of dust and soil particles during post-harvest handling and storage, as the material is often exposed to environmental conditions.

Another relevant component was the total phenolic content, which reached 10.72 mg GAE/g of bran, substantially higher than values reported in previous studies. For instance, Zhou et al. (2023) reported approximately 6 mg GAE/g in quinoa bran cultivated in Qinghai, China. This discrepancy may be attributed to variety and other several factors, particularly altitude-related environmental stress, and increased UV-B radiation exposure. These conditions stimulate the plant's defense mechanisms, leading to enhanced synthesis of phenolic compounds and flavonoids, which function as antioxidant and photoprotective molecules, protecting plant tissues from oxidative and radiation-induced damage (Hinojosa et al., 2018; Miranda et al., 2012; Tang & Tsao, 2017).

3.2. Saponin extraction using hydrodynamic cavitation

Saponins were extracted by hydrodynamic cavitation (HC) using hydroalcoholic solutions as solvents. Among the conditions evaluated, an 80% (v/v) ethanol solution exhibited the highest extraction efficiency, yielding a saponin concentration of 16 g/L, which was 14% higher than that obtained using 40% ethanol or water alone. As shown in Fig. 2, saponin concentrations rapidly increased to approximately 10 g/L within the first 5 min for all solvent systems. This rapid extraction can be attributed to the high solubility of saponins and the predominantly

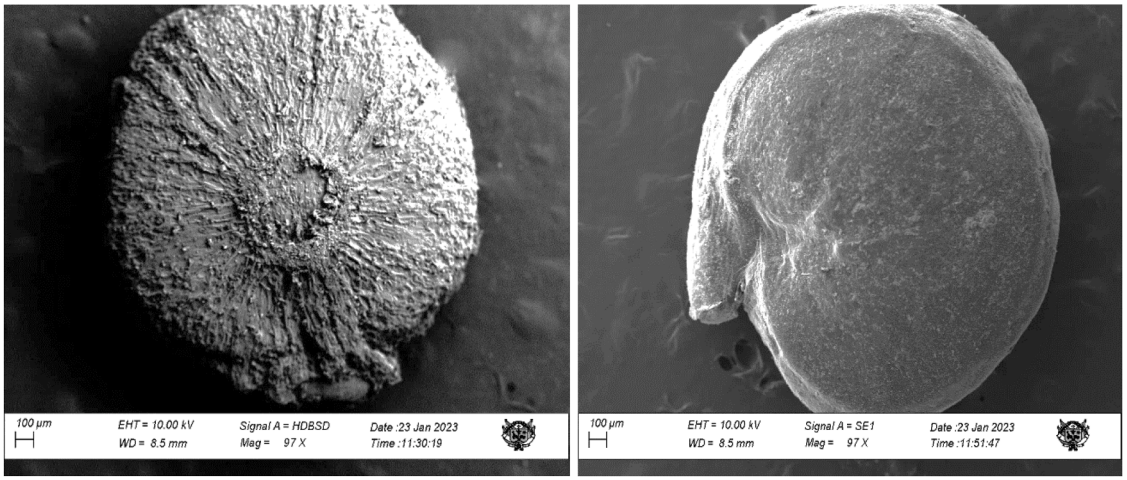


Fig. 1. Scanning electron microscopy (SEM) images of (A) whole quinoa seed showing the saponin-rich outer layer, and (B) grain after scarification and washing, revealing the saponin-free surface.

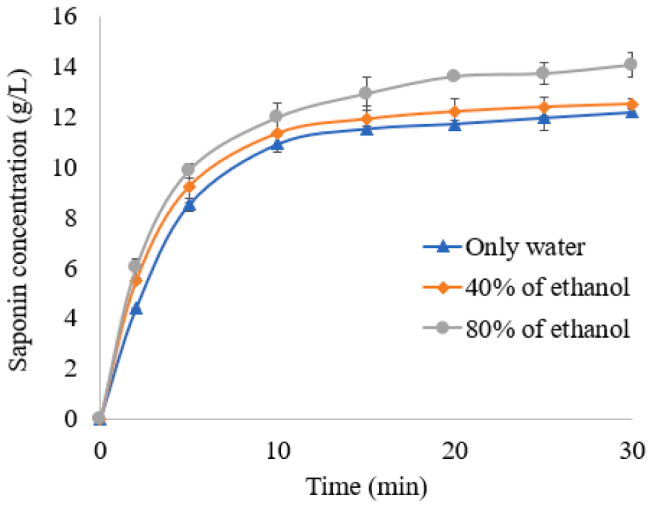


Fig. 2. Saponin concentration in the extraction solvent in a hydrodynamic cavitation process.

powdered particle size of the raw material, which facilitated fast dissolution and efficient mass transfer. In contrast, at longer extraction times, higher ethanol concentrations promoted additional saponin recovery, likely by enhancing the release of saponins associated with other cellular components, ultimately reaching an extraction efficiency of 66.54 ± 0.58%. Although no similar studies on saponin extraction using HC have been reported, comparable trends have been observed in ultrasound-assisted saponin extraction from *Xanthoceras sorbifolium* Bunge leaves (Chen et al., 2023), a technology based on comparable cavitation-driven physicochemical and mechanical effects. In that study, improved extraction performance was achieved after 30 min of processing using 70–80% ethanol and particle sizes below 0.25 mm, enabling extraction yields exceeding 7%. Importantly, the use of 80% ethanol in the present work also limits the co-extraction of highly water-soluble compounds such as starches, sugars, and proteins, which are undesirable during downstream purification, particularly in membrane-based separation processes.

Overall, the results indicate that prolonged exposure to HC significantly enhances saponin release when ethanol is employed as the extraction solvent. During HC, microbubbles are generated under low-pressure conditions and violently collapse upon entering high-pressure regions, producing localized hotspots with high temperature and pressure (Ranade et al., 2022). These extreme microenvironments disrupt cellular structures and intensify mass transfer, thereby facilitating the release of intracellular bioactive compounds (Imuetinyan et al., 2022). In addition, the intense turbulence associated with cavitation likely accelerates extraction by improving solvent penetration and increasing solvent–solid contact.

