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Compositional, Morphological, Thermal, Structural, and Rheological of Mexican Wild Potato (*Solanum cardiophyllum*) "papita Silvestre"

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ABSTRACT

The study examines the mineral composition, morphology, thermal, structural, and pasting properties of wild potatoes (*Solanum cardiophyllum*). The potatoes vary in size, averaging 2.11 ± 0.47 cm high, 2.84 ± 0.68 cm wide, and weighing 68.81 ± 8.79 g. Compared to white potatoes, they contain less potassium and have a unique worm and mummy-like starch morphology. The total starch content is 19.32%. The isolated nanocrystals from starch exhibit a hexagonal crystal structure with distinct thermal properties, including gelatinization peaks. The X-ray diffraction patterns show the role of water in maintaining the hexagonal crystal structure. Analysis of pasting properties shows that the starch has a pudding-like final viscosity, suggesting that it is not suitable for baby food production due to swallowing difficulties. This study provides valuable insights into the properties of wild potatoes and highlights potential applications.

1 | Introduction

Tubers, such as the potato, have been eaten all over the world for centuries. In Mexico and Central America, *Solanum cardiophyllum* is a wild potato species native to western, central, and southern Mexico. This variety is sold for human consumption in local markets in the Altiplano Potosino-Zacatecano and is also harvested on farms in Jalisco, where farmers grow three wild potato species (*S. cardiophyllum*, *Solanum ehrenbergii*, and *Solanum stoloniferum*) under irrigated conditions [1]. In Mexico, these potatoes are consumed as soups, tacos, mashed potatoes, and baked. Potatoes are rich in minerals, proteins, and other nutrients important for health, but the main component of potatoes is starch. Starch is the most important polymer in the food industry and the second most important polymer in nature. It is not only used for food, but also in the cosmetics, pharmaceutical, bioplastics, petrochemical, and biomaterial industries. There is therefore great interest in wild species for starch production, as these species are cheap and require little water. On the other hand, wild species in many cases have different physicochemical properties than conventional starch sources, which could expand their potential applications. The potential uses of starch are related to the ratio of amylose/amylopectin [2], ion content [3], amylose-lipid complexes [4], starch size, and intrinsic characteristics of starch granules that influence their physicochemical properties.

Wang et al. [5] investigated six different rice varieties about the extraction of starch from wild species. They found that the

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morphology, crystalline structure, swelling capacity, and water solubility index of waxy rice were unchanged. However, they differed in terms of amylose content, chain length, thermal, and pasting properties and crystallinity. However, this study does not address the identification of X-ray patterns related to the crystal structures found in these starches, the effects of crystalline properties on physicochemical properties, and so forth. Pineda-Gomez et al. [6] reported on the physicochemical characterization of six potato varieties from the Colombian Andes region. The authors found that these native potato varieties contain starches with unusual pasting properties; very high viscosities with a peak viscosity of 40 000–50 000 cP and the formation of a liquid gel at the final viscosity with viscosities of 10 000–20 000 cP. The X-ray pattern of the investigated grades exhibited a hexagonal crystal structure and showed differences in the crystallinity quality of the starches. In addition, the authors reported a high content of minerals in the potato starch, mainly P, K, Ca, Mg, and Fe, as well as the presence of an amylose-lipid complex detected by differential scanning calorimetry (DSC). However, the factors influencing starch quality are not clear.

Esquivel-Fajardo et al. [7] demonstrated the presence of orthorhombic and hexagonal crystal structures, when studying isolated avocado starch and redefined starch as micro- and/or submicron-sized particles composed mainly of amylose, amylopectin, fat, protein, salts, ions, bound and free water, and nanocrystals with orthorhombic or/and hexagonal crystal structure. This means that it is now necessary to include the behavior of these crystal structures and the effects on the physicochemical properties of the different starches in the starch analysis. They also pointed out that starches with orthorhombic crystal structure can be classified as A-type, starches with hexagonal crystal structure can be classified as B-type starches, and if the starches have nanocrystals with orthorhombic and hexagonal crystals at the same time, they are classified as C-type. At this point, it is important to note that A-, B-, and C-type are not crystal structures or starch polymorphisms, but a classification of starches.

Šimková et al. [8] investigated 16 potato varieties grown at five experimental sites regarding amylose and amylopectin content, P content and starch grain size. They found a correlation between starches with high amylopectin content and phosphorus content and evaluated the total starch in all samples analyzed. Regarding the identification of nanocrystals in starch, Rojas-Molina et al. [9] isolated these nanocrystals from corn and potatoes. However, they did not identify their crystal structure. The study of the physicochemical properties of starch and the search for new properties is important to find new and modern applications in different industrial fields.

The aim of this work was to investigate the physicochemical properties of the Mexican wild potato (*S. cardiophyllum*) "papita silvestre" and the presence of new worm-like and mummy-like starch morphologies. The focus was on the morphological characterization of the nanocrystals using transmission electron microscopy (TEM) and, for the first time, on the study of the hexagonal crystal structure and the effect of water molecules on it, and finally on a correlation between the pasting profile and the changes along this profile.

2 | Materials and Methods

2.1 | Wild Potatoes

The wild potatoes (*S. cardiophyllum*) were obtained from a local farmer in San Luis Potosi, Mexico. In November 2022, they were washed with distilled water and dried at 30°C for 10 min to prevent sprouting. They were then stored in a paper bag until use.

2.2 | Isolation of the Starch

The isolated starch was obtained according to the method proposed by Londoño-Restrepo et al. [10] and Lucas-Aguirre et al. [11]. The potatoes were washed and cut into small pieces. To obtain the isolated starch, these pieces were soaked in a citric acid solution (0.05 M) to avoid oxidation and kept in a refrigerator at 4°C for 24 h. Then, the material was drained and washed three times with distilled water to avoid mineral interference and obtain isolated starch. A total of 200 g of pulp and 800 mL of distilled water were ground in a blender for 4 min. The slurry was then sieved with a mesh size of 100 (147 μm). The liquid that passed through the sieve was allowed to settle for 12 h at 4°C; it was then decanted. The potato starch was dried at 40°C for 12 h. The dried starch was milled again to dissolve the piles formed during the drying phase; the milled starch was then sieved through a sieve with a mesh size of 100 (<147 μm).

