

Article

Determination and Metabolite Profiling of Mixtures of Triterpenoid Saponins from Seeds of Chilean Quinoa (*Chenopodium quinoa*) Germplasm

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Abstract: The seed pericarp of *Chenopodium quinoa* Willd. (quinoa) contains a mixture of triterpenoid saponins conferring undesired organoleptic properties. In this study, we evaluated saponin content and their corresponding sapogenins in 114 different quinoa accessions. Relative saponin content ranged from 0.22 to 15.04 mg/g of seed dry weight among the genotypes studied and the genotype effect was significant ($p < 0.001$). About 75% of the genotypes could be classified as low-saponin content lines which is promising in view of ongoing plant breeding efforts. In addition to the quantitative determination of saponins, metabolic profiling was performed by LC-FTICR-MS and LC-MS/MS. We obtained highly accurate mass estimation from ion spectra allowing the identification of twelve saponins of the oleanane type. These differ in their aglycons and in the number and type of glycoside units. Interestingly, we identified a saponin compound that, to our knowledge, had not been reported previously. Our study highlights that there is considerable variability concerning saponin content in quinoa, which contributes to the valorization of genetic resources towards the identification of genotypes that could be utilized in current and future quinoa breeding programs.

Keywords: quinoa; total saponins; sapogenins; GC-MS; LC-FTICR-MS; LC-MS/MS



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1. Introduction

Saponins, glycosylated secondary metabolites, are present in a wide range of plant species [1]. They consist of a triterpenoid (C_{30}) or steroid (C_{27}) aglycon (sapogenin) attached to sugar units varying by type, number, and position [2]. Saponins have been widely studied for their potential applications in agriculture due to their antifungal activity and in the food industry for use as preservatives, food additives, and flavor modifying properties [3,4]. Moreover, due to their significant role in anti-cholesterol activity and other bioactive properties including antioxidant, antiviral, antimicrobial and anti-inflammatory activities, saponins have been widely used in the cosmetic and pharmacology industry [5].

In recent years quinoa (*Chenopodium quinoa* Willd.), a member of the Amaranthaceae family, has gained attention for its high nutritional content [6–8] and its tolerance to abiotic stresses [9–11], showing potential to become an alternative crop to cereals, for example in defined crop rotations or on marginal lands. However, *C. quinoa* seeds contain a mixture of triterpenoid saponins in the seed pericarp that leads to bitterness. Saponin accumulation is not only limited to seeds but also other to plant organs including leaves, flowers, and fruits. The saponins in *C. quinoa* are a commixture of triterpenoid glycosides which are mainly derivatives of oleanolic acid (OA), hederagenin (HD), serjanic acid (SA), and phytolaccagenic acid (PA) [12–15]. A fifth sapogenin was characterized as 3,23,30-trihydroxy

olean-12-en-28 oic acid [16]. These sapogenins carry a hydroxy and carboxylic group at C-3 and C-28 position, respectively, which are linked to sugar units. Arabinose, glucose, and galactose are the major saccharides whereas glucuronic acid and xylose are present to a minor extent [16–23]. Up to the present, nearly 140 different triterpene saponins have been identified and annotated in *C. quinoa* seed samples [16,20,23,24]. Saponins confer a bitter flavor and, based on their content, *C. quinoa* varieties have been classified into “sweet-varieties” or “low saponin varieties” ($<0.11\%$ or <0.11 g/100 g FW, and ca of $\leq 0.6\%$ or ≤ 6.0 mg/g of DW) and “bitter-varieties” or “high saponin varieties” ($\geq 0.11\%$ or ≥ 0.11 g/100 g of FW, and ca of $\geq 1.0\%$ or ≥ 10.00 mg/g of DW) [6,25–27]. Since saponin compounds confer bitterness and other organoleptic properties to *C. quinoa* seeds, they must be removed before seeds can be used for human consumption. In general, saponins can be removed either by simple washing due to their amphiphilic nature or by a dehulling-abrasion process [23,28–30]. Because these processes consume water and require the use of dedicated machinery, the development of low saponin *C. quinoa* varieties is an important aim of current plant breeding programs. Today, several programs are in the process of developing saponin-free or low saponins varieties to be introduced in *C. quinoa* cultivation practice [31–33]. Saponin content in *C. quinoa* has been assessed routinely by hemolytic, gravimetric, and foam-based approaches [25,28,34]. However, these assays are mostly qualitative or at best semi-quantitative and are likely to lead to substantial errors resulting from overestimation or low recovery of saponins [34,35]. Therefore, recently, sophisticated technologies such as low-pressure lipid chromatography (LPLC), high-pressure liquid chromatography (HPLC), gas chromatography (GC), UV-vis spectroscopy, and gas chromatography-mass spectrometry (GC-MS) have emerged as appropriate methods for saponin separation and detection [20,23,24,26,36–38].

For plant breeding purposes, it is important to consider both the total saponin content and the individual saponin compounds. In the current study, we hypothesized that the abundance of saponins and their composition can differ depending on the ecotypes and genetic background. Therefore, we aimed at characterizing the extent of variability in saponin content among 114 Chilean *C. quinoa* accessions representing variations within the coastal-lowland and salares ecotypes. The *C. quinoa* diversity panel also included known varieties that have been previously characterized for their high or low saponin content, as positive and negative controls, respectively. Additionally, we focused on structure elucidation of saponins and on their fragmentation spectrum which enables detection of aglycones as well as sugar moieties and their positions in the saponins for these genotypes. These resources will be used in further studies to identify underlying genomic regions linked to saponins for future plant breeding efforts.

2. Materials and Methods

2.1. Chemicals

Oleanolic acid (OA) and Hederagenin (HD) were purchased from Sigma-Aldrich/Merck, (Darmstadt, Germany), and VWR, (Darmstadt, Germany), respectively. Silyl-991 (bis(trimethylsilyl)trifluoroacetamide (BSTFA)–trimethylchlorosilane (TMCS) (99:1)) was obtained from Chromatographie Service, (Langerwehe, Germany). Methanol (LC-MS grade), ethyl acetate, acetonitrile, water (LC-MS grade), pyridine, hydrochloric acid, sodium chloride, and sodium carbonate were supplied by VWR, (Darmstadt, Germany).

2.2. *C. quinoa* Diversity Panel

In the reported study the saponin content was evaluated in 114 different *C. quinoa* accessions including advanced breeding lines of the ongoing INIA's Quinoa Breeding Program (IQBP) in Chile. The *C. quinoa* diversity panel used for the experimental work was initially selected based on morphological characteristics (i.e., plant height, branching growth habit, panicle height, panicle shape) and yield traits (i.e., seed yield, seed diameter), and subsequently established by the Instituto de Investigaciones Agropecuarias (INIA), Chile. The *C. quinoa* panel (AZ = Arid Zones) was obtained by a combination of mass

selection, self-pollination of individual lines (through at least two seasons), and panicle-furrow selection. The entire *C. quinoa* panel belongs to the two groups of genotype that represent variations from two different biomes in Chile: the coastal-lowland and the salares ecotypes. Here, salares genotypes are under-represented compared to the coastal-lowland type. The *C. quinoa* diversity panel covered 7 genotypes (salarés ecotype) from the Chilean Altiplano (highlands region), 2 south Altiplano genotypes from Cancosa area, alongside 102 genotypes from the Chilean coastal-lowland regions. Most of the genotypes were cultivated and harvested from the Huasco experimental station (28°3' S, 70°4' W). In the studied genotypes, we also included the known *C. quinoa* cultivars (cv.) Titicaca (moderate to high saponin content, drought, and salinity tolerant), Vikinga (low saponin content, and drought and salinity tolerant), and ATLAS (sweet cv) [26,36,39,40]. These cultivars were provided by Dr. Sven Erik Jacobsen from the University of Copenhagen, Denmark, and INIA, Chile, respectively. Detailed information on the diversity panel and the collection of *C. quinoa* lines is given in Table 1.

2.3. Extraction and Hydrolysis of Saponins from *C. quinoa* Germplasm

Saponins were indirectly quantified via their corresponding sapogenins derived from hydrolysis, according to Jarvis et al. [24]. Briefly, 50 mg ground *C. quinoa* seeds were suspended in 1 mL methanol then vortexed for 1 min and treated in an ultrasonic bath for 10 min. After centrifugation for 2 min at 14 °C at 14,000 rpm using Eppendorf mini-spin (Hamburg, Germany), 900 µL of supernatant was withdrawn. The remaining solvent including the pellet was extracted a second time as mentioned above and the withdrawn supernatant (1000 µL) was combined with the first. The supernatant was evaporated to dryness and the residue hydrolyzed using 2 mL of 2.5 N hydrochloric acid at 90 °C for 2 h. After the addition of 0.25 g of NaCl, the solution was extracted twice with 1 mL of ethyl acetate by vigorous vortexing for 1 min. The combined ethyl acetate extracts (800 and 900 µL) were treated with 0.25 g of sodium carbonate. After centrifugation 1 mL solution was withdrawn and evaporated to dryness. For derivatization, 1 mL acetonitrile, 100 µL Silyl-991, and 100 µL pyridine were added to the residue and heated to 90 °C for 1 h. Afterward, derivatized samples were analyzed by gas chromatography-mass spectrometry (GC-MS).

2.4. Quantification of Sapogenins by Gas Chromatography-Mass Spectrometry (GC-MS) Analysis

The GC-MS system consisted of an Agilent 7890B gas chromatography and 7693 autosampler (Santa Clara, CA, USA) as well as a Jeol JMS-T200GC AccuTOF GCx mass spectrometer (Tokyo, Japan). Analytes were separated on a Zebron ZB-5 HT Inferno column (30 m × 0.25 mm i.d., 0.25 µm film thickness) (Phenomenex, Torrance, CA, USA). Helium was used as carrier gas at a constant gas flow of 1.0 mL/min. The oven temperature program employed for the analysis of silylated sapogenins was as follows: 180 °C (1 min), with 6 °C/min to 350 °C (3 min). The injector temperature was held at 340 °C, and all injections (1 µL) were made in the split mode (1:10). The mass spectrometer was used in the electron impact (EI, 70 eV) mode and scanned over the range m/z 35–750 with a sampling interval of 0.25 ns and a recording interval of 0.4 s. The GC interface and ion chamber were kept at 340 °C and 250 °C, respectively. Data processing was performed by use of the software MS Axel (Jeol) and XCalibur 2.0.7 (ThermoFisher Scientific, Waltham, MA, USA). Analysis of each quinoa genotype/cultivar was performed in duplicate. Quantification was done by the method of external calibration with standard solutions in the concentration range 25–200 µM. As phytolaccagenic acid (PA) was not commercially available, its quantification was carried out based on a linear regression equation with HD. This method was justified because of almost congruent regression lines for OA and HD.