A comparable mechanism was described by Imuetinyan et al. (2022), who reported that ultrasound-assisted extraction in deionized water induced rapid fragmentation of *Vernonia amygdalina* leaves and direct solubilization of sapogenins. This behavior was attributed to particle size reduction driven by shockwaves generated during bubble collapse, which enhanced extraction kinetics and yields by increasing the available surface area. Therefore, considering the complex composition of the present raw material including starch, proteins, phenolic compounds, and structural components such as lignin, cellulose, and hemicellulose it is plausible that cavitation similarly facilitates saponin release by disrupting cell wall architecture and promoting mass transfer.

To date, HC has not been reported for saponin extraction, particularly from quinoa processing residues. Therefore, further studies are required to systematically evaluate key operational parameters, including inlet pressure, cavitation device configuration, solid loading, and solid-to-liquid ratio. Considering its advantages reported in other extraction processes, HC represents a promising approach due to its operational simplicity, energy efficiency, and strong potential for industrial-scale implementation, advantages discussed extensively in the review of Xia et al. (2025) and Zoglopiti et al. (2025).

3.3. Purification by membrane process, adsorption, and liquid-liquid partition

Membrane filtration

Filtration experiments were conducted using Al_2O_3 membranes with nominal pore sizes of 800 nm (MF), 10 nm (UF) as well as a polyamide thin-film composite (PA-TFC) membrane with a molecular weight cut-off of 600–800 Da. The summarized results are shown in Fig. 3. The use of 800 nm and 10 nm Al_2O_3 membranes in the MF and UF steps led to an increase in saponin purity to 33.94% and 35.6%, respectively. Subsequently, the permeate was subjected to nanofiltration using a 5 kDa membrane, resulting in a further increase in purity to 37% in the retentate. Finally, filtration with the 600–800 Da PA-TFC membrane enabled effective saponin retention, achieving a purity of 40-42% and a saponin concentration of 33 g/L in the extract. It is important to emphasize that the present study was conducted in a 6 L-capacity crossflow filtration system using commercial tubular membranes, which enhances the practical relevance and scalability of the results. To the best of our knowledge, no membrane-based purification studies have previously been reported for saponins derived from quinoa processing residues. Although direct comparisons are therefore limited, similar purification trends have been observed in other plant matrices. For example, Yang et al. (2025) reported microfiltration-based purification of saponins from fenugreek seeds, where the use of a 50 nm membrane (membrane characteristics not detailed) increased saponin purity from 22.03% to 41.03%. Although saponin purities were not reported for the subsequent UF and NF steps in the same study, the authors indicated that 86% of impurities were removed using an 8–10 kDa membrane and 91% using a 200 Da membrane. However, saponin recovery decreased markedly along the filtration sequence (NF < UF < MF), resulting in recoveries of approximately 13% for UF (8 kDa) and only 3% for NF (200 Da). Nanofiltration has also been employed for saponin separation. Li et al. (2025b) reported total saponin rejections of 98% using a 100 Da (PA-TFC membrane) and 95% using an 800 Da (PA-TFC membrane), whereas sugar rejection at 800 Da was limited to 43%, indicating preferential retention of saponins over low-molecular-weight carbohydrates. These results are consistent with those obtained in the present study, where the 600–800 Da (PA-TFC membrane) achieved approximately 93% rejection of total saponins. This selective behavior can be attributed to the relatively high molecular weight and amphiphilic structure of saponins compared to sugars, small phenolic compounds, and other compounds, enabling effective separation by nanofiltration while allowing partial passage of smaller, more hydrophilic compounds (García Bustos et al., 2026). Consequently, the use of membranes in the 600–800 Da range appears particularly suitable for enhancing saponin purity while mitigating excessive losses and maintaining reasonable permeate fluxes (1 L/h).

Adsorption AB-8 resin

The adsorption results are presented in Fig. 4A. As shown, the resin adsorbed approximately 79% of the saponins within 4 h, increasing to >90% after 8 h. These results are consistent with previously reported data for *Xanthoceras sorbifolium* Bunge leaves (Chen et al., 2023), in which an adsorption rate of approximately 80% was achieved within 4 h, with a maximum adsorption efficiency of 84.94% after 6 h using AB-8 resin. Moreover, saponin purification from *Dioscoreae hypoglaucae* rhizomes using the same resin reached approximately 95% (Qin et al., 2025). With respect to total phenolic content (TPC), the adsorption efficiency of AB-8 resin reached approximately 97%, which is higher than that reported by Chai et al. (2025), who observed an adsorption rate of around 60% for flavonoids extracted from white tea.

The adsorption kinetics data were fitted to the pseudo-first-order

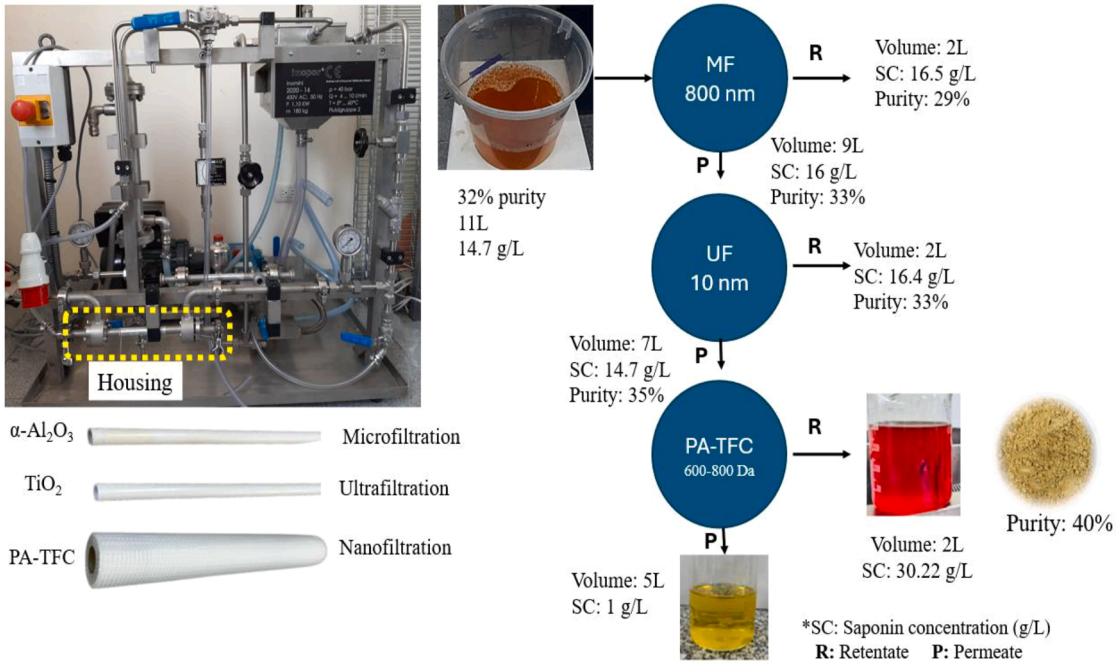


Fig. 3. Saponin concentration and purity obtained in each step of filtration using inorganic membranes (800 nm and 10 nm) and in the retentate of the PA-TFC (600–800 Da).