2.3 | Proximate Analysis, Apparent Amylose Content, and Total Starch Content of Isolated Starch

The moisture, fat, ash, and protein content were determined according to the AOAC [12] methods for moisture (method 925.10), fat (method 920.39), ash (method 942.05), and protein (method 920.15).

A Sigma standard for starch with a high amylose content (70% amylose) was used to determine the amylose content of wild potato starch. The method is based on Juliano et al. [13]. The amylose content was calculated using a calibration curve of the standard and a correction factor of 0.7 to obtain the correct value. Before measurement, the starch samples were degreased with acetone. In addition, the total starch content in the isolated starches was determined using a commercial kit (K-TSTA-100A, Megazyme, Bray, Ireland) according to the manufacturer's instructions. The procedure was performed in triplicate.

2.4 | Mineral Composition by Inductively Coupled Plasma (ICP)

The mineral content of isolated starch from white and wild potatoes was analyzed using the method proposed by Ramirez-Gutierrez et al. [14] using an inductively coupled plasma optical emission spectrometer (ICP- OES) (model Thermo iCAP 6500

Duo View). A sample of 10 g was converted to white ash by incineration in an oven at 550°C for 5 h. Subsequently, 0.1 g of each sample was digested with nitric acid (Baker 69%–70%); this step was performed in triplicate. The elements excited by the argon plasma were then identified by their characteristic emission spectra. The values were obtained in triplicate.

2.5 | Morphology of Isolated Potato Starch by Scanning Electron Microscopy (SEM)

The morphological characterization of the isolated starch and the dry samples obtained along the pasting profile was examined using a high-vacuum scanning electron microscope (JEOL, JSM-6060LV, Tokyo, Japan) with HV resolution. The starch was fixed on a sample holder with carbon tape and sputtered with gold. The analysis conditions were 20 kV electron acceleration voltage at 12–20 Pa pressure.

2.6 | Nanocrystals Isolation

The nanocrystals present in potato starch were isolated according to the method proposed by Rojas-Molina et al. [9] with slight modifications. The nanocrystals from isolated starch were isolated with sulfuric acid (H_2SO_4). A total of 50 g of starch was dispersed in 250 mL of H_2SO_4, 3.16 M. The suspension was mixed and heated at 45°C for 4 days with stirring. The mixture was centrifuged at 16 612 × *g* and washed with distilled water until a pH of 5 was reached. An ammonia treatment was performed to increase the pH to 8–8.5, which prevented the nanocrystals from dissolving in the solution. Finally, the sample was lyophilized.

2.7 | Transmission Electron Microscopy (TEM)

The TEM images of the isolated potato nanocrystals were taken with a JEOL JEM-2200 FS (Tokyo, Japan) TEM. The study was performed for the ICN sample according to the method of Zubieta-Otero et al. [15]. The sample was ultrasonically redispersed in isopropyl alcohol and extracted with a capillary tube to deposit a drop of it on a 3 mm copper grid in a sample holder. The sample was then placed in a plasma cleaner to remove volatile organics before being placed under the microscope for measurement. The accelerating voltage used for the study was 80 kV. The crystal size of the nanocrystal samples was determined using Gatan Digital Micrograph V4.0 software, and the array mask was applied to clean up the FFT signal and calculate the distances between planes to compare with the indexing proposed by Rodriguez-Garcia et al. [16].

2.8 | Structural Characterization of the Isolated Starch

X-ray diffraction patterns for wet and dry isolated starch were performed to identify the crystal structures present in this starch using the method proposed by Rojas-Molina et al. [9], with an Ultima IV diffractometer (Rigaku, Tokyo, Japan). The operating conditions were 35 kV and 15 mA, with a CuK_α radiation wavelength of $\lambda = 0.1540$ nm and an angle of 5°–35° at 2θ. The powder samples were tightly packed in an aluminum pan. The samples were prepared using high-resolution X-ray diffraction with a step size of 0.005° to obtain better intensity and resolution of each of the possible diffraction peaks.

The unit cell parameters for an orthorhombic crystalline structure were calculated using Equation (1) and Bragg's law (Equation 2):

$$\frac{1}{d_{hkl}^2} = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2} \quad (1)$$

$$d_{hkl} = \frac{\lambda}{2sin\theta} \quad (2)$$

where *hkl* is the Miller index, *a*, *b*, and *c* are the lattice parameters of the unit cell, d_{hkl} is the interplanar distance (Equation 2), λ is the X-ray wavelength (0.154 nm), and θ is the angle at which diffraction is permitted.

The crystallite size was obtained using the Sherer equation (Equation 3),

$$CS = \frac{0.94 \times \lambda}{\beta \times \cos\theta} \quad (3)$$

where, CS = Average Crystallite size, and β = Line broadening in radians (FWHM: Full width at half maximum).

Regarding the calculation of relative crystallinity, the method proposed by Rojas-Molina et al. [9] was used in this work. In brief: The X-ray patterns in starch arise from the presence of nanocrystals with orthorhombic or hexagonal structures, which generate elastic and inelastic X-ray contributions that cannot be separated. This means that the crystalline areas do not correspond to the pure elastic contribution. An alternative technique to study the changes in the hexagonal structure involves analyzing the relational shift between two crystal planes containing two or three Miller indices. In this case, the peaks ⟨032⟩at 24.175° and ⟨121⟩ at 17.239° are selected due to their high intensity and lack of overlap [16].