Table 1. Accession name, seed source, and collection region of the *C. quinoa* lines studied for saponin content.

Quinoa Line	Accession Name	Type	Seed Source	Collection Region		Quinoa Line	Accession Name	Type	Seed Source	Collection Region	
				Latitude	Longitude					Latitude	Longitude
AZ-1	Javi	Selfed line	INIA	−34.49778	−72.00444	AZ-27	CHENO 047	Selfed line	INIA	−34.70000	−72.01667
AZ-2	Javi	Selfed line	INIA	−34.49778	−72.00444	AZ-29	CHENO 207	Selfed line	INIA	−34.49750	−72.02111
AZ-3 ^b	Cancosa	Selfed line	INIA	−20.49083	−69.32917	AZ-30	CHENO 207	Selfed line	INIA	−34.49750	−72.02111
AZ-4	Cáhuil	Selfed line	INIA	−34.28111	−71.85722	AZ-31	FARO	Selfed line	INIA	−34.46778	−71.82583
AZ-5 ^b	Cancosa	Selfed line	INIA	−20.49083	−69.32917	AZ-32	FARO	Selfed line	INIA	−34.46778	−71.82583
AZ-6	U de C9	Selfed line	INIA	−35.73306	−72.53306	AZ-33	EM10-1	Selfed line	INIA	−34.53167	−71.98722
AZ-7	Palmilla	Selfed line	INIA	−34.57722	−71.38000	AZ-34	EM10-1	Selfed line	INIA	−34.53167	−71.98722
AZ-8	Palmilla	Selfed line	INIA	−34.57722	−71.38000	AZ-35	EMPO 10-17	Selfed line	INIA	−34.65083	−71.89500
AZ-9 ^a	R49	Selfed line	INIA	−19.27639	−68.64000	AZ-36	EMPO 10-15	Selfed line	INIA	−34.64667	−71.90806
AZ-10	U de C9	Selfed line	INIA	−35.73306	−72.53306	AZ-37	EMPO 10-14	Selfed line	INIA	−34.52833	−71.99278
AZ-11 ^a	R49	Drought tolerant line	INIA	−19.27639	−68.64000	AZ-38	EMPO 10-14	Selfed line	INIA	−34.52833	−71.99278
AZ-12	Peñablanca-VI	Selfed line	INIA	−34.61139	−71.64083	AZ-39	EMPO 10-10	Selfed line	INIA	−34.51861	−71.98028
AZ-13	–	Selfed line	INIA	–	–	AZ-40	EMPO 10-9	Selfed line	INIA	−39.48194	−72.13416
AZ-14 ^a	Mix	Selfed line	INIA	−19.27639	−68.64000	AZ-41	EMPO 10-8	Selfed line	INIA	−34.51444	−71.69722
AZ-15	Peñablanca-VI	Selfed line	INIA	−34.61139	−71.64083	AZ-42	EMPO 10-7	Selfed line	INIA	−34.64139	−71.91194
AZ-16	Dorada P Paredones	Selfed line	INIA	−34.65750	−71.97889	AZ-43	EMPO 10-6	Selfed line	INIA	−34.65806	−71.92889
AZ-17 ^a	Mix	Selfed line	INIA	−19.27639	−68.64000	AZ-44	EMPO 10-5	Selfed line	INIA	−34.63667	−71.95944
AZ-18	Cáhuil	Breeding line	INIA	−34.28111	−71.85722	AZ-45	EMPO 10-4	Selfed line	INIA	−34.62361	−71.68778
AZ-19	Villarrica	Selfed line	INIA	−39.81944	−73.24528	AZ-46	EMPO 10-2	Selfed line	INIA	−34.69389	−71.91917
AZ-20	Villarrica	Selfed line	INIA	−39.81944	−73.24528	AZ-47	EMPO 10-1	Breeding line	INIA	−34.53639	−71.96917
AZ-21	KM21	Selfed line	INIA	−39.48194	−72.13417	AZ-48	PJEV 029	Selfed line	INIA	−36.05806	−72.47306
AZ-22	KM23	Selfed line	INIA	−39.48194	−72.13417	AZ-49	PJEV 028	Selfed line	INIA	−35.95444	−72.42139
AZ-23	KM23	Selfed line	INIA	−39.48194	−72.13417	AZ-50	PJEV 027	Selfed line	INIA	−35.93667	−72.70639
AZ-24	KM30	Selfed line	INIA	−39.48194	−72.13417	AZ-51	PJEV 026	Breeding line	INIA	−35.93528	−72.70694
AZ-25	CHENO 042	Selfed line	INIA	−34.78667	−72.04917	AZ-52	PJEV 025	Selfed line	INIA	−35.91444	−72.68972
AZ-26	CHENO 046	Breeding line	INIA	−34.70000	−72.01667	AZ-53	PJEV 006	Selfed line	INIA	−34.52778	−71.94611

Table 1. Cont.

Quinoa Line	Accession Name	Type	Seed Source	Collection Region		Quinoa Line	Accession Name	Type	Seed Source	Collection Region	
				Latitude	Longitude					Latitude	Longitude
AZ-54	PJ001	Selfed line	INIA	−34.70000	−72.01667	AZ-76	PRJ3	Selfed line	INIA	−34.49778	−72.00444
AZ-55	PJ002	Selfed line	INIA	−34.53917	−71.92833	AZ-77	PRJ3	Selfed line	INIA	−34.49778	−72.00444
AZ-56	PJEV 007	Selfed line	INIA	−34.53222	−71.98556	AZ-78	PJEV 016	Breeding line	INIA	−35.12694	−71.91722
AZ-57	PJEV 008	Selfed line	INIA	−34.49833	−72.02278	AZ-79	PJEV 017	Selfed line	INIA	−35.01667	−71.91833
AZ-58	PJ003	Selfed line	INIA	−34.52028	−71.97722	AZ-80	Palmilla	Selfed line	INIA	−34.57722	−71.38000
AZ-59	PJ005	Selfed line	INIA	−34.53556	−71.58583	AZ-81	PJEV 018	Selfed line	INIA	−35.00889	−71.92611
AZ-60	PJEV 009	Selfed line	INIA	−34.68417	−71.99667	AZ-82	PJEV 019	Selfed line	INIA	−35.04583	−71.91194
AZ-61	PJEV010	Selfed line	INIA	−34.68583	−72.00139	AZ-83	PJEV 020	Selfed line	INIA	−35.50111	−72.08278
AZ-62	EAM 1	Breeding line	INIA	−34.76833	−72.07556	AZ-84	Dorada y Paredones	Selfed line	INIA	−34.65750	−71.97889
AZ-54	PJ001	Selfed line	INIA	−34.70000	−72.01667	AZ-85	PJEV 021	Selfed line	INIA	−35.50361	−72.08306
AZ-55	PJ002	Selfed line	INIA	−34.53917	−71.92833	AZ-86	PJEV 022	Selfed line	INIA	−35.59028	−72.60917
AZ-56	PJEV 007	Selfed line	INIA	−34.53222	−71.98556	AZ-87	Roja Paredones	Selfed line	INIA	−34.65750	−71.97889
AZ-57	PJEV 008	Selfed line	INIA	−34.49833	−72.02278	AZ-88	PJEV 003	Selfed line	INIA	−34.61278	−71.65139
AZ-59	PJ005	Selfed line	INIA	−34.53556	−71.58583	AZ-86	PJEV 022	Selfed line	INIA	−35.59028	−72.60917
AZ-60	PJEV 009	Selfed line	INIA	−34.68417	−71.99667	AZ-87	Roja Paredones	Selfed line	INIA	−34.65750	−71.97889
AZ-61	PJEV010	Selfed line	INIA	−34.68583	−72.00139	AZ-88	PJEV 003	Selfed line	INIA	−34.61278	−71.65139
AZ-62	EAM 1	Breeding line	INIA	−34.76833	−72.07556	AZ-89	PJEV 003	Selfed line	INIA	−34.61278	−71.65139
AZ-63	EAM 1	Selfed line	INIA	−34.76833	−72.07556	AZ-91	PJEV 023	Selfed line	INIA	−35.91083	−72.68556
AZ-64	EAM 1	Selfed line	INIA	−34.76833	−72.07556	AZ-92	PJEV 23	Selfed line	INIA	−35.91083	−72.68556
AZ-65	EAM 2	Selfed line	INIA	−34.98639	−71.42750	AZ-93	PJEV 024	Selfed line	INIA	−35.91028	−72.68667
AZ-66	PJEV 011	Selfed line	INIA	−34.76472	−72.07806	AZ-94	PJEV 024	Selfed line	INIA	−35.91028	−72.68667
AZ-67	PJEV012	Selfed line	INIA	−34.83667	−72.05944	AZ-95	PJEV 05	Selfed line	INIA	−34.53583	−71.95694
AZ-68	EAM 3	Selfed line	INIA	−34.49778	−72.00444	AZ-96	PJEV 05	Selfed line	INIA	−34.53583	−71.95694
AZ-69	EAM 4	Selfed line	INIA	–	–	AZ-97	Plantas Verdes	Breeding line	INIA	–	–

Table 1. Cont.