(PFO), pseudo-second-order (PSO), and intraparticle diffusion models, and the results are presented in Fig. 4B Among the tested models, the PSO model provided the best fit, exhibiting the highest linear correlation coefficient ($R^2 = 0.9998$). The corresponding kinetic parameters were $k_2 = 0.036\ g{\cdot}mg^{-1}{\cdot}h^{-1}$ and $Q_e = 56.84$ mg/g, which is in close agreement with the experimental value (55.54 mg/g). This excellent agreement indicates that the adsorption process is predominantly governed by chemisorption, involving electron sharing or exchange between the adsorbent and adsorbate. The PSO model accurately predicts the equilibrium adsorption capacity ($Q_e \approx 56.84$ mg/g) and suggests rapid uptake until saturation of the active sites.

In contrast, the PFO model showed a poor fit to the experimental data, with a low correlation coefficient ($R^2 = 0.5087$) and estimated parameters of $k_1 = 0.044\ h^{-1}$ and $Q_e = 25.76$ mg/g, which significantly deviated from the experimental value. Furthermore, the intraparticle diffusion plot (Fig. 4B) exhibited two distinct linear regions, indicating a multi-step adsorption mechanism. The first stage (0–8 h) corresponds to rapid adsorption on the external surface and diffusion through the boundary layer, while the second stage (8–24 h) represents slower intraparticle diffusion within the resin pores. The non-zero intercepts of the linear segments indicate that intraparticle diffusion is not the sole rate-limiting step and that film diffusion also plays a significant role in the overall adsorption process.

As shown in Fig. 4C, the desorption rate of saponins increased with increasing ethanol concentration, reaching high values at 80–90% (v/v) ethanol, while decreasing markedly under anhydrous ethanol conditions. Accordingly, an 80% (v/v) ethanol–water solution was identified as the optimal eluent for saponin desorption from AB-8 resin, achieving a desorption efficiency of approximately 85%. This behavior can be attributed to the progressive decrease in eluent polarity with increasing ethanol concentration, which favors the elution of saponins from the nonpolar resin matrix (Chai et al., 2025; Chen et al., 2023; Qin et al., 2025).

In contrast, total phenolic content (TPC) exhibited a different desorption pattern. As also shown in Fig. 4C, higher desorption efficiencies were obtained at lower ethanol concentrations, with a maximum desorption rate of approximately 50% achieved using a 40% (v/v) ethanol–water solution, followed by a decline at higher ethanol concentrations. This trend suggests that lower ethanol concentrations enhance the solubility of phenolic compounds, thereby promoting their desorption from the resin (Chai et al., 2025).

Finally, the extract obtained during the desorption process was dried, and the saponin purity of the resulting powder was determined; the results are presented in Fig. 4D As shown, the highest saponin purity (67.39%) was achieved using 90% (v/v) ethanol for desorption; however, the resulting extract concentration was low (0.35 g/L), leading to a limited recovery of saponin powder. In contrast, desorption with 50% (v/v) ethanol produced a lower saponin purity (54%) but yielded a substantially higher amount of recovered powder, with an extract concentration of 2.12 g/L saponin. The observed increase in saponin purity at higher ethanol concentrations can be further explained by the trends shown in Fig. 4C, where phenolic compounds are preferentially removed during the initial washing steps using lower ethanol concentrations.

Purification by L-L partition

Liquid–liquid partition using ethyl acetate was performed on the saponin-rich powder obtained after membrane filtration, which initially exhibited a purity of 42%. It should be noted that the extraction was carried out in a ternary system consisting of water with 10% methanol and ethyl acetate, rather than a simple binary water–ethyl acetate mixture, making the organic phase semi-polar rather than fully nonpolar (Rao & Rao, 1957). The presence of methanol modifies the liquid–liquid equilibrium, increasing the mutual solubility of the phases and allowing saponins with intermediate polarity to partially partition into the organic phase, while highly polar impurities remain predominantly in the aqueous–methanol phase.

Following solvent removal by rotary evaporation, the resulting powder reached a saponin purity of 75.5 ± 0.1%, surpassing the values obtained through resin adsorption (65%). The high saponin content observed in the semi-polar ethyl acetate fraction likely reflects the intermediate polarity of the saponins present in the saponin-rich powder (SRP, 42% purity). The increase in saponin purity to 75% can be attributed to the reduced solubility of highly polar compounds such as organic acids, polysaccharides, and proteins which remain predominantly in the aqueous phase (Chua et al., 2019; Ho et al., 2022). In contrast, relatively less polar constituents, including terpenoids and saponins, preferentially partition into the organic phase. However,