2.9 | Differential Scanning Calorimeter Analysis

The thermal analysis of both the isolated starch (IS) and the defatted starch (DS) was performed using the method proposed by Lucas-Aguirre et al. [11] with a differential scanning calorimeter DSC 1 (Mettler Toledo, Greifensee, Switzerland). The calibrations were performed with pure indium with a melting temperature of 28.4 J/g heat fusion and a melting temperature of 156.6°C. Deionized water was then added to the calorimeter. Deionized water was then added to the calorimeter. Deionized water was then added to the dish of each sample until a humidity of 85% (w/w) was reached and the pans were then hermetically sealed (3 mg of starch sand 9 μL water). The temperature range for the analysis was set between 30°C and 80°C with a heating rate of 7.5°C/min for IS and between 30°C and 120°C for D-IS. An empty aluminum pan was used as a reference. The temperatures for the onset (T_o), peak (T_p), and the end (T_e) were determined and the gelatinization enthalpy (ΔH) was integrated. Each measurement was performed by triplicate.

2.10 | Pasting Profile

The viscosity profile of the isolated starch-water suspension was determined using an MCR-102 rheometer (Anton Paar, Graz, Austria). To determine the rheological regime, the pasting profiles were performed with different ratios of starch/water: 2/19, 2.5/18.5, 3/18, and 3.3/17.7 g/mL. The moisture content for each starch/water ratio evaluated was 91.70%, 89.62%, 87.55%, and 86.31%, respectively. The measurement was performed according to the methodology proposed by Esquivel-Fajardo et al. [7]. At the beginning, the system temperature was set to 50°C and kept constant for 1 min. Then the sample was heated from 50°C to 90°C for 5.3 min and kept at this temperature for 5.3 min. The sample was cooled down to 50°C in 5.3 min. Finally, this temperature was maintained for 1 min.

To investigate the changes in paste morphology along the pasting profile, SEM images were taken at three different time points. The first window of the pasting profile was run from 0 to 250 s (window 1), which corresponds to the beginning of gelatinization and the change in the slope of the pasting profile. Window 2 ranges from 255 to 309 s and ends with the peak viscosity. And finally, window 3 (309–1380 s) is the end of the pasting profile. When the system reached the end of each time window, the rheometer was stopped, the sample was cooled in liquid nitrogen and freeze-dried using a Freezone 2.5 (Labconco, Kansas City, USA) for 48 h. The morphology of each of these freeze-dried samples was analyzed by scanning electron spectroscopy.

2.11 | Statistical Analysis

Experiments were performed in triplicate; data are the mean ± standard deviation. ANOVA analysis was used to determine differences between groups. Tukey test to assess significant differences ($p \leq 0.05$).

3 | Results and Discussion

3.1 | General Characteristics of the Wild Potato (*S. cardiophyllum*)

Figure 1 shows the general morphology of the wild potato. These potatoes showed a wide range of sizes, the width interval ranged from 1.31 to 3.35 cm, and the size ranged from 1.83 to 3.95 cm. On average, the samples were 2.11 ± 0.47 cm high, 2.84 ± 0.68 cm wide, and 68.81 ± 8.79 g in weight ($n = 100$) (Figure 1). The amylose content of these potatoes was 32.4 ± 2.10%, the fat content 1.65 ± 1.89%, the ash content 0.33 ± 0.05%, and the moisture content 12.84 ± 0.90%.

3.2 | Chemical Proximate Analysis

The amylose content of this isolated starch was 32.4 ± 2.10%, the fat content 1.65 ± 0.189%, the ash content 0.33 ± 0.05%, and the moisture content 12.84 ± 0.90%. The total starch content was 19.34 ± 1.32%. Šimková et al. [8] reported the total starch of 16 selected potato varieties grown in five locations in the Czech Republic with different climatic conditions and reported 18.79% and 22.21%, and an average value of 20.23%. The fat content in the literature for potato starch ranges from 0.28% for Indian potatoes [17] and recently Lucas-Aguirre et al. [11] reported a fat content of 1.80 ± 0.11 for Colombian creole potatoes.

3.3 | Mineral Composition

Figure 1b shows the mineral content of the wild potato and a comparison with the white potato. The results show that the wild potato has a lower content of minerals, especially potassium, which is considered a common mineral in tubers. However, the magnesium content was similar in both samples, and the wild potato had a higher calcium content in its composition. Noda et al. [18] found the same five elements in other potato starch varieties grown in Japan and reported values between 400 and 800 ppm for K. However, compared to the wild potato studied here, it has the lowest K content (43 ppm).

3.4 | SEM Morphology of Isolated Starch

Figure 2a (500×) and 2b (1000×) show that this starch forms spherical and semispherical grains with a size of 4–40 μm. However, a detailed analysis of these images allowed us to identify two new morphologies in this starch (Figures 2 and 3). These starch grains consist of planes folded on themselves, as can be seen in Figure 2c (5000×) and 2d (10 000×), at a low concentration. The dimensions of this new morphology are 12–15 μm wide and 20–55 nm high; the layer thickness is about 1 μm. Figure 2e, taken at 25 000×, shows that these layers are separated (mummy-like), but the layers that form them are together; the distance between the layers is about 200 nm (see Figure 2e, 25 000×). The presence of this worm-like starch could strongly influence the physicochemical properties, especially the rheological ones. Some authors suggest that the size and shape of the starch granules may influence physicochemical properties such as gelatinization, crystallinity, and solubility [19]. Energy dispersion spectroscopy performed on these starches has shown that the new morphology is mainly formed by C and O and has demonstrated the presence of minerals.

Figure 3a–f shows the morphology study of the worm-like starches. As mentioned above, EDS (energy dispersion spectroscopy) has shown that this type of starch is composed of C, O, K, Mg, and other components. This starch morphology has not been reported anywhere else.