Quinoa Line	Accession Name	Type	Seed Source	Collection Region		Quinoa Line	Accession Name	Type	Seed Source	Collection Region	
				Latitude	Longitude					Latitude	Longitude
AZ-70	PJEV 013	Selfed line	INIA	−34.84194	−72.14194	AZ-98	Plantas Moradas	Breeding line	INIA	−39.81944	−73.24528
AZ-71	EAM 5	Selfed line	INIA	−34.53556	−71.58583	AZ-99	Kinia	Breeding line	INIA	−39.48194	−72.13417
AZ-72	PJEV 014	Selfed line	INIA	−34.92806	−72.17944	AZ-100	Javi	Selfed line	INIA	−39.48194	−72.13417
AZ-73	PJEV 015	Selfed line	INIA	−35.00944	−71.91833	AZ-101	Javi	Selfed line	INIA	−39.48194	−72.13417
AZ-74	JML01	Selfed line	INIA	−35.86611	−71.59694	AZ-102	Cancosa	Selfed line	INIA	−34.57722	−71.38000
AZ-103	Cáhuil	Selfed line	INIA	−34.65750	−71.97888	AZ-113	Peñablanca-VI	Selfed line	INIA	−34.57722	−71.38000
AZ-104	Cáhuil	Selfed line	INIA	−35.91083	−72.68555	AZ-114 ^a	MIX	Selfed line	INIA	−34.57722	−71.38000
AZ-105	Javi	Selfed line	INIA	−34.49777	−72.00444	AZ-115	Dorada P Paredones	Selfed line	INIA	−34.65750	−71.97888
AZ-107	Palmilla	Selfed line	INIA	−34.57722	−71.38000	AZ-129	CHEN0207	Selfed line	INIA	−34.49750	−72.02111
AZ-108 ^a	R49	Selfed line	INIA	−34.57722	−71.38000	Cq-1	Vikinga	Variety	Uni. of Copenhagen	–	–
AZ-110	Palmilla	Selfed line	INIA	−34.65750	−71.97888	Cq-2	Titicaca	Variety	Uni. of Copenhagen	–	–
AZ-111 ^a	R49	Selfed line	INIA	−35.91083	−72.68555	Cq-3	ATLAS	Variety	INIA	–	–
AZ-112	Dorada P Paredones	Selfed line	INIA	−34.49777	−72.00444						

^a Selected salares quinoa genotypes from the Altiplano region of Chile (~19° S and ~68° W) and ^b locality of Cancosa (~20° S and ~69° W).

2.5. Identification of Saponins by LC-FTICR-MS and LC-MS/MS

Liquid chromatography-Fourier transform ion cyclotron resonance mass spectrometry (LC-FTICR-MS) experiments were carried out using an Agilent 1200 series HPLC system consisting of a binary pump, autosampler, and column oven (Santa Clara, CA, USA). Saponins from the extraction with methanol (Section 2.3) were separated on an Aqua 3 μm C18 column (150 $\times$ 2 mm, 3 μm particle size) equipped with a pre-column filter from Phenomenex (Waltham, MA, USA). The mobile phase consisted of 1 mM aqueous ammonium acetate (A) and methanol + 1 mM ammonium acetate (B). Samples were separated at 40 $^{\circ}\text{C}$ and a flow rate of 0.3 mL/min using gradient elution: isocratic at 90% A for 1 min, linear gradient to 1% A over 29 min, isocratic at 1% A for 10 min, linear gradient to 90% A over 1 min and equilibration at 90% A for 4 min (total run time: 45 min). The injection volume was 10 μL . Mass spectrometry was performed using a hybrid linear ion trap-FTICR-mass spectrometer LTQ-FT Ultra (ThermoFisher Scientific, Waltham, MA, USA) equipped with a 7 T supra-conducting magnet. The electrospray ionization (ESI) source was operated in the negative mode with a spray voltage of 2.80 kV. Nitrogen was employed as both sheath gas (8.0 arbitrary) and auxiliary gas (0 arbitrary). The transfer capillary temperature was set to 275 $^{\circ}\text{C}$. Voltages for capillary and tube lens were set to -33 V and -135 V, respectively. Mass spectra were recorded in a full scan from 150 to 1500 Da with a mass resolution of 100,000 at m/z 400 (full width at half maximum). The automatic gain control for providing a constant ion population in the ICR cell was set to 5E5 for the FTMS full scan mode. The maximum ion trap fill time was set to 10.0 ms and the maximum ICR cell fill time to 500 ms. The accurate masses of quasi-molecular ions $[\text{M}-\text{H}]^{-}$ were used for the calculation of chemical formulae with the Qual Browser in Xcalibur software version 2.0.7. The search algorithm contained the isotopes ^1H , ^{12}C , ^{13}C , and ^{16}O . Each compound had to be represented by 3 mass peaks: the base peak and the peaks of the corresponding ^{13}C - and $^{13}\text{C}_2$ -isotopologues. Search results were restricted to mass errors of 3.0 ppm for the ^{12}C - and the corresponding ^{13}C - and $^{13}\text{C}_2$ -isotopologues.

Liquid chromatography-tandem mass spectrometry (LC-MS/MS) was carried out on a Waters ACQUITY[®] UHPLC system (binary pump, autosampler) coupled to a Waters Xevo TQ-S[®] triple-quadrupole mass spectrometer (Waters Technologies Corp., Milford, MA, USA). Separation of saponins from the extraction with methanol (Section 2.3) was achieved on a Nucleoshell RP18 column (100 $\times$ 4.6 mm., 2.7 μm .; Macherey-Nagel, Düren, Germany). The column was equipped with a pre-column (Macherey-Nagel, Düren, Germany). The mobile phases were water (A) and acetonitrile (B) each containing 0.1% formic acid, at a flow rate of 1.0 mL/min. The gradient program was as follows: 85% A, to 15% A within 20 min, back to 85% A within 0.1 min, and holding for 2.9 min. The injection volume was 10 μL . The electrospray ionization (ESI) interface of the mass spectrometer was driven in the negative mode. The capillary voltage was set to 2.0 kV. The cone voltage was 35 V. The desolvation temperature and source temperature were 600 $^{\circ}\text{C}$ and 150 $^{\circ}\text{C}$, respectively. The desolvation gas flow was set to 1000 L/h and the cone gas flow at 150 L/h using nitrogen in both cases. MS/MS spectra were obtained in the daughter ion scan mode on precursor ions which were determined by LC-FTICR-MS before. Nitrogen was used as the collision gas at a flow of 0.15 mL/min and ionization voltage was set to 30 and 50 eV, respectively.

2.6. Statistical Analysis

All analyzed results are reported as mean $\pm$ standard deviation (SD) values of the independent sample extractions ($n = 4$). To determine the significant difference in saponin content among *C. quinoa* accessions, the dataset was analyzed as a one-way analysis of variance ANOVA (Tukey's-Honestly Significant Difference multiple comparisons) using the R-package Agricolae [41]. A p -value ≤ 0.05 was considered as a statistically significant difference. Principal component analysis (PCA) and cluster analysis were done for the complete dataset to present the entire correlation distance matrix, and to group according to specific variables. Hierarchical clustering was performed based on the Euclidean distance

and complete grouping method using PCA scores. The genotypic effect was defined according to a linear additive model:

$$y_{ij} = \mu + G_i + \varepsilon_{ij} \quad (1)$$

where y_{ij} is the phenotypic value measured for the trait y on the plant j of the genotype i ; μ corresponds to the overall mean; G_i is the random effect of genotype i representing the effect of each genotype or genotypic effect on trait y , and ε_{ij} is the random residual error per plant j of the genotype i . V_g was estimated according to the restricted maximum likelihood (REML) variance components using the lme4 library of R [42]. The significance of the effects was assessed using the Akaike and Bayesian criteria and tested by the likelihood ratio.

3. Results and Discussion

3.1. Extraction and Quantification of Triterpenoid Saponins in *C. quinoa* Germplasm

Saponin content in *C. quinoa* seeds was evaluated in terms of their sapogenins (aglycons) derived from hydrolysis of seed samples. In total 114 different *C. quinoa* genotypes including breeding lines from the INIA breeding program and cultivars were analyzed for saponin content. Quantification of sapogenins was carried out by use of external calibration curves for OA and HD. For this analysis, standard solutions were prepared over a concentration range of 25–200 μ M which were similar to those in the extracts. The obtained correlation coefficients (r^2) were in the range of 0.986–0.999. Next, the calibration curve of HD was used for the quantification of PA since the calibration curves of OA and HD were almost identical.

The ion mass chromatogram of silylated sapogenins from *C. quinoa* obtained by GC-MS is shown in Figure 1. The gas chromatogram shows three main and two minor peaks. Four of them could unambiguously be identified as silylated OA, HD, SA, and PA by comparison of their retention times (25.7, 26.6, 27.9, and 28.7 min, respectively) and mass spectra to the standard compounds and published data, respectively [15,26,36]. The mass spectrum of the fifth sapogenin was insufficient to obtain any information about its structure. Mass spectra of silylated sapogenins are characterized by very low abundances of their molecular peaks M^+ . Fragmentation reactions mainly occurred under the elimination of CH_3 , $Me_3SiO(H)$, and $Me_3SiOOCH$. Further, the mass spectrum peaks of TMS-OA were detected at m/z 600 (M^+), 585 ($M^+ - Me$), 482 ($M^+ - Me_3SiOOCH$), and 393 ($M^+ - Me_3SiOOCH - Me_3SiO$). TMS-HD fragment ions were found at m/z 688 (M^+), 673 ($M^+ - Me$), 570 ($M^+ - Me_3SiOOCH$), and 481 ($M^+ - Me_3SiOOCH - Me_3SiO$). The fragmentation pattern of TMS-SA was found at m/z 644 (M^+), 629 ($M^+ - Me$), 554 ($M^+ - Me_3SiOH$), 526 ($M^+ - Me_3SiOOCH$), and 467 ($M^+ - Me_3SiOOCH - MeOCO$). TMS-PA peaks were spotted at m/z 732 (M^+), 717 ($M^+ - Me$), and 614 ($M^+ - Me_3SiOOCH$). These mass spectra are similar to those in the literature [15,26,36,43].