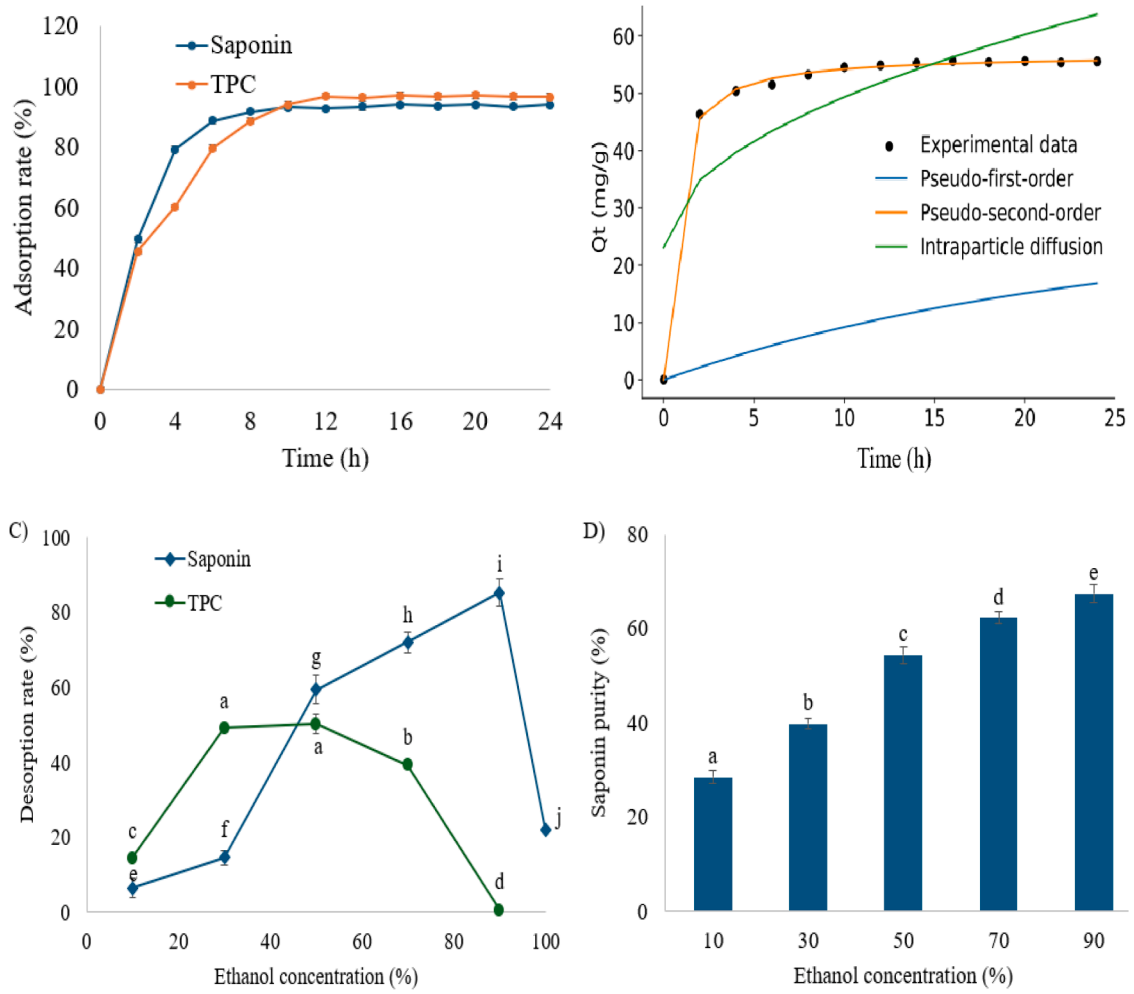


Fig. 4. Purification of saponins by adsorption using AB-8 resin: Experimental adsorption kinetics (A), Kinetic model fitting (B), Desorption efficiency (%) at different ethanol concentrations (v/v) (C), Saponin purity of the recovered powder after desorption (D).

achieving efficient purification requires a prior partial purification step through membrane filtration, as liquid–liquid extraction applied directly to the crude quinoa residue powder yielded only 33% saponin purity in the ethyl acetate phase.

To date, no studies have been reported that allow for a direct comparison of these results particularly those involving quinoa residues, which contain very small granules of starch, proteins, phenolic compounds, and saponins, among other components that complicate purification. Nevertheless, ethyl acetate has been successfully employed in several liquid–liquid partitioning processes for plant extracts. For example, Ho et al. (2022) reported the use of ethyl acetate for the extraction of phytochemicals from *Peperomia pellucida* (L.) Kunth, obtaining a fraction with a high saponin content (249 QSE/g, expressed as Quillaja saponin equivalents). This value was significantly higher than those achieved with other solvents, including methanol, hexane, chloroform, *n*-butanol, and water, which yielded a maximum of 80 QSE/g when using *n*-butanol.

Overall, the integrated process is summarized in Fig. 5. As shown, the developed methodology primarily involves hydrodynamic cavitation for extraction and membrane technology for partial purification, yielding a powder with 42% saponin purity. These technologies exhibit good scalability, having been preliminarily scaled up to 50 L for the cavitation process and 150 L for the membrane process (data not shown). This level of purity is suitable for agricultural applications, including use as a biostimulant, plant growth promoter, and for pest and pathogen control, comparable to commercial products such as QL Agri® 35, which contains 35% (w/v) Quillaja saponin extract (*Quillaja saponaria*). However, if higher purity is required, the process can be extended to include adsorption and liquid–liquid partition steps, enabling the production of saponin-rich powders suitable for use in natural cosmetics, phytotherapeutic, or pharmaceutical formulations.

3.4. Critical micelle concentration (CMC) analysis

The critical micelle concentration (CMC) analysis indicates that the purification strategy significantly influences the interfacial behavior of quinoa saponins (Fig. 6). The extract purified by AB-8 resin adsorption (65% purity) exhibited a lower CMC (0.33 g/L) than the extract obtained by liquid–liquid partitioning with ethyl acetate (75% purity; CMC = 0.50 g/L), although both samples reached a similar minimum surface tension (~35 mN/m). This observation suggests that increasing saponin purity does not necessarily result in enhanced micellization efficiency. Therefore, these differences may be attributed to variations in the sapogenin profile and/or to the presence of co-extracted surface-active compounds (phenols, glycosides, organic acids), as the solubility and selective recovery of these components are influenced by the polarity of the solvent used during purification. Such compositional differences may promote or disrupt synergistic interactions during micelle formation. Further characterization of the sapogenin (aglycone) profiles of the different fractions is required to fully elucidate the structure–function relationships governing the observed interfacial properties.