3.5 | Transmission Electron Microscopy in Isolated Nanocrystals From Isolated Starch

Figure 4 shows the TEM images of isolated nanocrystals from isolated potato starch. Figure 4a shows the TEM images of isolated nanocrystals (100 nm). These structures consist of elongated nanoplatelets with an average crystal size (2D) of 40 ± 5 nm in length and 15 ± 2 nm in width. Figure 4b shows a selected area with isolated nanocrystals (10 nm). This image was used to determine the interplanar distances. In addition, the image shows highly ordered nanocrystals that appear to be independent

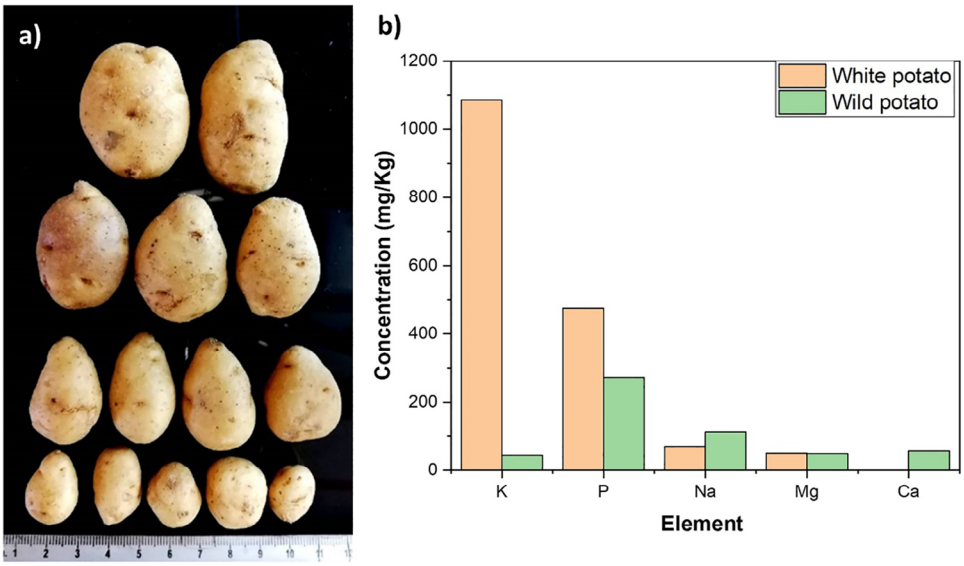


FIGURE 1 | (a) Picture of the wild potato (*Solanum cardiophyllum*) and (b) mineral content of the wild potato compared to the common white potato.

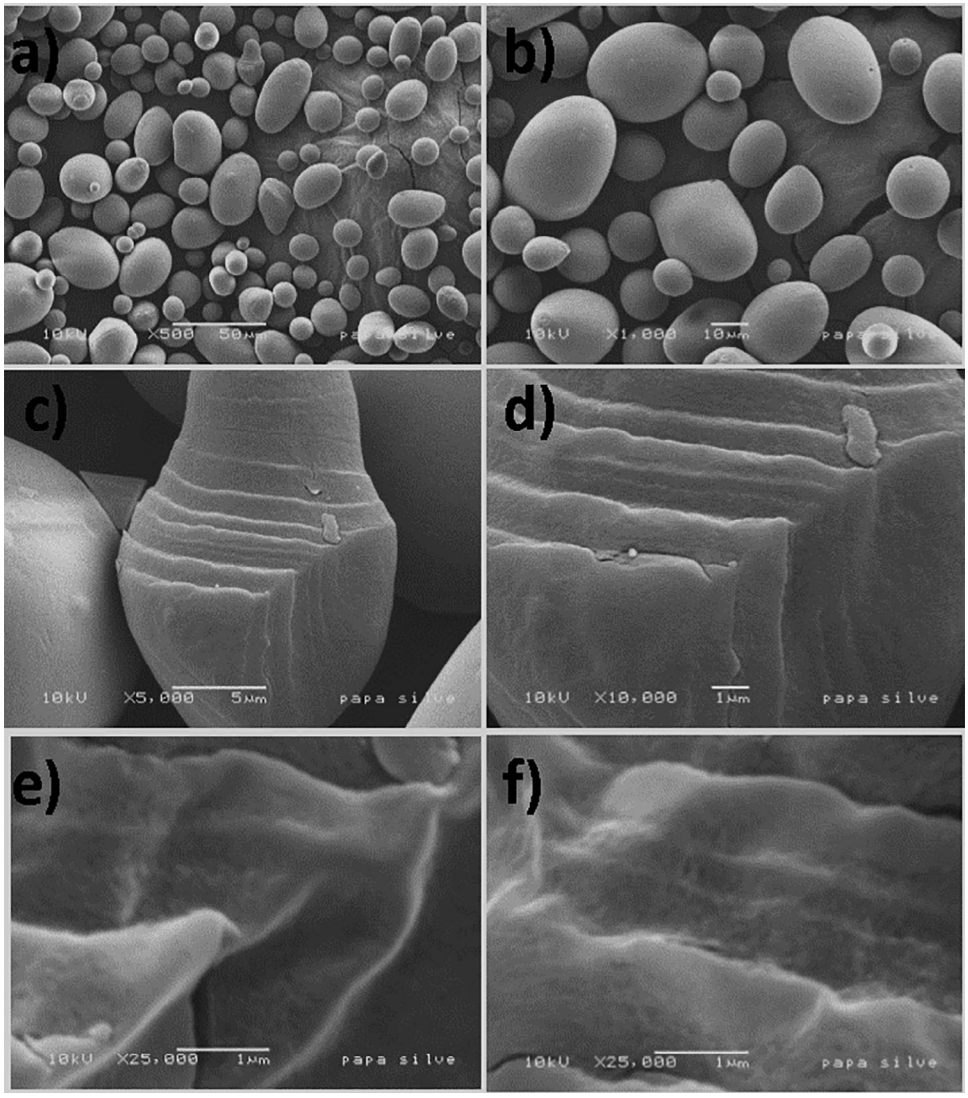


FIGURE 2 | SEM images of isolated starch from wild potatoes. (a and b) Spherical and semi-spherical starches, (c and d) mummy-like starch, and (f and g) the layers of mummy-like starch.

