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Effects of continuous and repeated dry heat treatment on the technological properties of green banana (*Musa paradisiaca*) starch

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Abstract

Starch is an important ingredient used in numerous industrial applications. The utilization of nonconventional sources of this carbohydrate enables the improvement of functional properties and reduces waste from certain botanical sources such as green bananas. This study aimed to evaluate the effects of dry heat modification with varying cycles (1–3) and times (3–9 h) on the thermal, paste, structural, and morphological properties, and digestibility of green banana starch, comparing them with native starch. The gelatinization enthalpy decreased with the applied treatment, especially for starches treated with repeated cycles. The peak viscosity, as observed in the RVA curve, decreased after treatment. X-ray diffractometry remained unchanged, while relative crystallinity decreased. The morphology exhibited slight alterations after the treatment. The slow digestibility of the treated starches showed a significant increase compared to the digestibility of native starch.

Keywords: technological properties; physical modification; industrial application.

Practical Application: Native starches from various botanical sources are rarely used industrially due to their limited functional properties. An alternative to this challenge is the modification of the biopolymer. Dry heat modification has proven to be interesting for the application of low-viscosity foods such as dairy drinks. In addition, the treatment represents an additive-free modification with green technology. Green banana starch sources have high resistant starch content and can be linked to functional foods. Therefore, this study aimed to modify green banana starch through dry heat treatment using different cycles and times.

1 INTRODUCTION

Starch is one of the most abundant polysaccharides in nature, with various applications in the food industry and other sectors. This biopolymer consists of two main chemical structures: amylose and amylopectin (Yashini et al., 2022). They can be classified according to their nutritional aspects after ingestion and digestibility: rapidly digestible starch (RDS), which causes a rapid increase in blood glucose and insulin levels; slowly digestible starch (SDS), which releases glucose into the bloodstream slowly and continuously, resulting in a low glycemic response; and resistant starch (RS), which is not digested and can be fermented by the microflora in the large intestine, then acting as a functional fiber (Maior et al., 2021; Yashini et al., 2022).

RS plays an important role in health by preventing cardiovascular diseases, diabetes, obesity, and dyslipidemia and possessing functional properties. It is worth noting the potential for its use in healthier food options for consumers (Maior et al., 2021; Yashini et al., 2022). Despite its various industrial applications, native starch has some limitations due to its low flowability and tendency to retrograde, low paste transparency, and the requirement of high temperatures for gelatinization. To overcome these limitations and improve its functional properties, starch undergoes prior modification, which can be physical, chemical, enzymatic, genetic, or even a combination thereof (Almeida et al., 2022; Yashini et al., 2022).

Modifications by physical methods have been extensively studied and employed as they differ from chemical methods by not generating reagent residues (Almeida et al., 2022). Among these, dry heat treatment (DHT) involves sample heating at temperatures between 110 and 150°C for a pre-established period, with moisture content below 10%. It is an advantageous method as it alters the physicochemical properties of starch without destroying its granular structure (Liu et al., 2022; Sun et al., 2014). This method can be classified as continuous DHT when starch is subjected to uninterrupted heating and repeated DHT, which involves heating and cooling through multiple cycles (Liang et al., 2021; Liu et al., 2022).

Starches subjected to DHT can acquire interesting characteristics concerning gelatinization, thermal stability, solubility, and textures in various foods. In this regard, DHT is a simple and safe method that does not generate chemical residues or effluents, as no chemical reagents are used, thus having no environmental or toxic impacts and characterizing it as a green technology (Liang et al., 2021; Maniglia et al., 2020). The green banana starch is an unconventional alternative source with growing demand in the food industry due to its physicochemical

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and functional properties, including a higher amylose content compared to some conventional starch sources (Yashini et al., 2022). Banana is the most produced fruit in the world, with a production of 150 million tons on 8 million ha (Cardoso et al., 2023; FAO, 2021; Sá et al., 2021). Furthermore, according to FAO (2021), it is estimated that global banana production will grow by approximately 1.5% per year in the coming years.

Unripe bananas are not usually consumed due to their high astringency and hardness, caused by phenolic compounds that degrade as they ripen (Sá et al., 2021). Thus, there is significant post-harvest waste due to low acceptance, leading to inadequate disposal of green bananas with physical irregularities. As a key to reducing waste and providing a low-cost option, the utilization of green bananas as starch in the food industry is an alternative (Nwakego et al., 2022). Therefore, the present study aimed to analyze the effect of thermal treatment on green banana (*Musa paradisiaca*) starch using DHT, examining its thermal, structural, morphological, and paste properties.

2 MATERIALS AND METHODS

The green banana used for starch extraction in this study was obtained from the local market in Curitiba (25° 25' 42" S, 49° 16' 24" W), Paraná, Brazil. All reagents used in the experiment were of analytical grade. Porcine pancreatic α-amylase (EC 3.2.1.1, specifications 8 x USP, P7545) and *Aspergillus niger* amyloglucosidase (EC 3.2.1.3, 300 U/mL, A7095) were obtained from Sigma Chemical Co. (St. Louis, MO, USA).