Because saponin content was, to our knowledge, never determined in earlier work, with a few exceptions, for the studied genotypes originating from Chile direct comparisons with previously published values are not currently possible for the whole dataset. However, we were able to compare our results with previously published data for the positive and negative control lines. Certain quinoa lines (AZ-18, AZ-26, AZ-47, AZ-51, AZ-62, AZ-78, AZ-97, AZ-98, and AZ-99) are advanced breeding lines of IQBP. In our experiment, 26.3% of the genotypes were noted as high saponin quinoa lines, whereas 73.6% of the genotypes were noted as low saponin quinoa lines. The relative saponin content among the genotypes studied ranged from 0.22 mg/g to 15.04 mg/g of seed dry weight. We found that variation in total saponin content was highly significant ($p < 0.001$) (Figure 2a, Tables S1 and S2). Considering the breeding lines we studied (Table 1), AZ-51 and AZ-26 revealed a high content of saponins with 11.60 mg/g and 9.42 mg/g of seed dry weight, respectively. In contrast, the remaining breeding lines had lower saponin content in the range of 4.33 mg/g to 6.79 mg/g of seed dry weight (Figure 2a, Table S1). Furthermore, the Danish cultivar Titicaca (Cq-2) showed very high saponin content with a concentration of 15.04 mg/g of seed dry weight among all genotypes. We detected a higher concentration

of PA with 7.76 mg/g of total saponins in comparison to other sapogenins in this cultivar (Table S1). Our data is comparable with data from Medina-Meza et al. [26] in which the Titicaca variety had an average total saponin content of 16.75 mg/g. Additionally, another study also revealed a high percentage of PA compared with the other sapogenins OA and HA in the bitter variety Titicaca, which is also in agreement with our result [39]. For the few previously investigated *C. quinoa* genotypes, total average saponins among Cahuil accessions AZ-4, AZ-18, AZ-103, and AZ-104 were 9.24 mg/g, 5.23 mg/g, 4.08 mg/g, and 7.69 mg/g of seed dry weight, respectively. The reported average amount of saponins in this coastal-lowland Chilean genotype was comparable to the average values reported by Medina-Meza [26] and Ward [35] (10.95 mg/g and 4.65 mg/g, respectively). However, the average saponins amount for the Cahuil genotype in our case was higher compared with the one reported in another study (0.39 mg/g of saponins) [44]. Possible differences in the variation in total saponins reported in various studies might occur due to numerous factors including agronomical and environmental conditions as well as the handling of the standardized procedures that have been used for the extraction and quantification of saponins. Concerning these points, the seeds of the Cahuil genotype used in Medina-Meza's and Ward's experiments have been cultivated at different experimental locations in the United States. Furthermore, in Miranda's experiment, saponins were analyzed based on an HPLC procedure although seeds of the Cahuil genotype were all collected in Chile. Moreover, another central Chilean genotype, FARO (AZ-31 and AZ-32) showed on average 5.33 mg/g of total saponins. This value was higher compared with the one found by Miranda's study [44] (~0.30 mg/g of total saponins). Similarly, Cancosa corresponding to south Altiplano ecotype (AZ-3, AZ-5) and south Chilean coastal-lowland ecotypes from Villarrica locality (AZ-19, AZ-20) contained on average 8.87 mg/g and 6.53 mg/g of saponins, values which were higher than those reported by Miranda [44] (~0.20 mg/g and 0.89 mg/g), respectively. Such contradictory results relating to the amount of saponins can be concerned with the fact that in Miranda's study the characterization of saponins was carried out based on the reversed-phase HPLC approach. In the studied low saponins cultivar that we included as negative controls, Vikinga (Cq-1) showed an average saponin content of 6.49 mg/g of seed dry weight, which is lower than 1% of total saponins. The relative concentration of sapogenins OA and HD in Vikinga were detected in a 1:1 ratio, while the concentration of PA was in comparison slightly lower than OA and HD (Table S1). This result is nearly identical to the findings of a previous study where the authors reported a 1:1 OA:HD ratio with a relatively low amount of PA in Vikinga [39]. Among the entire panel of genotypes, we found that cv ATLAS (Cq-3) had a very low amount of saponins, as expected (0.22 mg/g of seed dry weight). The GC-MS chromatogram of this variety had 56.2% and 24.9% of OA and HD, respectively, while PA was 18.8% of total sapogenins (Figure 2b). This result implies a high ratio of OA:HD. This result can be explained by the fact that a high ratio of OA to HD is connected, to some extent, with the sweetness of seeds and a low ratio, to some extent, with the bitterness of seeds [14,39].

Our GC-MS results show that PA was the main compound of sapogenins as such representing 38.4% of the total saponin content followed by OA and HD with 33.0% and 28.6%, respectively (Figure 2b). This result is very similar to other previous experiments where PA was reported as the main class of sapogenins (42–43%) followed by OA (30%–34%) and HD (24–27%) in coastal-lowland ecotypes [15]. Overall, we found a positive correlation between PA and total saponins ($p < 0.001$, $r = 0.854$; (Figure S1), as previously reported [26]. It has been also noted that bitterness of *C. quinoa* seeds can be linked with a higher content of PA, whereby sweet *C. quinoa* genotypes have low or no apparent PA content [26,39,45]. However, in other studies, OA was identified as the main class of sapogenins in *C. quinoa* [14,36]. The variation in the relative amount of sapogenins can be linked with cross-pollination, which has been noted up to 9.9% in the *C. quinoa*, and its accumulation in the various portion of the grain [14,46].

In general, results revealed that the seven *C. quinoa* genotypes Cq-2, AZ-3, AZ-11, AZ-25, AZ-51, AZ-52, AZ-129 had a total saponin content above the threshold percentage (>1%)

among the genotypes we studied in this experimental trial. We adopted this empirical threshold based on a prior study [26]. Thus, these genotypes can be categorized as bitter genotypes and need to be passed through the post-harvesting process to remove saponins before products can be used for human consumption. Besides, 22 genotypes (AZ-4, AZ-7, AZ-9, AZ-12, AZ-15, AZ-26, AZ-27, AZ-29, AZ-30, AZ-34, AZ-35, AZ-46, AZ-67, AZ-68, AZ-88, AZ-104, AZ-107, AZ-108, AZ-111, AZ-113, AZ-114, AZ-115) showed total saponins level near to this threshold percentage (close to 1%), and these can also be considered as high saponin content genotypes. The other genotypes with a lower percentage of total saponin content, i.e., below the median of ca 0.6%, can be classified as low saponins genotypes. Among all genotypes and cultivars, ATLAS (Cq-3) can be classified as a sweet genotype due to its very low percentage of total saponin content. This complete assessment was similar to that of a previous study [26].

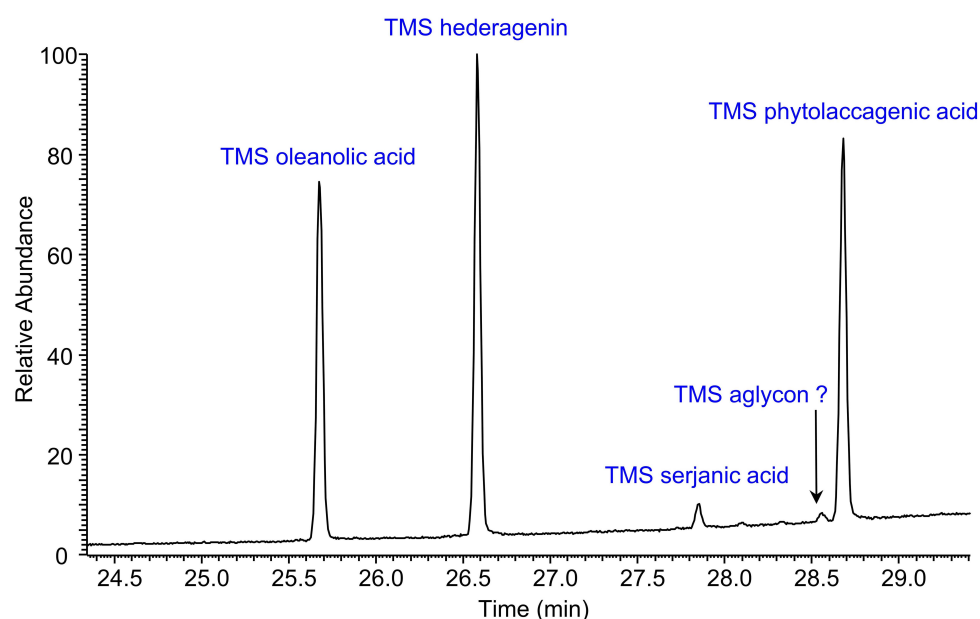


Figure 1. Ion mass chromatogram of trimethylsilylated saponins from *C. quinoa* obtained by GC-MS. GC-MS chromatogram profile shows the separated saponins from *C. quinoa* seed extract. Saponins were quantified by indirect quantification of their corresponding saponin aglycones derived from the hydrolysis of saponins from *C. quinoa* seed. Mass spectra of silylated oleanolic acid, hederagenin, serjanic acid, and phytolaccagenic acid were assigned by comparison of retention times (25.7, 26.6, 27.9, and 28.7 min, respectively) and mass spectra to the corresponding standards.

3.2. Evaluation of Triterpenoid Saponins of *C. quinoa* Seeds

Saponins not only confer bitterness but also comprise various biological activities which include cytotoxic, immunomodulatory, hepatoprotective, antidiabetic, hypolipidemic, antiosteoporosis, antiviral, antifungal, and anthelmintic actions [47]. Therefore we also characterized saponins from *C. quinoa* choosing the following analytical approach. First, saponins were separated by HPLC (Figure 3) and detected by high-resolution FTICR-MS in the full scan mode. The high accurate masses obtained allowed the calculation of chemical compositions with mass deviations lower than 3.0 ppm. Additional calculation of the corresponding ^{13}C - and $^{13}\text{C}_2$ -isotopologues confirmed their correctness. In consideration of the molecular ion adduct $[\text{M}-\text{H}]^-$ formed by ESI (-) ionization, molecular formulas had been derived. In the second step, LC-MS/MS was used to obtain product ion spectra from the formerly determined precursor ions $[\text{M}-\text{H}]^-$ and additionally the corresponding formate adducts $[\text{M} + \text{FA}-\text{H}]^-$. The fragmentation patterns were used to identify the aglycones as well as the types of sugar and their sequence in the saponins. Out of the 12 identified saponins, 11 had been previously reported (Table 2). Compound 8 was

assigned as a novel saponin. The product ion spectrum of compound 4 (Figure 4) chosen as an example for the other saponins is characterized by gradual neutral losses of sugar units representing their sequence and the aglycone-specific product ion m/z 515, $[PA-H]^-$. The initial fragmentation of 4 (m/z 971) resulted in m/z 809, corresponding to $[M-H-162]^-$ or the loss of a hexose residue. The loss of 28-*O*-linked hexose was also observed for nine other saponins, as this is the energetically favored fragmentation pattern, in comparison to 3-*O*-linked saccharides [16]. However, compounds 11 and 12 differ from that pattern displaying loss of pentose $[M-H-132]^-$ as the initial step. This result might be due to the negative ESI mode, whereas published data are based on ESI (+) conditions [16]. Another possibility is a 28-*O*-linked pentose instead of hexose which has not been described in the literature so far. The majority of saponins bore the common aglycons OA (m/z 455), HD (m/z 471), SA (m/z 499), and PA (m/z 515). Compound 2 showed an aglycone at m/z 485 which suggests a structure similar to HD but with ethyl instead of a methyl group at C-20 [16].