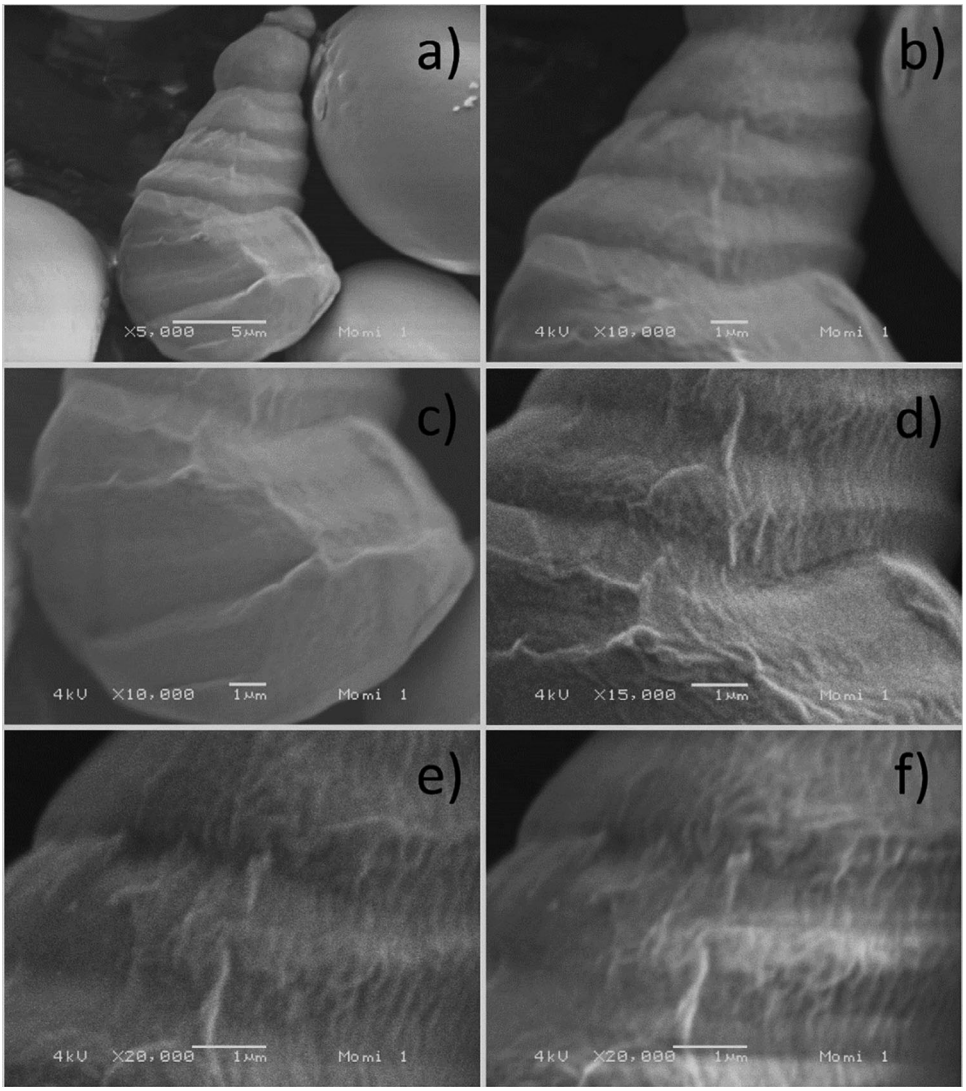


FIGURE 3 | (a and b) SEM images of the worm-like isolated starch from the potato, (c and d) a section of worm-like starch (10 000×), (e and f) magnification of a section of the worm-like starch (20 000 ×).

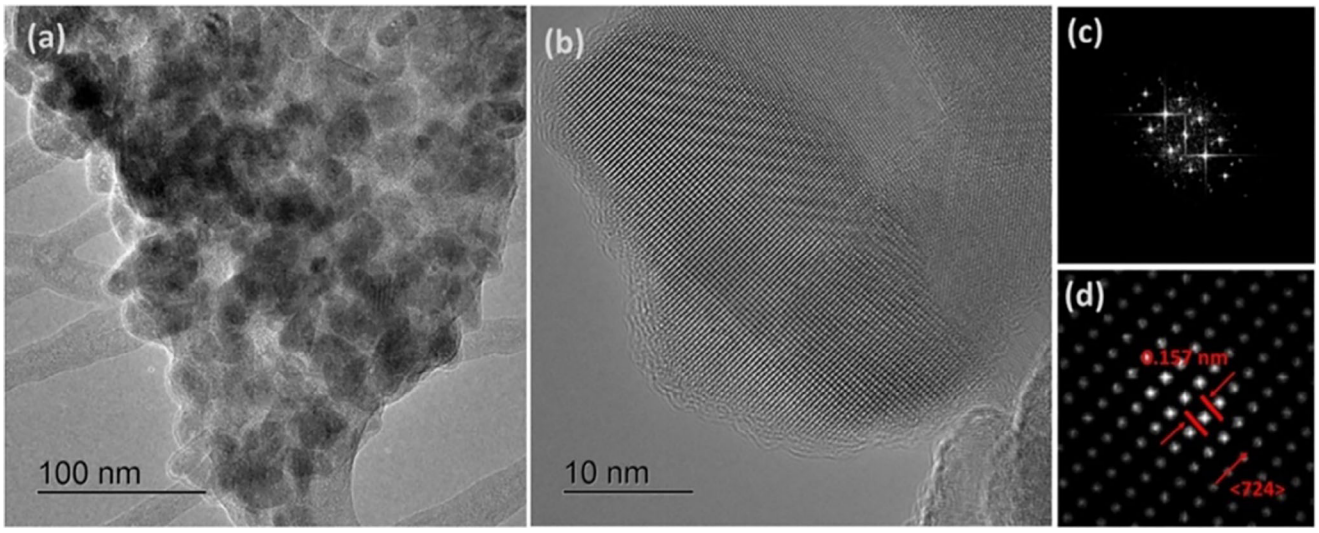


FIGURE 4 | (a) TEM images of isolated nanocrystals, (b) characteristic section of the isolated nanocrystals, (c) representation of the selected section in FT space, and (d) the representation in inverse FT space.