2.1 Starch extraction

The banana starch was obtained following the methodology described by Izidoro et al. (2011) with slight modifications. Green bananas were washed, peeled, and cut. To prevent enzymatic browning, they were processed with a bisulfite solution (1%, 1:2 w/v). After processing, starch isolation was carried out through aqueous extraction. Deionized water was added in a ratio of 4:1 (v/v). The mixture was then triturated using a blender (Siemsen, BR), model LS-08, until a homogeneous paste was obtained. Subsequently, the formed paste was filtered through a 150-mesh sieve, followed by a 270-mesh sieve. The residual liquid from sieving was centrifuged (Himac, model CR-21 GII; 8500 rpm/5 min). The decanted fraction obtained from centrifugation was dried in a forced air circulation oven at 40°C for 24 h and ground (60 mesh sieve). The extracted starch was stored in a desiccator until the modification step was performed.

2.2 Dry heat treatment

The DHT modification was carried out on green banana starch according to a previously published methodology with slight modifications (Zhou et al., 2021). For this purpose, pre-drying (45°C for 24 h) was performed to reduce the moisture content (> 10%). The samples were subjected to heat treatment in a forced air oven (Tecnal, TE 394/1, Piracicaba, SP, Brazil) for 1, 2, and 3 DHT cycles (1 cycle corresponds to 3 h/120°C) and labeled as RDHT1, RDHT2, and RDHT3, respectively. The samples subjected to continuous DHT treatment were heated at 120°C for 3, 6, and 9 h, labeled as CDHT3, CDHT6, and CDHT9, respectively. Samples CDHT3 and DHT1 represent the same modification condition; therefore, only RDHT1 was discussed. The treatments were kept in a desiccator until further analysis.

2.3 Powder X-ray diffractometry

The samples were kept in an oven (40°C/24 h) to prevent granule aggregation during the analysis. The diffractograms of native and treated green banana starch were obtained using an Ultima IV X-ray diffractometer (Rigaku, Japan). CuKα radiation (λ = 1.541 Å) was used, with a voltage of 40 kV and current of 20 mA. The angular range for detection of scattered radiation was set from 3° to 40° at 2θ, with a scanning speed of 2° min^{-1} and a step size of 0.02° (Bet et al., 2018). From the generated diffractograms, the relative crystallinity (RC) of the samples was calculated based on the peak area ratio to the total, according to Equation 1 (Nara & Komiya, 1983).

$$RC\% = \frac{Ca}{(Aa+Ca)} \times 100 \quad (1)$$

where:

Aa: the amorphous area;

Ca: the crystalline area of the diffractogram.

2.4 Pasting properties

Viscoamylography analysis was used to evaluate the paste properties of native starch and the promoted treatments. For this purpose, an RVA-4 instrument (Newport Scientific, Australia) was used for the evaluation. An 8% (w/w) starch suspension (on a dry basis), with a total mass of 28 g, was prepared and subjected to heating up to 95°C, followed by maintaining the temperature for 6 min, and then controlled cooling under constant rotational agitation (160 rpm). The heating and cooling rate used was 6°C min^{-1}. The equipment measures resistance in the rotation of the suspension, with higher resistance indicating greater viscosity generated by the sample, and temperatures are recorded during the process, resulting in an RVA viscosity profile (Bet et al., 2018).

2.5 Differential scanning calorimetry

The DSC curves were measured using a DSC-Q200 instrument (TA Instruments, USA), which was previously calibrated with indium (purity grade: 99.99%), having a melting point of 156.6°C and ΔH_{fusion} = 28.56 J g^{-1}. For each analysis, approximately 2.5 mg of starch sample on a dry basis was added to deionized water at a mass ratio of 4:1 (water to starch, w/w) in hermetically sealed aluminum crucibles. The airflow rate used was 50 mL/min, with a heating range of 30 to 100°C and a heating rate of 5°C min^{-1}. The onset, peak, and conclusion temperatures of the event are collected, and ΔH_{gel} is calculated through integration of the graph generated in the analysis (Kubiaki et al., 2018).

2.6 Field emission gun scanning electron microscopy

The sample's morphology was analyzed using a field emission scanning electron microscope (FEG-SEM) MIRA 3 (Tescan, Czech Republic). The starch samples were sprayed onto a carbon tape and then metalized with gold and palladium (150 s; 20 mA) to create a conductive surface for electron imaging. A tungsten filament lamp was used to generate electrons in the field emission gun with an electron beam voltage of 15 kV (Ito et al., 2018).