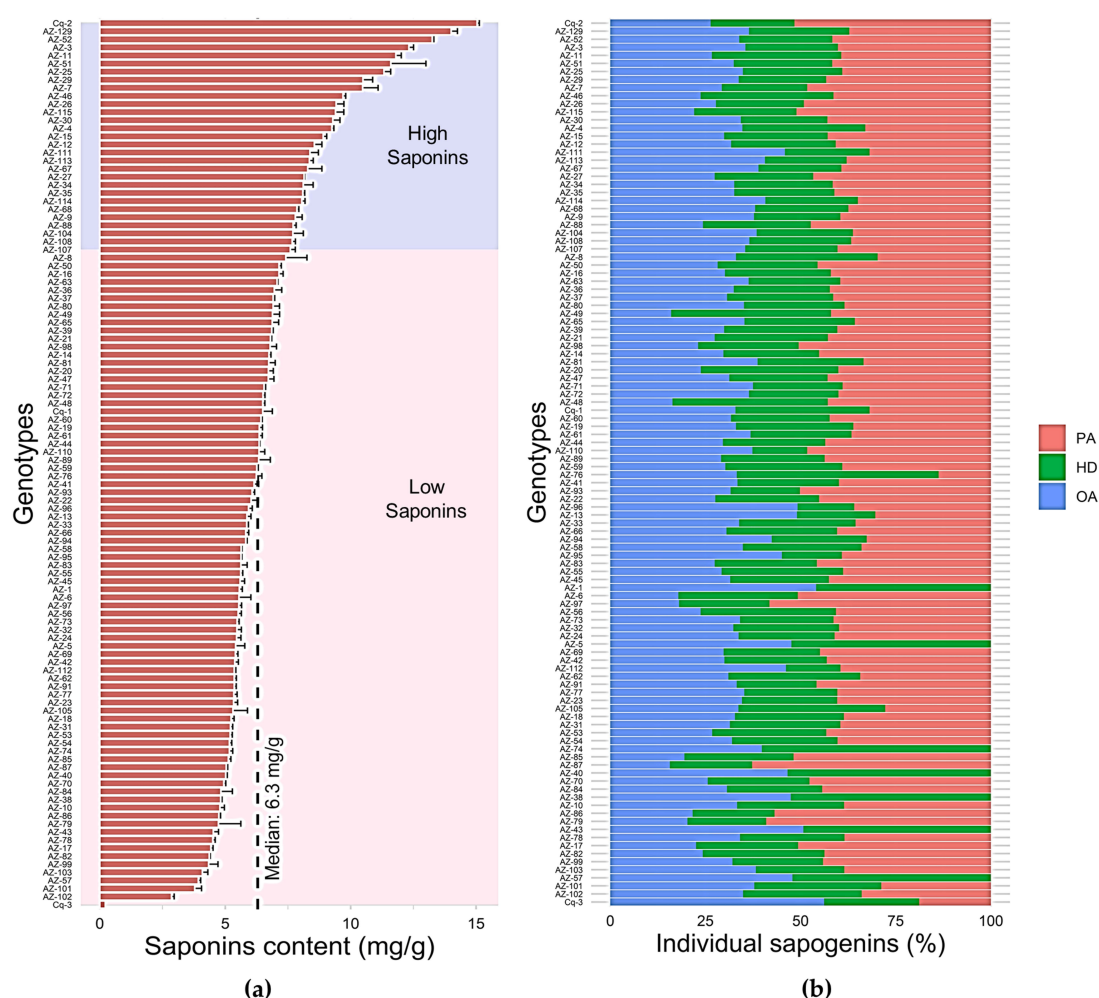


Figure 2. Total saponin content (a) and percentage of individual saponogenins (b) in the *C. quinoa* panel. (a) A bar graph showing relative saponin content in different *C. quinoa* accessions. Quantification of saponins was indirectly performed via their corresponding saponogenins. Analyzed data are reported as mean $\pm$ standard deviation of independent sample extractions. Statistical analysis was performed by ANOVA test (Tukey's $\pm$ HSD, $\alpha = 0.05$). A significant difference ($p < 0.001$) in relative saponin content was noticed and saponins concentration ranged from 0.22 mg/g to 15.04 mg/g of seed DW. The median line shows the average of the total saponin content of all studied genotypes. (b) Stacked bar graph showing individual saponogenins and outlined in % of total saponins. Light blue: Oleanolic acid (OA), Green: Hederagenin (HD), and Light red: Phytolaccagenic acid (PA).

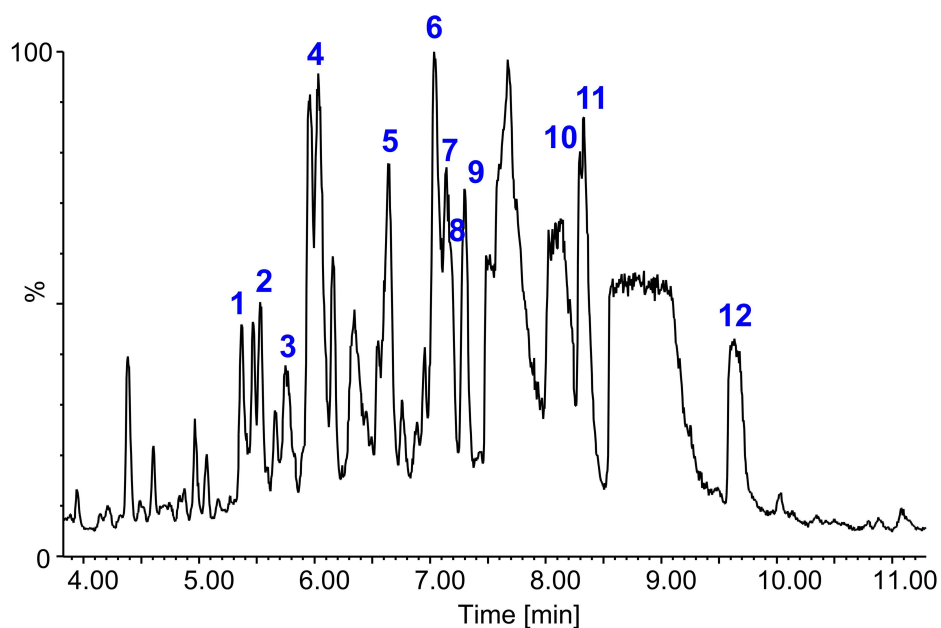


Figure 3. LC-ESI (-)-MS chromatogram of saponins from seeds of quinoa genotype AZ-129. Available saponins in seeds of quinoa accession AZ-129 were detected by FTICR-MS. The LC-MS chromatogram shows separated saponins obtained from quinoa seeds after extraction with methanol. The saponins 1 to 12 are assigned in Table 2.

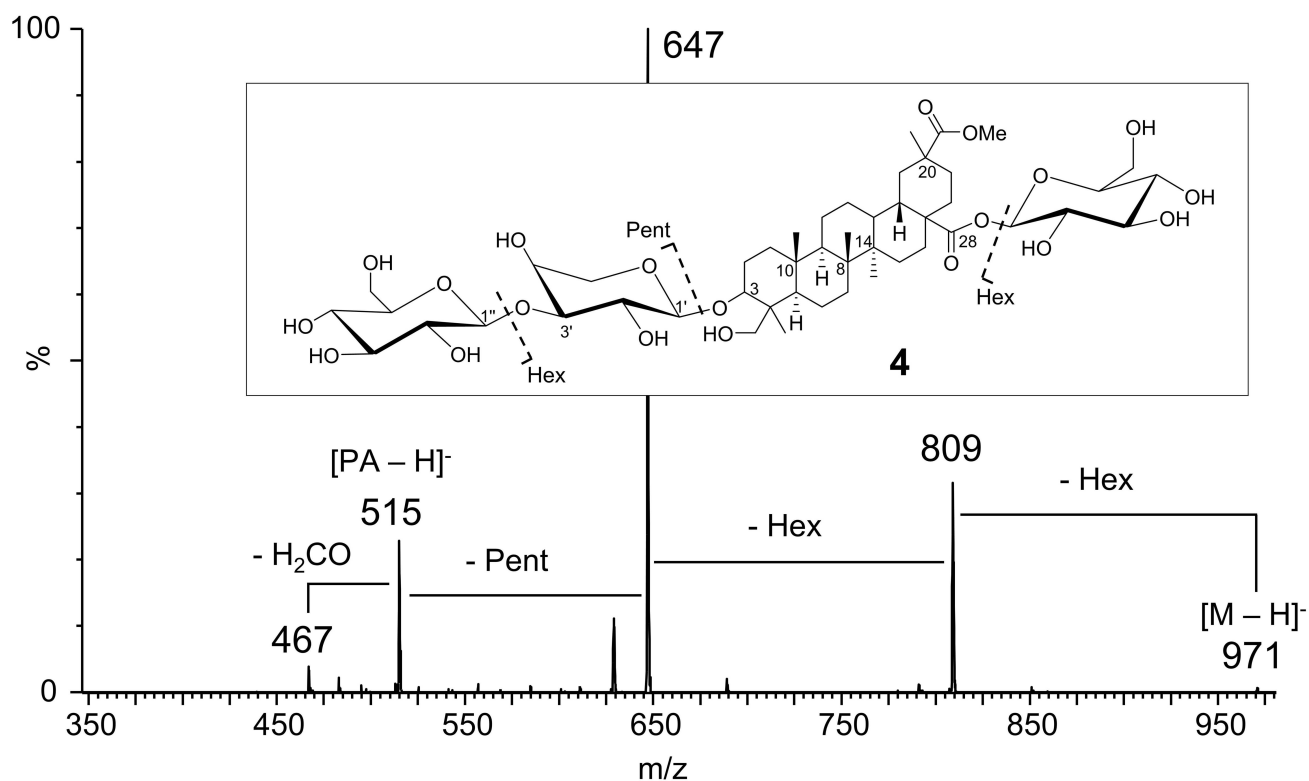


Figure 4. Product ion spectrum on $[M-H]^-$ of compound 4 (m/z 971), which was identified in genotype AZ-129. The fragment ion series m/z 809, 647, and 515 show the consecutive loss of sugar units from the saponin as is indicated in the inserted structural formula. The fragment ion m/z 515 is characteristic of phytolaccagenic acid as the aglycon.