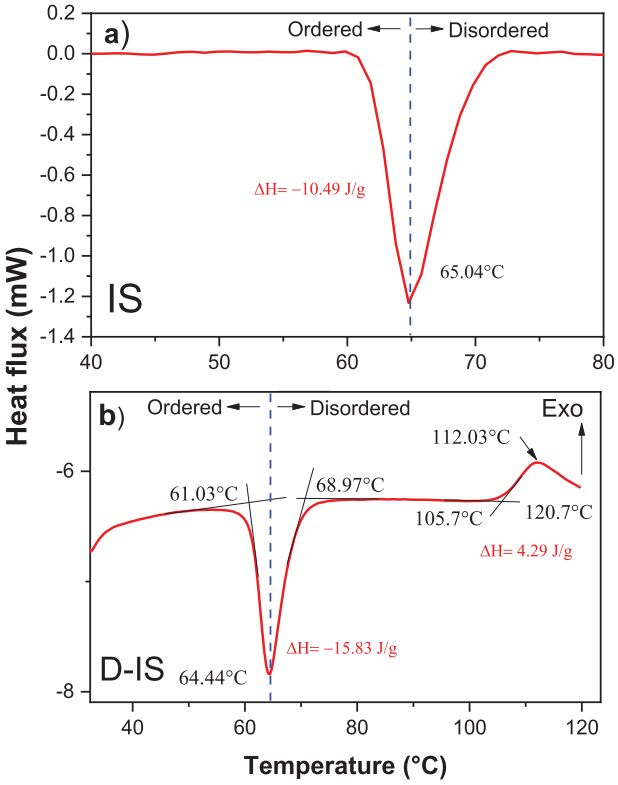


FIGURE 5 | (a) DSC thermogram of isolated potato starch and (b) DSC of defatted isolated starch (D-IS).

of amylose or amylopectin molecules, as they were obtained by acid hydrolysis.

Figure 4c shows the investigated regions in the nanocrystals after applying the FFT (Fast Fourier Transform) with the Digital Micrograph software. The image in the spatial domain was converted to the frequency domain. This method provides information about the crystal structure of the isolated nanocrystals (orientation and spacing of the crystal planes). Figure 4d is the image after applying the mask of the FFT space. This makes it possible to focus on specific areas and reduce the noise to examine the crystal structures of the obtained nanocrystals in detail [19].

Figure 4d shows an interplanar distance of 0.157 nm in the crystal direction ⟨724⟩ and confirms that the starch of the wild potato consists of nanocrystals with a hexagonal structure. Comparing the distances obtained by TEM analysis with the values reported by Rodriguez-Garcia et al. [16] for interplanar distances with hexagonal crystal structure, it can be concluded that the isolated nanocrystals have a hexagonal crystal structure.

3.6 | Thermal Properties

Since the isolated starch is rich in fat (1.65%), it was defatted to investigate the influence of fat on the DSC thermograms. Figure 5a shows the DSC thermogram of IS. The peak at 65.04°C is partly related to the gelatinization phenomena (endothermic) which according to various authors Biliaderis et al. [20] reflects the disorganization or melting of the starch crystallites. Esquivel-Fajardo et al. [7] have shown that the gelatinization is partly the result of solvation of nanocrystals with orthorhombic or/and hexagonal crystal structure, leading to an endothermic transition from T_o to T_p the ordered system; and from T_p to T_e, the disordered system (amorphous matrix). This endothermic peak can also be associated with the partial modification of amylose and amylopectin.

The DSC thermogram of defatted isolated starch (D-IS) is shown in Figure 5b. Two well-defined peaks can be recognized in the temperature range investigated. The first peak at 64.44°C is related to the gelatinization phenomena (endothermic), while the second peak at about 112°C is exothermic and could be related to the formation of the amylose-lipid complexes.

3.7 | X-Ray Diffraction

Once the starch had been isolated, the grains were kept in distilled water without drying; this starch is known as wet starch. The sample was then dried by the heat generated by the X-ray analysis and the X-ray pattern was recorded (dry starch). Figure 6 shows the X-ray diffraction patterns of wet and dry isolated starch from wild potatoes. The vertical lines in these patterns correspond to the identification of the hexagonal crystal structure (B-type starch) and the numbers in brackets (*hkl*) are the Miller indices according to Rodriguez-Garcia et al. [16]. Table 1 shows the (*hkl*) diffraction planes, 2θ (°), d (Å), and the relative intensity calculations for our group for the high intensity diffraction planes. Considering Equation (4) to obtain the d distance.

$$n\lambda = 2d\,\text{sen}\theta \tag{4}$$

where, n is the first diffraction, d is the interplanar distance, and θ is the position of a particular diffraction plane in the X-ray pattern. Here, it is important to remember that the wet starch has a better definition of diffraction planes compared to the dry samples. This means that water plays an important role in the hexagonal structure of the nanocrystals present in the starch. The shift of diffraction planes to higher angles is partly related to the entry of water into the lattice and an increase in the lattice parameter. As mentioned above, preliminary tests with EDS-TEM showed the presence of K, Mg, and Na, in the nanocrystals, which could also change the crystal size of the hexagonal crystal structure.

Using the intensity ratio for the hexagonal structure of the planes (⟨032⟩/⟨121⟩), you can determine the changes in the crystallinity of the starch sample due to the wetting process. If a crystal structure remains unchanged after any physicochemical treatment, this ratio remains constant before and after the process, which means that changes in the structure can be detected by changes in the intensity of the peaks. As you can see in Figure 3b, the intensity of the plane. In the wet sample, the water molecules are part of the crystal structure and improve the crystalline quality (see peak ⟨032⟩). As a result of the water inclusion in the hexagonal lattice, the crystallinity of the starch is increased. These water molecules are in fact, incorporated into the nanocrystals with hexagonal crystal structure.