The CMC values obtained in this study are comparable to those

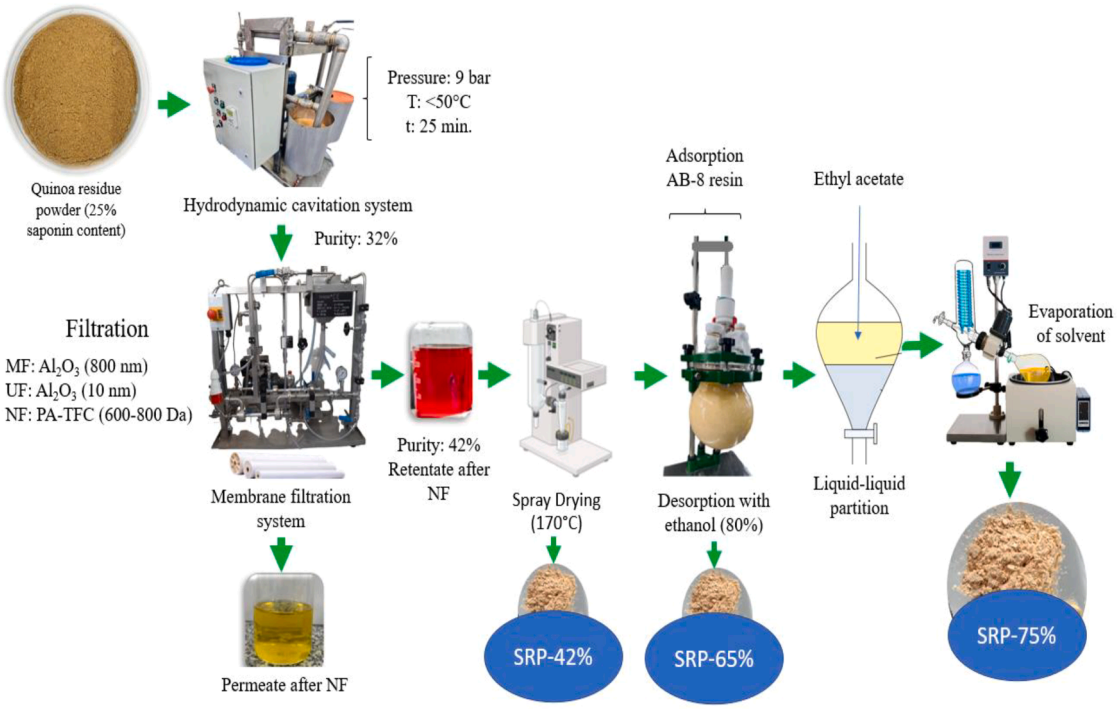
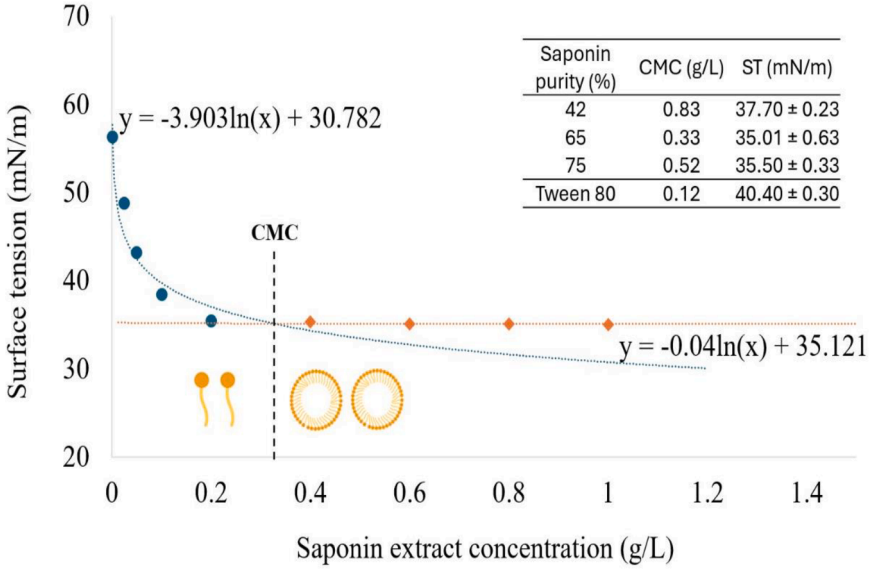


Fig. 5. Integrated process combining cavitation, membrane filtration, adsorption, and liquid–liquid partition to produce saponin-rich powders.



Saponin purity (%)	CMC (g/L)	ST (mN/m)
42	0.83	37.70 ± 0.23
65	0.33	35.01 ± 0.63
75	0.52	35.50 ± 0.33
Tween 80	0.12	40.40 ± 0.30

Fig. 6. CMC values for rich saponins extracts obtained through tensiometer method.

reported for Quillaja saponins (CMC ≈ 0.28 g/L) and saponins from *Furcraea foetida* (CMC ≈ 0.24 g/L) (Randriamamonjy et al., 2022), although the latter exhibited higher equilibrium surface tension values. In contrast, saponins extracted from *Camellia oleifera* shells required substantially higher concentrations (1.3 g/L) to reduce the surface tension to 33 mN/m (Ning et al., 2023). Such differences may be associated with variations in aglycone composition and purification method used. For instance, quinoa saponins are primarily composed of oleanolic acid, hederagenin, and phytolaccagenic acid (Lim et al., 2020), whereas Quillaja saponins mainly contain quillaic acid, gypsogenin, phytolaccinic acid, and echinocystic acid as dominant aglycones (Morais et al., 2025).

Overall, the results indicate that quinoa saponins exhibit interfacial performance comparable to, or in some cases exceeding, that of the synthetic surfactant Tween 80, highlighting their potential as efficient and sustainable biosurfactants.

3.5. *Determination of total phenolic content and profile*

The total phenolic content (TPC) of the untreated quinoa bran powder and the saponin-rich powders (42%, 65%, and 75% purity) was determined. The untreated quinoa residue powder exhibited a TPC of 10.72 ± 0.09 mg GAE/g, whereas powders containing 42%, 65%, and 75% saponins reached 12.31 ± 0.26, 23.82 ± 0.01, and 23.66 ± 0.18 mg GAE/g, respectively. These results demonstrate a clear increase in phenolic content with rising saponin concentration in the powders.

The extract with 42% saponin content was obtained by nanofiltration using a membrane with a molecular weight cut-off (MWCO) of 600–800 Da, which concentrated the phenolic compounds, mainly glycosylated flavonoids and, to a lesser extent, aglycone flavonoids due to their lower molecular weight. This behavior is primarily related to the molecular characteristics of phenolic compounds and their electrostatic and hydrophobic interactions with the membrane (Zagklis & Paraskeva, 2015). Glycosylated flavonoids, such as rutin (MW ≈ 610 Da), were retained by the membrane, reaching 9.98 mg/g in the powder an increase of 63% compared to the untreated sample. In contrast, smaller aglycones like quercetin (MW ≈ 302 Da) were able to permeate through the membrane, resulting in a slightly lower concentration (3.10 mg/g) than in the untreated powder. Consequently, glycosylated phenolics became moderately enriched in the retentate. No significant differences were observed for other phenolic compounds listed in Table 2.