Table 2. Existing triterpenoid saponins from seeds of *C. quinoa* accession AZ-129.

No.	Saponin ^a	LC-FTICR-MS					LC-MS/MS		
		t _R ^b (min)	m/z Experimental	Rel. Int. (%)	Composition (M-H) [−]	Δ ^c [ppm]	Molecular Formula	m/z	Lit.
1	3-O-Hex-Hex-PA 28-O-Hex	5.36	1001.49539 1002.49931 1003.50333	100 59.07 14.02	C49 H77 O21 C48 [13]C H77 O21 C47 [13]C2 H77 O21	−0.89 −0.33 0.34	C ₄₉ H ₇₈ O ₂₁	1001 [M-H] [−] , 839 [M-H-Hex] [−] , 677 [M-H-2 Hex] [−] , 515 [M-H-3 Hex] [−] or [PA-H] [−]	[16,21,22]
2	3-O-Hex-Pent- AG485 28-O-Hex	5.53	941.43785 942.44187 943.44482	100 52.49 15.17	C46 H69 O20 C45 [13]C H69 O20 C44 [13]C2 H69 O20	−0.98 −0.27 −0.7	C ₄₆ H ₇₀ O ₂₀	941 [M-H] [−] , 779 [M-H-Hex] [−] , 617 [M-H-2 Hex] [−] , 485 [M-H-2 Hex-Pent] [−] or [AG485-H] [−]	[16,24]
3	3-O-HexA-Pent-PA 28-O-Hex	5.75	985.46400 986.46742 987.47110	100 60.18 8.02	C48 H73 O21 C47 [13]C H73 O21 C46 [13]C2 H73 O21	−1 −0.93 −0.6	C ₄₈ H ₇₄ O ₂₁	985 [M-H] [−] , 823 [M-H-Hex] [−] , 647 [M-H-Hex-HexA] [−] , 515 [M-H-Hex-HexA-Pent] [−] or [PA-H] [−]	[24]
4	3-O-Hex-Pent-PA 28-O-Hex	6.03	971.48585 972.48963 973.49181	100 52.7 17.3	C48 H75 O20 C47 [13]C H75 O20 C46 [13]C2 H75 O20	0.14 0.57 −0.63	C ₄₈ H ₇₆ O ₂₀	(1017 [M + FA-H] [−]) ^d , 971 [M-H] [−] , 809 [M-H-Hex] [−] , 647 [M-H-2 Hex] [−] , 515 [M-H-2 Hex-Pent] [−] or [PA-H] [−]	[16–19,21,22]
5	3-O-Hex-Hex-SA 28-O-Hex	6.63	985.46519 986.46874 987.47249	100 54.6 11.4	C48 H73 O21 C47 [13]C H73 O21 C46 [13]C2 H73 O21	0.2 0.41 0.79	C ₄₈ H ₇₄ O ₂₁	(1031 [M + FA-H] [−]) ^d , 985 [M-H] [−] , 823 [M-H-Hex] [−] , 661 [M-H-2 Hex] [−] , 499 [M-H-3 Hex] [−] or [SA-H] [−]	[24]
6	3-O-Hex-Pent-SA 28-O-Hex	7.03	955.49035 956.49438 957.49710	100 56.18 16.08	C48 H75 O19 C47 [13]C H75 O19 C46 [13]C2 H75 O19	−0.47 0.23 −0.43	C ₄₈ H ₇₆ O ₁₉	(1001 [M + FA-H] [−]) ^d , 955 [M-H] [−] , 793 [M-H-Hex] [−] , 631 [M-H-2 Hex] [−] , 499 [M-H-2 Hex-Pent] [−] or [SA-H] [−]	[16,18]
7	3-O-HexA-Hed 28-O-Hex	7.14	809.43306 810.43673 811.43956	100 43.43 10.93	C42 H65 O15 C41 [13]C H65 O15 C40 [13]C2 H65 O15	0.2 0.59 −0.05	C ₄₂ H ₆₆ O ₁₅	809 [M-H] [−] , 647 [M-H-Hex] [−] , 471 [M-H-Hex-HexA] [−] or [Hed-H] [−]	[16]
8	3-O-HexA-SA 28-O-Hex	7.27	837.42806 838.43165 839.43421	100 57.59 11.22	C43 H65 O16 C42 [13]C H65 O16 C41 [13]C2 H65 O16	0.3 0.58 −0.37	C ₄₃ H ₆₆ O ₁₆	837 [M-H] [−] , 675 [M-H-Hex] [−] , 499 [M-H-Hex-HexA] [−] or [SA-H] [−]	
9	3-O-Hex-Pent-Hed 28-O-Hex	7.30	927.43863 928.50152	100 44.27	C47 H75 O18 C46 [13]C H75 O18	2.96 2.45	C ₄₇ H ₇₆ O ₁₈	(973 [M + FA-H] [−]) ^d 927 [M-H] [−] , 765 [M-H-Hex] [−] , 603 [M-H-2 Hex] [−] , 471 [M-H-2 Hex-Pent] [−] or [Hed-H] [−]	[18,22,24]
10	3-O-HexA-OA 28-O-Hex	8.30	793.43723 794.44077 795.44454	100 48.31 9.08	C42 H65 O14 C41 [13]C H65 O14 C40 [13]C2 H65 O14	−0.94 −0.71 −0.19	C ₄₂ H ₆₆ O ₁₄	793 [M-H] [−] , 631 [M-H-Hex] [−] , 455 [M-H-Hex-HexA] [−] or [OA-H] [−]	[16,18,20–22]
11	3-O-Pent-HexA-Hed 28-O-Hex	8.38	941.44005 942.44388 943.44724	100 50.0 16.2	C46 H69 O20 C45 [13]C H69 O20 C44 [13]C2 H69 O20	1.28 1.75 1.77	C ₄₆ H ₇₀ O ₂₀	941 [M-H] [−] , 809 [M-H-Pent] [−] , 647 [M-H-Pent-Hex] [−] , 471 [M-H-Pent-Hex-HexA] [−] or [Hed-H] [−]	[16–19,21,22]
12	3-O-Pent-HexA-OA 28-O-Hex	9.60	925.47997 926.48382 927.48743	100 53.69 15.5	C47 H73 O18 C46 [13]C H73 O18 C45 [13]C2 H73 O18	−0.29 0.24 0.52	C ₄₇ H ₇₄ O ₁₈	925 [M-H] [−] , 793 [M-H-Pent] [−] , 631 [M-H-Pent-Hex] [−] , 455 [M-H-Pent-Hex-HexA] [−] or [OA-H] [−]	[16–19,21,22]

^a PA: phytolaccagenic acid; SA: serjanic acid; HD: hederagenin; OA: oleanolic acid. Pent: pentose; Hex: hexose; HexA: corresponding sugar acid. ^b t_R: retention time. ^c Δ: deviation between experimental and theoretical mass in ppm. ^d ESI(−) molecular ion adduct formation with formate: (M + FA-H)[−].

3.3. Principal Component Analysis and Clustering

Principal component analysis (PCA) was performed to find a small number of linear orthogonal combinations of all variables that captured the greatest amount of variation present in our dataset as a whole. The overall dataset of total saponins and individual sapogenins was used to outline the main axes of the principal component analysis.

The PCA analysis revealed 74.8% of the variation for PC1 and 16.1% of the variation for PC2 among all *C. quinoa* genotypes studied (Figure 5a). As stated in Figure 5a, the total saponin content is well described by PC1, while the content of OA and HD are well described by PC2. Further, cluster analysis was done based on the Euclidean distance and complete grouping method using the PCA score (Figure 5b). The data output of each variable and for each of the genotypes grouped into two major clusters in proportion to the total saponin content. Based on the PCA score, cluster 4 had the lowest value for PC1. Since the main component of PC1 was negatively correlated with the PA and total saponin content, cluster 4 grouped the genotypes that have a high content of saponins. Cluster 3 pooled those genotypes that had a high amount of PA compared to the rest of the genotypes from other clusters, except cluster 4. On the contrary, cluster 5 contained a very low score PA and total saponins, which confirms the known genotypes with extremely low saponin content. Further, the remaining clusters (clusters 2 and 1) showed scattering near the core boundary of PC2. These clusters grouped those genotypes characterized with low PA contents, and thus low saponin content. Figure 5 shows uninterpreted divergence among sub-groups of the major two groups without clear separation. Interpretation of the high saponins cluster showed consistent variation within and among sub-groups, which represented accessions from both salares and coastal-lowland ecotypes (and regions). Moreover, the low saponin content genotypes scattered at a close-range distance compared with the genotypes that had high saponin content. The low saponins cluster segregated into PC1, including accessions from the coastal-lowland region and European cultivars. However, sub-groups shared some accessions from salares (AZ-14 and AZ-17) and south-altiplano (AZ-5). These data revealed an interpolation of coastal-lowland and salares genotypes in both PCA and dendrogram analysis. An interpolation of genotypes in two major clusters could likely be due to the genetic similarity between highland and coastal-lowland *C. quinoa* genotypes [48]. Another study also revealed the existing genetic diversity within and among the different *C. quinoa* genotypes from different biomes of Chile, and such genetic diversity could be a primary reason for this possible variation in saponin content [49]. Therefore, it is interesting to study the genetic background of these accessions to understand potential genomic variation resulting in relative saponin content in *C. quinoa*.