As for the calculation of the crystalline percentage, it has been described that this is not possible because the crystalline

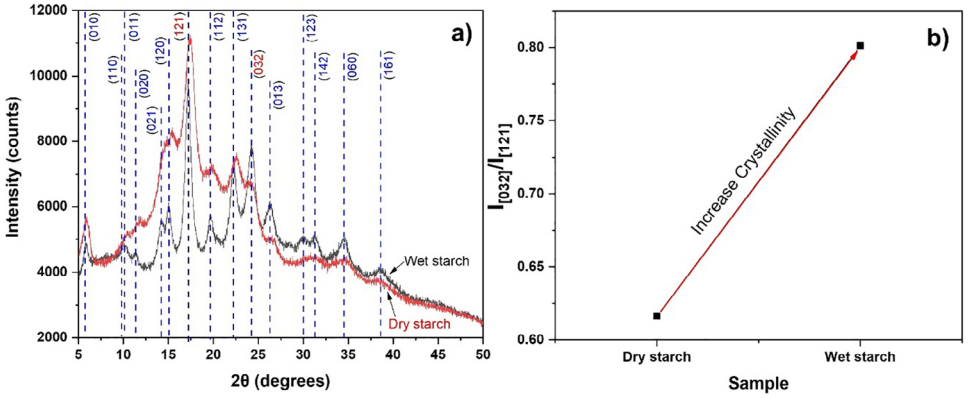


FIGURE 6 | (a) X-ray diffraction patterns and (b) relationship between two diffraction peaks for the hexagonal crystal structure in wet and dry isolated wild potato starch.

TABLE 1 | Identification of the allowed peaks of the hexagonal crystal structure.

	Theoretical		Experimental wet	
(*hkl*)	2θ (°)	*d* (Å)	2θ (°)	*d* (Å)
(010)	5.639	15.660	5.8025	15.219
(110)	9.776	9.040	9.794	9.024
(011)	10.223	8.646	10.038	8.805
(020)	11.292	7.829	11.314	7.815
(021)	14.163	6.248	14.042	6.302
(120)	14.957	5.918	14.985	5.907
(121)	17.238	5.140	17.256	5.134
(112)	19.723	4.497	19.760	4.489
(131)	22.174	4.005	22.271	3.988
(032)	24.175	3.678	24.241	3.668
(013)	26.384	3.375	26.408	3.372
(123)	29.912	2.984	30.071	2.969
(142)	31.327	2.853	31.370	2.849
(060)	34.334	2.609	34.563	2.593
(161)	38.662	2.327	38.679	2.326

structures in starch consist of nanoparticles, and the elastic and inelastic scattering contributions are present in the X-ray pattern [9, 21]. But the hexagonal crystal structure, due to the water inclusion, improves its crystallinity quality.

3.8 | Pasting Properties

One of the most used methods to study the pasting properties of starch is to analyze the relative viscosity or pasting properties using an excess of water. The test conditions for analyzing starch are typically a 1:6 ratio of sample to water according to AACC [22] Method 76-21 for viscosity analysis of flours and starchy products. However, the test must be performed as a function of the rheological regime, as we have suggested elsewhere Esquivel-Fajardo et al. [7]. The regime should be unique for each starch.

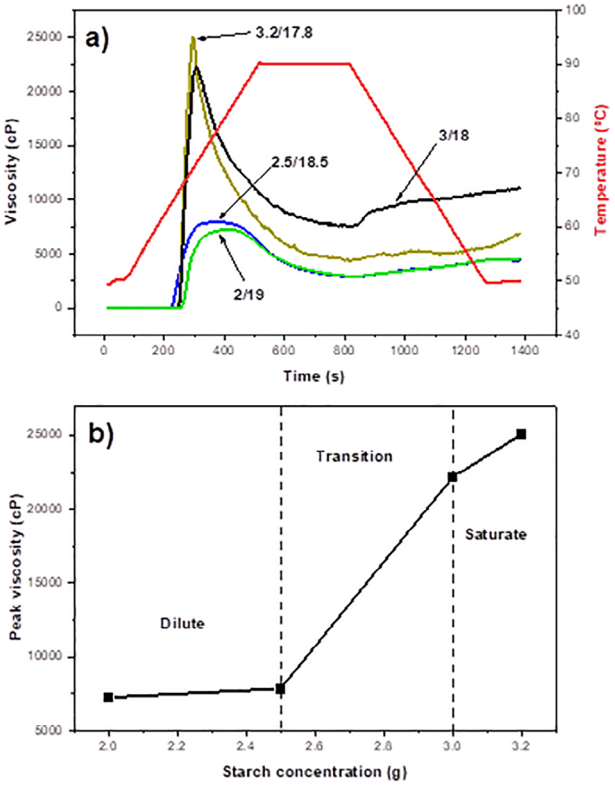


FIGURE 7 | (a) Pasting profiles of isolated starch from wild potatoes at different starch/water ratios and (b) regimes in terms of peak viscosity and starch concentration.

Figure 7a shows the pasting profile of isolated starch from wild potatoes for starch/water ratios of 3.2/17.8, 3/18, 2.5/18.5, and 2/19 as a function of time and shows that the sample develops greater peak viscosities with increasing starch concentration. When peak viscosity as a function of starch concentration is used as a parameter to identify the rheological regime [23], there is an abrupt change in peak viscosity when the starch content exceeds 2.5 g, indicating that the samples are transitioning from the dilution regime to the transition regime and that 3 g/18 mL of water can be used to analyze the pasting profile.