The powder obtained after the nanofiltration process was subjected to an adsorption step using macroporous resin AB-8 to achieve higher saponin purity. The application of AB-8 resin for the purification and concentration of phenolic compounds has been extensively documented (Chai et al., 2025; Min & Xiaojing, 2025; Zhao et al., 2011). In this study, enrichment was mainly observed for rutin and quercetin, and to a lesser extent for kaempferol and procyanidin A2. The pore size of AB-8 is well suited for the adsorption and purification of flavonoids and their glycosides. Moreover, glycosylated flavonoids become increasingly polar as more sugar moieties are attached to their backbone, which enhances their adsorption onto the weakly polar AB-8 resin through combined hydrophobic and π–π interactions (Bajkacz et al., 2021; Li & Chase, 2010).

Finally, the powder obtained after the nanofiltration process was subjected to a liquid–liquid partition using ethyl acetate. No significant differences were observed in the phenolic profile, which can be attributed to the high polarity of the phenolic compounds present in the extract.

3.6. Antioxidant activity of saponin extracts

The antioxidant capacity of the quinoa residue powder and the saponin-rich fractions (40%, 65%, and 75% purity) was assessed using the oxygen radical absorbance capacity (ORAC) assay. The results revealed a progressive increase in antioxidant capacity with the enrichment of saponins and co-extracted phenolic compounds. The untreated quinoa residue extract exhibited an antioxidant activity of 212.51 ± 18.09 μmol TE/g. After extraction and purification by filtration, the resulting powder (40% purity) displayed an enhanced antioxidant activity of 427.13 ± 25.25 μmol TE/g. The powder with 65% purity reached 538.94 ± 65.19 μmol TE/g, while the fraction with 75% purity obtained through liquid–liquid extraction showed the highest value, 614.52 ± 11.44 μmol TE/g. Although the increase in antioxidant capacity followed the rise in saponin content, this enhancement may also be attributed to synergistic contribution of multiple bioactive compounds present in the extract, particularly phenolic compounds like rutin and quercetin, which remained in the purified fractions and are known for their strong radical-scavenging activity (Abderrahim et al., 2015; Yang et al., 2022; Zhou et al., 2023). In addition, *C. quinoa* saponins are composed of triterpenoid sapogenins such as hederagenin, oleanolic acid, phytolaccagenic acid, and serjanic acid, which have been reported to exhibit antioxidant properties (Lim et al., 2020). For example, the combination of hederagenin and its glycoside isolated from quinoa enhanced in vitro antioxidant activity (Zhang et al., 2024). Similarly, oleanolic acid has demonstrated antioxidant activity comparable to or even greater than certain commercial oxidizing agents such as tert-butyl hydroperoxide (tBHP) (Wang et al., 2010). To date, no studies have evaluated the antioxidant capacity of extracts from residues at different purity levels; previous studies have focused solely on determining the antioxidant capacity of quinoa from various varieties (Yang et al., 2024) or crops from different regions, such as China (Zhou et al., 2023), or different plant parts (Lim et al., 2020). In general, quinoa bran extracts have shown higher antioxidant activity as assessed by DPPH radical-scavenging activity, ABTS free radical-scavenging activity (Lim et al., 2020) or Ferric Ion-Reducing Antioxidant Power (FRAP) (Yang et al., 2024).

Therefore, the obtained extract, rich in saponins and co-extracted polyphenolic compounds, exhibits strong antioxidant potential. These bioactive properties could be harnessed for the development of diverse value-added products, including natural cosmetics (Kanlayavattanakul et al., 2024), phytotherapeutic or pharmaceutical formulations (Hovaneț et al., 2022), and biofungicides or biopesticides for agricultural applications (Taglienti et al., 2025).

Table 2
Phenolic profile of QPR and saponin rich powder.

Components	Saponin-rich powders			
	QRP* (mg/100 g)	40% (mg/100 g)	65% (mg/100 g)	75–80% (mg/100 g)
Gallic acid	0.08	0.11	0.21	0.20
Catechin	0.02	0.02	0.03	0.03
Caffeic acid	0.03	0.05	0.07	0.07
Procyanidin B2	0.02	0.03	0.07	0.07
Epicatechin	0.01	0.03	0.28	0.28
Vanillic acid	0.06	0.28	0.37	0.37
Rutin	3.68	9.98	11.83	11.72
Procyanidin A2	0.25	0.08	0.88	0.87
Resveratrol	0.00	0.01	0.04	0.04
Quercetin	3.42	3.10	4.39	4.35
Kaempferol	0.94	0.95	1.28	1.27

* QRP: Quinoa residue powder – untreated.

3.7. Cytotoxic and clonogenic effect of saponin rich extracts

The cytotoxic effects of saponin-rich powders with different purities were evaluated and the results are shown in Fig. 7. The 42% SRP extract obtained after membrane filtration exhibited cytotoxic activity against the MCF-7, MDA-MB-231, and HCT-15 cancer cell lines, with IC_{50} values of 183.82 ± 3.30, 821.31 ± 3.30, and 1326.00 ± 4.50 μg/mL, respectively. In contrast, no cytotoxic activity was observed in the A549 cell line treated with the 42% saponin extract.

The 65% SRP, obtained after AB-8 resin adsorption, showed higher cytotoxic activity compared to the 42% and 75% SRP in the MDA-MB-231, HCT-15, and A549 cell lines, with IC_{50} values of 84.87 ± 2.2, 492.34 ± 4, and 735.22 ± 4.6 μg/mL, respectively. In MCF-7 cells, the IC_{50} value was 491.37 ± 3.1 μg/mL, which was higher than those obtained with the 42% and 75% saponin extracts.

The 75% SRP, obtained after liquid–liquid extraction, exhibited cytotoxic activity in 3 of the 4 tested cell lines, with IC_{50} values of 764.23 ± 4.9 μg/mL for MDA-MB-231, 628.51 ± 2.6 μg/mL for HCT-15, and 144.33 ± 2.7 μg/mL for MCF-7 (the lowest among the three purities tested). As with the 42% SRP, no cytotoxic activity was observed against A549 cells, suggesting that cytotoxicity activity in specific cell lines depends not only on total saponin content but also on the specific saponin composition and co-extracted bioactive compounds, which vary according to the extraction or purification method.

Clonogenic assay was also performed. In all cases, the negative control maintained a survival rate above 90%, whereas the positive control exhibited almost complete inhibition of colony formation. In most cases, SRP at 42% purity produced lower inhibition compared to SRP at 65% and 75%.