3.4. Variance by the Genotypic Effect

To estimate the effect of genetic diversity pattern, the percentages of variance explained by genotypic effect (Vg) in the total phenotypic variance for saponin content were estimated using a mixed linear model. This variance explained by genotypic effect (Vg) was calculated according to the restricted maximum likelihood (REML) variance components using the lme4 library of R [42]. As a result, we found a significant genotypic effect ($p \leq 0.05$) which shows that each genotype expresses the phenotype of the measured traits differently, i.e., there is a genetic diversity that would explain the variation of saponin content. The significant effect of genotype represented by Vg validated the existence of genetic diversity up to 94.5% within the tested population for saponin content (Table S3).

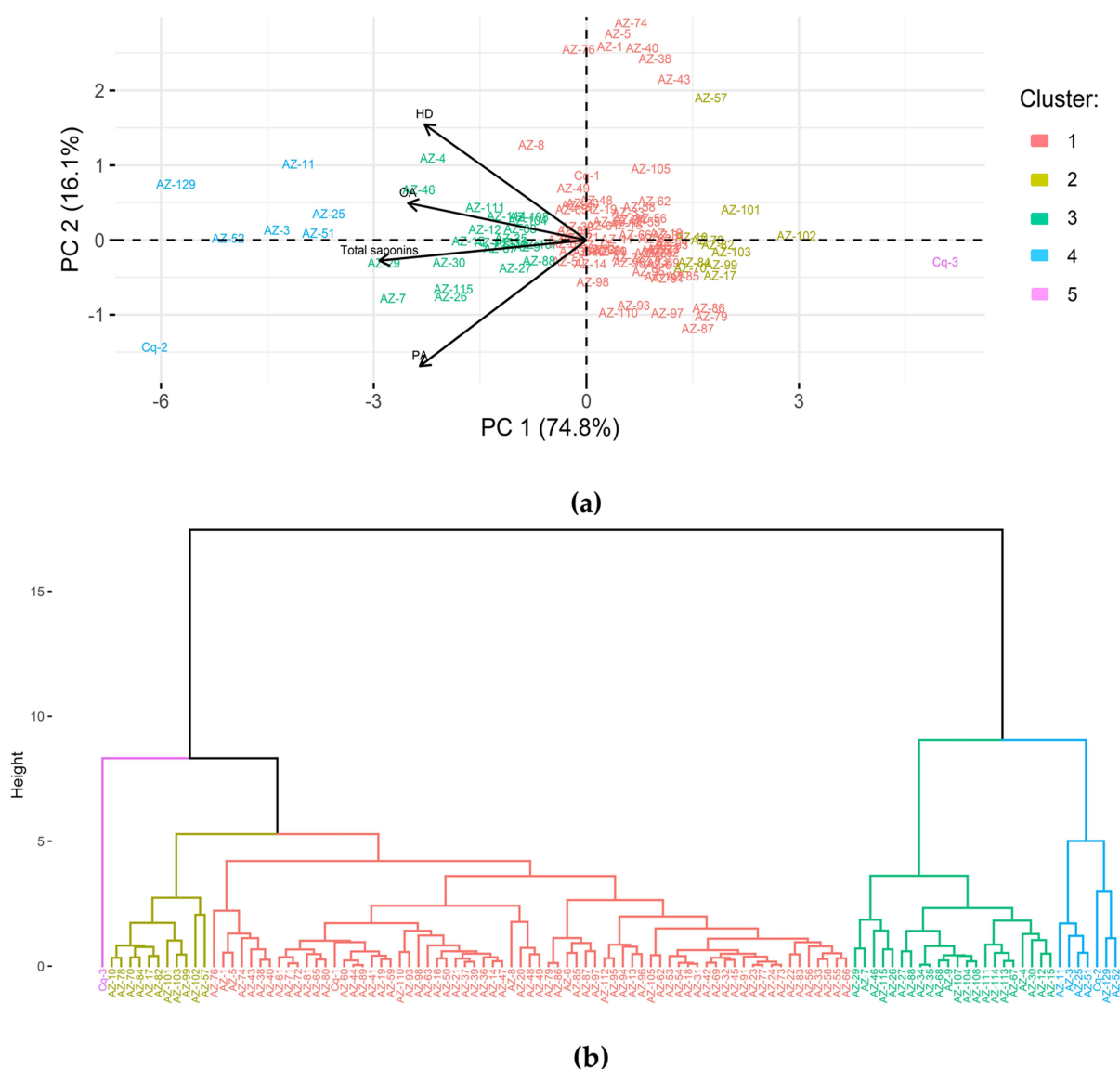


Figure 5. Principal component analysis (a) and hierarchical cluster (b) of triterpenoid saponins of *C. quinoa*. Bi-plot showing that two main components PC1 and PC2 explained 90.9% of the total variation in saponin content. Arrows represent each variable and the length of arrows approximates the variance of the variables, whereas the angle between arrows indicates their correlation. The scores of each quinoa genotype are outlined as points. The distance between each point explains how similar the observations are to each other. The cluster colors correspond to the cluster numbers in the legend of a panel (a).

4. Conclusions

Conclusively, the GC-MS profiling addressed the high degree of significant variance in relative saponin content, which ranges from 0.22 mg/g to 15.04 mg/g among the 114 different *C. quinoa* genotypes. In total 29 genotypes were categorized as high saponin content, and thus require the removal of saponins before products can be used for human consumption, while the rest of the genotypes were categorized as low-saponins or saponin-free lines. In this study, PA was reported as a prominent sapogenin, among others. Overall cluster data revealed uninterpreted divergence among sub-groups of the major two groups without clear separation. These dissimilarities in the sapogenins can be attributed to the existing genetic diversity in *C. quinoa*. The high percentages of variance explained by genotypic effect (Vg) in the total phenotypic variance for saponin content confirmed the existing diversity in terms of saponin content, which could become a target for future plant breeding efforts based on these accessions. Linked to this consideration, further genetic

investigation such as using genome-wide association studies (GWAS) will be used in future studies to identify underlying genomic regions linked with saponin content to be employed in plant breeding of quinoa through marker-assisted selection.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/agronomy11091867/s1>, Figure S1: Pearson’s correlation heat map of total saponins and individual sapogenins, Table S1: Total saponin content (mg/g) in *C. quinoa* lines, Table S2: Tukey’s-HSD multiple comparisons for saponin content, Table S3: Variance by genotypic effect.

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References

1. Vincken, J.P.; Heng, L.; de Groot, A.; Gruppen, H. Saponins, classification and occurrence in the plant kingdom. *Phytochem* **2007**, *68*, 275–297. [\[CrossRef\]](#)
2. Cheok, C.Y.; Salman, H.A.K.; Sulaiman, R. Extraction and quantification of saponins: A review. *Food Res. Int.* **2014**, *59*, 16–40. [\[CrossRef\]](#)
3. Stuardo, M.; Martin, R.S. Antifungal properties of quinoa (*Chenopodium quinoa* Willd.) alkali treated saponins against *Botrytis cinerea*. *Ind. Crop. Prod.* **2008**, *27*, 296–302. [\[CrossRef\]](#)
4. FAO & CIRAD. *State of the Art Report of Quinoa in the World in 2013*; Bazile, D., Bertero, D., Nieto, C., Eds.; FAO & CIRAD: Rome, Italy, 2015.
5. Güclü-Üstündag, Ö.; Mazza, G. Saponins: Properties, applications and processing. *Crit. Rev. Food Sci. Nutr.* **2007**, *47*, 231–258. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Vega-Galvez, A.; Miranda, M.; Vergara, J.; Uribe, E.; Puente, L.; Martinez, E.A. Nutrition facts and functional potential of quinoa (*Chenopodium quinoa* Willd.), an ancient Andean grain: A review. *J. Sci. Food Agric.* **2010**, *90*, 2541–2547. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Rodríguez Gómez, M.J.; Matías Prieto, J.; Cruz Sobrado, V.; Calvo Magro, P. Nutritional characterization of six quinoa (*Chenopodium quinoa* Willd.) varieties cultivated in Southern Europe. *J. Food Compos. Anal.* **2021**, *99*, 103876. [\[CrossRef\]](#)
8. Mhada, M.; Metougui, M.L.; El Hazzam, K.; El Kacimi, K.; Yasri, A. Variations of Saponins, Minerals and Total Phenolic Compounds Due to Processing and Cooking of Quinoa (*Chenopodium quinoa* Willd.) Seeds. *Foods* **2020**, *9*, 660. [\[CrossRef\]](#)
9. Adolf, V.I.; Shabala, S.; Andersen, M.N.; Razzaghi, F.; Jacobsen, S.E. Varietal differences of quinoa’s tolerance to saline conditions. *Plant Soil* **2012**, *357*, 117–129. [\[CrossRef\]](#)
10. Hariadi, Y.; Marandon, K.; Tian, Y.; Jacobsen, S.E.; Shabala, S. Ionic and osmotic relations in quinoa (*Chenopodium quinoa* Willd.) plants grown at various salinity levels. *J. Exp. Bot.* **2011**, *62*, 185–193. [\[CrossRef\]](#)
11. Jacobsen, S.E.; Mujica, A.; Jensen, C.R. The resistance of quinoa (*Chenopodium quinoa* Willd.) to adverse abiotic factors. *Food Rev. Int.* **2003**, *19*, 99–109. [\[CrossRef\]](#)
12. Burnoufradosevich, M.; Delfel, N.E.; England, R. Gas chromatography-mass spectrometry of olealane-type and ursane-type triterpenes—Application to chenopodium-quinoa triterpenes. *Phytochem* **1985**, *24*, 2063–2066. [\[CrossRef\]](#)
13. Cuadrado, C.; Ayet, G.; Burbano, C.; Muzquiz, M.; Camacho, L.; Cavieres, E.; Lovon, M.; Osagie, A.; Price, K.R. Occurrence of saponins and sapogenols in andean crops. *J. Sci. Food Agric.* **1995**, *67*, 169–172. [\[CrossRef\]](#)