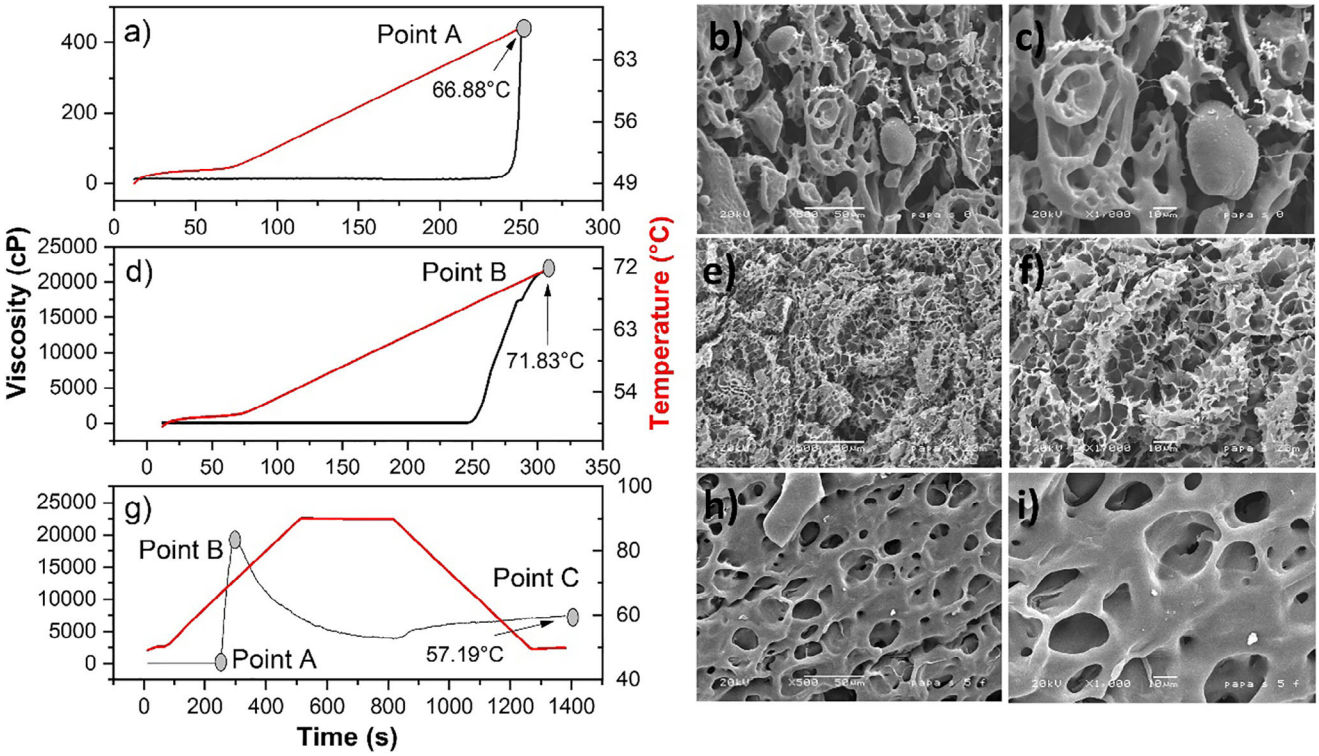


FIGURE 8 | Pasting profiles (a, d, and g) and SEM images (b, c, e, f, g, and i) of isolated starch from wild potatoes at different times of gelatinization.

The pasting profile depends on intrinsic parameters such as the chemical composition of the starch granule, the size of the starch granule, the mineral composition [24], and others. And on extrinsic parameters such as the isolated method, the drying process, the enzymatic attack before processing the sample and others. The end viscosity is between a custard and a hydrogel [2]. This end viscosity indicates a low value of kinetic viscosity.

Figure 8a shows the pasting profile of isolated starch from wild potatoes stopped at point A at a temperature of 66.88°C. At this point, whole granules and other damaged granules can still be seen, forming a starch-water network (Figure 8b,c). In this case, when the sample reaches the peak viscosity (point b), all the starch grains break down and the slurry behaves like a custard [2], as can be seen in Figure 8e,f, the slurry forms a disordered lattice. At point C, the apparent viscosity decreases at the end of the pasting experiment, indicating the formation of a hydrogel. This system forms when the water forms channels through the sample due to the rotation of the impeller, creating a hydrogel. Figure 8g,h shows the formation of microchannels. The pasting properties of this starch indicate that it is not recommended to produce baby food as it can be difficult to swallow.

4 | Conclusions

The present study provides a comprehensive understanding of the general characteristics, mineral composition, starch morphology, thermal properties, X-ray diffraction patterns and pasting properties of the isolated starch of wild potato (*S. cardiophyllum*). The wild potatoes show a wide size range, with remarkable differences in amylose content, fat content, ash, and moisture content compared to white potatoes. The analysis of the mineral composition shows a lower content of minerals, especially potassium, in the wild potato, with a particular morphology observed in the starch grains.

SEM analysis shows a novel worm-like and mummy-like starch morphology, which could have implications for physicochemical properties. The TEM images of isolated nanocrystals indicate hexagonal crystal structures, and thermal analysis shows the influence of fat on gelatinization phenomena. The X-ray diffraction patterns indicate that water plays a crucial role in the hexagonal structure of the nanocrystals, and the presence of minerals further influences the crystal size.

The study of the pasting properties shows a unique pasting profile for isolated starch from wild potatoes, indicating a transition from the dilution regime to the transition regime at higher starch concentrations. The final viscosity behavior, which resembles a transition from pudding to hydrogel, indicates challenges in the production of baby food due to possible swallowing difficulties.

In conclusion, this research sheds light on the various characteristics and properties of isolated wild potato starch and provides valuable insights for further exploration of its potential applications in various fields such as nutrition and agriculture.

Author Contributions

Mario Enrique Rodriguez-Garcia: conceptualization, supervision, investigation, resources, funding acquisition, writing–review and editing. **Brenda Lizbeth Correa-Piña, Guadalupe Nieves-Hernandez**: writing–original draft, data curation, investigation, formal analysis. **Marcela Gaytan Martínez**: investigation, formal analysis, writing–

review and editing. **Oscar Yael Barron-Garcia**: writing – original draft, data curation, methodology, investigation, formal analysis, writing–review and editing.

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Data Availability Statement

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

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