In A549 cells, treatment with 65%-purity SRP reduced colony formation to 26.6 ± 2.7%, compared to 95.9 ± 3.6% in the negative control. In MCF-7 cells, the greatest reduction in colony formation was observed with 75%-purity SRP (66.7 ± 1.6%), while 65%-purity SRP showed the lowest inhibition (90.6 ± 1.1%). In MDA-MB-231 cells, SRP

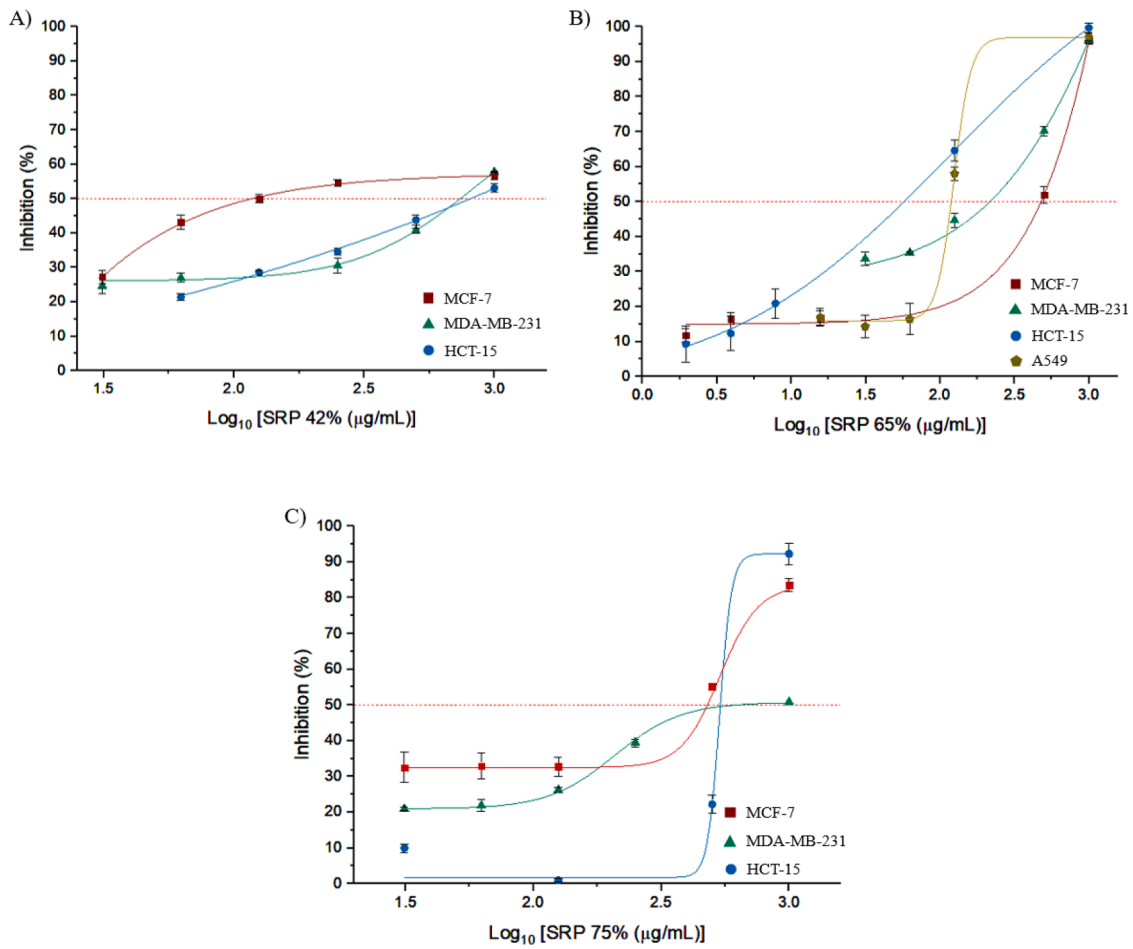


Fig. 7. Cytotoxic activity of saponin rich powder at different purity levels: 42% (A), 65% (B) and 75% (C) and their percentage of inhibition in MCF-7, MDA-MB-231, HCT-15, and A549 cell lines.

at 65% purity demonstrated the strongest inhibitory effect (5.4 ± 5.7%), followed by 75% (20.4 ± 4.1%) and 42% (39.8 ± 4.9%). Similarly, in HCT-15 cells, 65%-purity SRP was the most effective treatment, reducing colony formation to 13.2 ± 2.5%, followed by 75% (23.3 ± 3.4%) and 42% (50.7 ± 5.7%), indicating that the antiproliferative effect is associated with the purity level of the SRP.

The Tukey post hoc test confirmed that the differences between treatments and controls were statistically significant ($p < 0.05$). Overall, a purity-dependent trend was observed, in which SRP with higher purification levels exerted a more pronounced cytotoxic effect on the clonogenic capacity of the cells (Fig. 8). This behavior suggests that the relative concentration of bioactive compounds, such as triterpenoid sapogenins, increases with purity, thereby enhancing the inhibition of cell growth in most of the evaluated cell lines.

The cytotoxic activity of saponins depends on several structural and chemical factors, including their charge, the presence or absence of specific aglycones or sugar moieties, as well as the biological source from which they are extracted. Different triterpenoid sapogenins, such as oleanolic acid (OA), ursolic acid (UA), and hederagenin (HED), have been reported to exhibit cytotoxic activity against various cancer cell lines, including A549 (lung), HeLa (cervical), HepG2 (liver), and SH-SY5Y (neuroblastoma). Among these, UA showed the strongest cytotoxic effect in HeLa and SH-SY5Y cells, with IC_{50} values of 11.2 ± 0.05 and 6.9 ± 0.05 µM, respectively, whereas OA exhibited the highest potency in A549 cells (IC_{50} = 21.9 ± 0.05 µM) (Carpio-Paucar et al., 2023). Semi-purified saponin extracts obtained from *Holothuria poli* demonstrated strong cytotoxic activity against colorectal cancer cell lines HCT-116, HT-29, and T84, with IC_{50} values of 36.05 ± 0.47, 31.41 ± 2.2, and 34.79 ± 0.9 µg/mL, respectively. However, in the ovarian cancer cell line EFO-27, the same extract displayed lower cytotoxicity, with an IC_{50} value of 94.65 ± 0.00 µg/mL (Mert-Ozupek et al., 2022). These findings suggest that extracts containing multiple saponin fractions may act synergistically, enhancing their overall cytotoxic effects. Similarly, saponin-rich fractions extracted from *Gymnema sylvestre* (GSSRF) exhibited cytotoxic activity against breast cancer cell lines MCF-7 (IC_{50} = 63.77 ± 0.23 µg/mL) and MDA-MB-468 (IC_{50} = 103.14 ± 1.05 µg/mL), further supporting the potential role of saponins as bioactive compounds with selective antitumor properties (Ghosh et al., 2023).