14. Mastebroek, H.D.; Limburg, H.; Gilles, T.; Marvin, H.J.P. Occurrence of saponin in leaves and seeds of quinoa (*Chenopodium quinoa* Willd.). *J. Sci. Food Agric.* **2000**, *80*, 152–156. [\[CrossRef\]](#)
15. Ridout, C.L.; Price, K.R.; Dupont, M.S.; Parker, M.L.; Fenwick, G.R. Quinoa saponins—Analysis and preliminary investigations into the effects of reduction by processing. *J. Sci. Food Agric.* **1991**, *54*, 165–176. [\[CrossRef\]](#)
16. Madl, T.; Sterk, H.; Mittelbach, M. Tandem mass spectrometric analysis of a complex triterpene saponin mixture of *Chenopodium quinoa*. *J. Am. Soc. Mass Spectrom.* **2006**, *17*, 795–806. [\[CrossRef\]](#)
17. Dini, I.; Schettino, O.; Simioli, T.; Dini, A. Studies on the constituents of *Chenopodium quinoa* seeds: Isolation and characterization of new triterpene saponins. *J. Agric. Food Chem.* **2001**, *49*, 741–746. [\[CrossRef\]](#)
18. Dini, I.; Tenore, G.C.; Dini, A. Oleanane saponins in “kancolla”, a sweet variety of *Chenopodium quinoa*. *J. Nat. Prod.* **2002**, *65*, 1023–1026. [\[CrossRef\]](#)
19. Dini, I.; Tenore, G.C.; Schettino, O.; Dini, A. New oleanane saponins in *Chenopodium quinoa*. *J. Agric. Food Chem.* **2001**, *49*, 3976–3981. [\[CrossRef\]](#)
20. Kuljanabhagavad, T.; Thongphasuk, P.; Chamulitrat, W.; Wink, M. Triterpene saponins from *Chenopodium quinoa* Willd. *Phytochem* **2008**, *69*, 1919–1926. [\[CrossRef\]](#)
21. Mizui, F.; Kasai, R.; Ohtani, K.; Tanaka, O. Saponins from bran of quinoa, *Chenopodium quinoa* WILLD. II. *Chem. Pharm. Bull.* **1990**, *38*, 375–377. [\[CrossRef\]](#)
22. Zhu, N.Q.; Sheng, S.Q.; Sang, S.M.; Jhoo, J.W.; Bai, N.S.; Karwe, M.V.; Rosen, R.T.; Ho, C.T. Triterpene saponins from debittered quinoa (*Chenopodium quinoa*) seeds. *J. Agric. Food Chem.* **2002**, *50*, 865–867. [\[CrossRef\]](#)
23. El Hazzam, K.; Hafsa, J.; Sobeh, M.; Mhada, M.; Taourirte, M.; El Kacimi, K.; Yasri, A. An Insight into Saponins from Quinoa (*Chenopodium quinoa* Willd.): A Review. *Molecules* **2020**, *25*, 1059. [\[CrossRef\]](#)
24. Jarvis, D.E.; Ho, Y.S.; Lightfoot, D.J.; Schmockel, S.M.; Li, B.; Borm, T.J.A.; Ohyanagi, H.; Mineta, K.; Michell, C.T.; Saber, N.; et al. The genome of *Chenopodium quinoa*. *Nature* **2017**, *542*, 307–312. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Kozioł, M.J. Afrosimetric estimation of threshold saponin concentration for bitterness in quinoa (*Chenopodium quinoa* Willd.). *J. Sci. Food Agric.* **1991**, *54*, 211–219. [\[CrossRef\]](#)
26. Medina-Meza, I.G.; Aluwi, N.A.; Saunders, S.R.; Ganjyal, G.M. GC-MS Profiling of Triterpenoid Saponins from 28 Quinoa Varieties (*Chenopodium quinoa* Willd.) Grown in Washington State. *J. Agric. Food Chem.* **2016**, *64*, 8583–8591. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Martinez, E.A.; Veas, E.; Jorquera, C.; San Martin, R.; Jara, P. Re-Introduction of Quinoa into Arid Chile: Cultivation of Two Lowland Races under Extremely Low Irrigation. *J. Agro. Crop Sci.* **2009**, *195*, 1–10. [\[CrossRef\]](#)
28. Chauhan, G.S.; Eskin, N.A.M.; Tkachuk, R. Nutrients and antinutrients in quinoa seed. *Cereal Chem.* **1992**, *69*, 85–88.
29. Gomez-Caravaca, M.A.; Iafelice, G.; Verardo, V.; Marconi, E.; Caboni, M.F. Influence of pearling process on phenolic and saponin content in quinoa (*Chenopodium quinoa* Willd.). *Food Chem.* **2014**, *157*, 174–178. [\[CrossRef\]](#)
30. Lundberg, L. Saponin Removal from Quinoa by Abrasion Processing. Ph.D. Thesis, California Polytechnic State University, San Luis Obispo, CA, USA, 2019.
31. Zurita-Silva, A.; Fuentes, F.; Zamora, P.; Jacobsen, S.E.; Schwember, A.R. Breeding quinoa (*Chenopodium quinoa* Willd.): Potential and perspectives. *Mol. Breeding* **2014**, *34*, 13–30. [\[CrossRef\]](#)
32. van Erp, W. Marker Development for Bitter-Tasting-Saponin Gene in Quinoa (*Chenopodium quinoa*): Final report; Wageningen UR: Wageningen, The Netherlands, 2016; Available online: <http://edepot.wur.nl/394421> (accessed on 5 May 2021).
33. Murphy, K.M.; Matanguihan, J.B.; Fuentes, F.F.; Gómez-Pando, L.R.; Jellen, E.N.; Maughan, P.J.; Jarvis, D.E. Quinoa Breeding and Genomics. In *Plant Breeding Reviews*; Goldman, I., Ed.; Wiley: New York, NY, USA, 2018; Volume 42.
34. Reichert, R.D.; Tatarynovich, J.T.; Tyler, R.T. Abrasive dehulling of quinoa (*Chenopodium quinoa*)—Effect on saponin content as determined by an adapted hemolytic assay. *Cereal Chem.* **1986**, *63*, 471–475.
35. Ward, S.M. Response to selection for reduced grain saponin content in quinoa (*Chenopodium quinoa* Willd.). *Field Crops Res.* **2000**, *68*, 157–163. [\[CrossRef\]](#)
36. Gómez-Caravaca, A.M.; Iafelice, G.; Lavini, A.; Pulvento, C.; Caboni, M.F.; Marconi, E. Phenolic Compounds and Saponins in Quinoa Samples (*Chenopodium quinoa* Willd.) Grown under Different Saline and Nonsaline Irrigation Regimens. *J. Agric. Food Chem.* **2012**, *60*, 4620–4627. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Ruales, J.; Nair, B.M. Saponins, phytic acid, tannins and protease inhibitors in quinoa (*Chenopodium quinoa*, Willd) seeds. *Food Chem.* **1993**, *48*, 137–143. [\[CrossRef\]](#)
38. Woldemichael, G.M.; Wink, M. Identification and biological activities of triterpenoid saponins from *Chenopodium quinoa*. *J. Agric. Food Chem.* **2001**, *49*, 2327–2332. [\[CrossRef\]](#)
39. Ruiz, K.B.; Khakimov, B.; Engelsens, S.B.; Bak, S.; Biondi, S.; Jacobsen, S.E. Quinoa seed coats as an expanding and sustainable source of bioactive compounds: An investigation of genotypic diversity in saponin profiles. *Ind. Crop. Prod.* **2017**, *104*, 156–163. [\[CrossRef\]](#)
40. Jacobsen, S.E. Quinoa Quality. Available online: <https://www.quinoaquality.com/contact-quinoa-quality> (accessed on 5 May 2021).
41. de Mendiburu, F. Agricolae: Statistical Procedures for Agricultural Research. Available online: <https://CRAN.R-project.org/package=agricolae> (accessed on 7 April 2021).

42. Bates, D.; Maechler, M.; Bolker, B.; Walker, S.; Christensen, R.H.B.; Singmann, H.; Dai, B.; Grothendieck, G.; Green, P. Package 'lme4': Linear Mixed-Effects Models Using 'Eigen' and S4. Available online: <https://github.com/lme4/lme4/> (accessed on 16 April 2021).
43. Verza, S.G.; Kaiser, S.; de Resende, P.E.; Ortega, G.G. Determination and Characterization of *Chenopodium quinoa* Willd. Saponins. *Lat. Am. J. Pharm.* **2017**, *36*, 326–331.
44. Miranda, M.; Vega-Galvez, A.; Quispe-Fuentes, I.; Rodriguez, M.J.; Maureira, H.; Martinez, E.A. Nutritional aspects of six quinoa (*Chenopodium quinoa* Willd.) ecotypes from three geographical areas of Chile. *Chil. J. Agric. Res.* **2012**, *72*, 175–181. [[CrossRef](#)]
45. Ng, K.G.; Price, K.R.; Fenwick, G.R. A TLC method for the analysis of quinoa (*Chenopodium quinoa*) saponins. *Food Chem.* **1994**, *49*, 311–315. [[CrossRef](#)]
46. Ando, H.; Chen, Y.C.; Tang, H.J.; Shimizu, M.; Watanabe, K.; Mitsunaga, T. Food components in fractions of quinoa seed. *Food Sci. Technol. Res.* **2002**, *8*, 80–84. [[CrossRef](#)]
47. Mroczek, A. Phytochemistry and bioactivity of triterpene saponins from Amaranthaceae family. *Phytochem. Rev.* **2015**, *14*, 577–605. [[CrossRef](#)]
48. Christensen, S.A.; Pratt, D.B.; Pratt, C.; Nelson, P.T.; Stevens, M.R.; Jellen, E.N.; Coleman, C.E.; Fairbanks, D.J.; Bonifacio, A.; Maughan, P.J. Assessment of genetic diversity in the USDA and CIP-FAO international nursery collections of quinoa (*Chenopodium quinoa* Willd.) using microsatellite markers. *Plant Genet. Resour.* **2007**, *5*, 82–95. [[CrossRef](#)]
49. Fuentes, F.F.; Martinez, E.A.; Hinrichsen, P.V.; Jellen, E.N.; Maughan, P.J. Assessment of genetic diversity patterns in Chilean quinoa (*Chenopodium quinoa* Willd.) germplasm using multiplex fluorescent microsatellite markers. *Conserv. Genet.* **2009**, *10*, 369–377. [[CrossRef](#)]