Finally, the saponin-rich extracts (65% and 75% purity) also contained phenolic compounds, primarily glycosylated forms such as rutin and quercetin, which have been reported to exhibit cytotoxic activity against MCF-7 and MDA-MB-231 breast cancer cell lines (Chekuri et al., 2025), with IC_{50} values of 22.31 ± 1.28 µg/mL (MCF-7) and 20.43 ± 0.81 µg/mL (MDA-MB-231) after 24 h. The comparatively higher IC_{50} values observed in the present study may be attributed to the lower purity of the evaluated extracts. Moreover, the rutin concentration in the 65% and 75% purity samples, estimated at approximately 0.12 µg/mL at a total extract concentration of 100 µg/mL of SRP, is substantially lower than that tested by Chekuri et al. (2025), who used purified rutin.

4. Conclusion

From an industrial perspective, the results demonstrate that quinoa residues generated during scarification can be effectively valorized into saponin-rich extracts with significant commercial potential. The

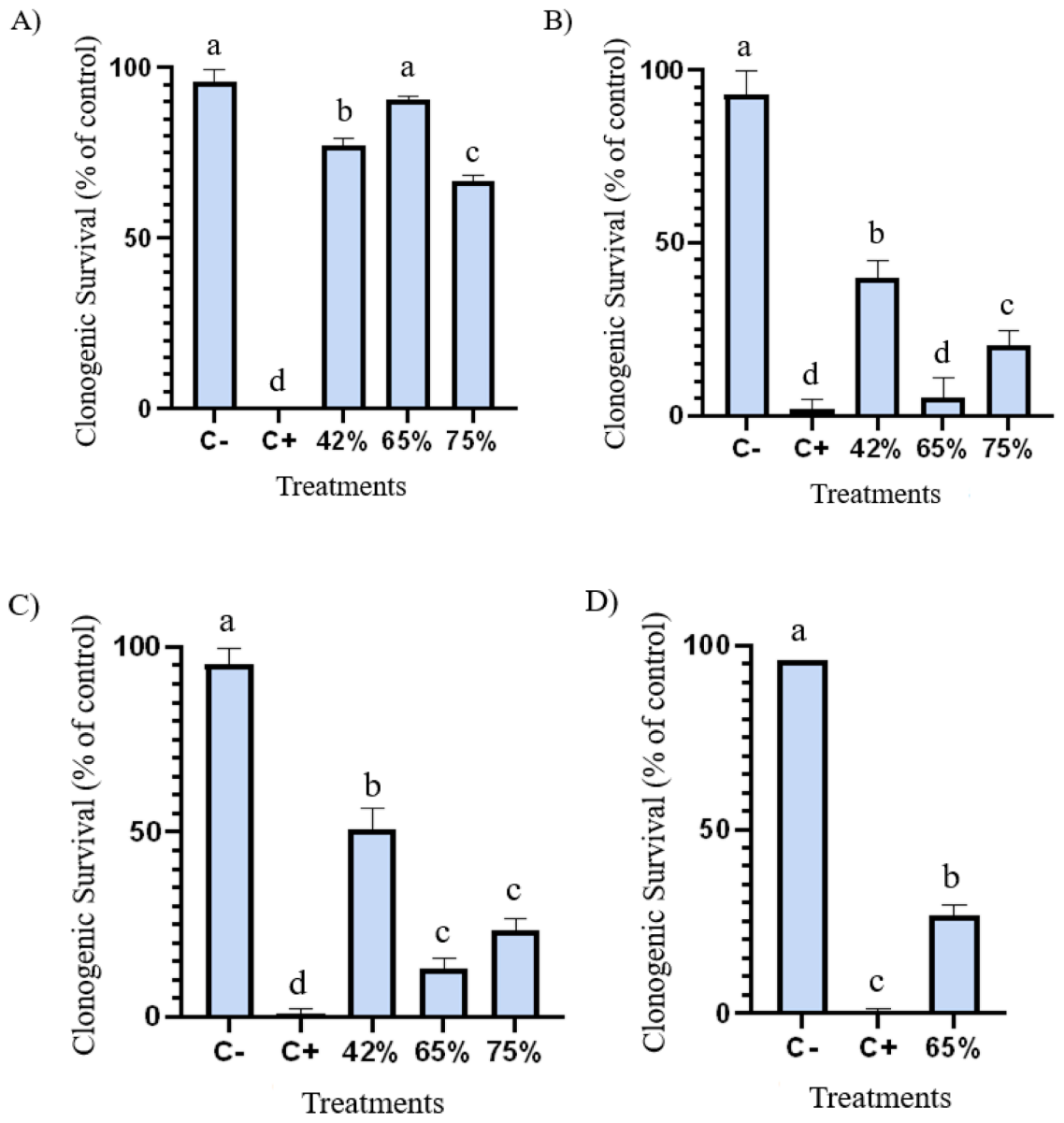


Fig. 8. Clonogenic survival of MCF-7 (A), MDA-MB-231 (B), HCT-15 (C), and A549 (D) cells treated with saponin rich powders of different purity. Different letters indicate statistically significant differences ($p < 0.05$).

proposed process combines hydrodynamic cavitation and membrane filtration both scalable and industry-compatible technologies with downstream adsorption and liquid–liquid partitioning, enabling the selective production of fractions with varying saponin purities. High-purity fractions are particularly relevant for applications in surfactant formulations, antioxidant systems, and bioactive ingredients with reported cytotoxic activity, although further validation is required to confirm their suitability for these uses. Importantly, extracts with intermediate purities (42–65%) may be directly suitable for agricultural applications, such as bio-inputs or plant protection formulations, reducing the need for extensive purification. Overall, this study outlines a technically feasible and scalable valorization route with clear potential for pilot-scale implementation, contributing to the sustainable management of quinoa processing by-products and supporting circular economy strategies in agro-industrial systems.

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Declaration of generative AI in scientific writing

During the preparation of this work the author(s) used partially ChatGPT 4.0 only in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Ethical statement - studies in humans and animals

The authors declare that no experiments were conducted on animals in this research.

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Declaration of competing interest

The authors declare that they have no competing interests

Data availability

Data will be made available on request.

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