2.7 In vitro digestibility

The *in vitro* digestibility analysis was performed following the methodology proposed by Englyst et al. (1992). Granular starch (0.9 g) was suspended in 20 mL of sodium acetate buffer (0.1 M; pH 5.2). Then, the samples were incubated at 37°C for 15 min, and hydrolysis was carried out with an enzymatic solution (5 mL) containing pancreatic α-amylase and amyloglucosidase from *Aspergillus niger* (Sigma-Aldrich Co., St. Louis, MO, USA) under continuous agitation (100 strokes min^{-1}). Aliquots of 0.25 mL were taken and placed in 66% ethanol after 20 and 120 min of incubation to measure the digestible fractions of starch. The results were determined using the glucose oxidase/peroxidase (GOPOD) kit (Megazyme, K-GLUC, USA). The portion that was not hydrolyzed after the 120-min period was considered RS. The final hydrolyzed concentration was referred to as the total glucose concentration (TG). The contents of SDS, RDS, and RS fraction were calculated using the Equations 2, 3 and 4:

$$RDS = G_{20} \times 0.9 \quad (2)$$

$$SDS = (G_{120} - G_{20}) \times 0.9 \quad (3)$$

$$RS = (GT - G_{120}) \times 0.9 \quad (4)$$

Where:

G_{20}: the fraction hydrolyzed after 20 min;

G_{120}: the fraction hydrolyzed after 120 min of incubation;

0.9: the conversion factor of starch to glucose (calculated from the starch monomer and the molecular weight of glucose).

2.8 Statistical analysis

The results were expressed as mean ± standard deviation, and the STATISTICA StatSoft 8.0.360 software (Tulsa, USA) was used. An analysis of variance was performed to analyze the behavior of the samples. Tukey's tests were conducted to evaluate significant differences between samples at a confidence level of 95% ($p < 0.05$) (Ito et al., 2018).

3 RESULTS AND DISCUSSION

3.1 Powder X-ray diffractometry

X-ray diffractograms were used to assess the diffraction pattern of the starches. According to the established classification, starch sources can be divided into three different types (A, B, and C) based on their crystallinity. Starch with a type B diffraction pattern exhibits higher diffraction peaks at 2θ ≅ 5,6°, 15°, 17°, 22°, and 24°, as evidenced in this study (Figure 1) (Yang et al., 2022). Similar results were observed by Marta et al. (2019) when extracting starch from bananas from various locations in Indonesia. They also demonstrated the presence of a broad peak between 22 and 24° (2θ), as observed in the present study. Several factors can influence the starch diffraction pattern, such as the banana cultivar, plant growth conditions, and the extraction technique employed (Marta et al., 2019; Yang et al., 2022).

The RC of the samples was calculated (Table 1), and a gradual decrease in RC is observed as the treatment time and cycles increase. Native green banana starch had the highest RC value (32.08%), while starch treated with 9 h of continuous DHT showed the lowest value (26.51%). Similar observations were reported in previous studies when modifying corn and rice starches using DHT, respectively (Xu et al., 2018; Zou et al., 2020). The reduction in RC may be associated with the collapse of amylopectin crystallites and the movement of double helices during modification, leading to a reorientation of the crystallite and a decrease in RC. For all the treatments in this study, although there is no variation in the characteristic diffraction peaks, there is a decrease in peak intensity, indicating that DHT modification was not able to promote significant changes in terms of the diffraction pattern, remaining of type B. Similar results were found in previous studies, where no changes were observed in this parameter (Gou et al., 2019; Oh et al., 2018; Zhou et al., 2021).

3.2 Pasting properties

Pasting properties are relevant to evaluating the behavior of a starch suspension in water when subjected to heating under

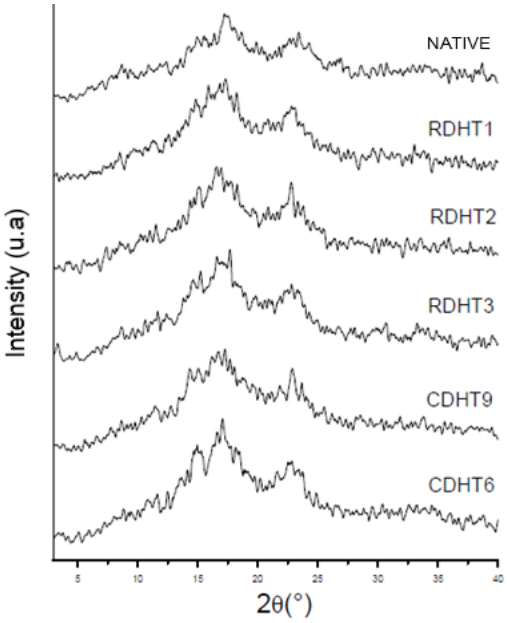

Figure 1. Diffractograms of native and heat-treated starches. RDHT1, RDHT2, and RDHT3 represent treatment by repetition under 1, 2, and 3 cycles, respectively. CDHT6 and CDHT9 represent continuous treatment for 6 and 9 h, respectively.

agitation. Additionally, the analysis provides an estimation of the tendency for retrogradation that occurs during the cooling period. Important parameters are measured through the pasting property. Table 2 shows the pasting property parameters for native and modified starches through continuous and repetitive DHT treatment. Compared to untreated starch (3003 mPa s), the viscosity of the treated starches significantly decreased ($p < 0.05$) and differed among all analyzed samples. The lowest peak viscosity value was observed for the green banana starch treated with continuous DHT for 9 h (243.50 mPa s), indicating that the viscosity alteration was most effective under this modification condition.

The gelatinization viscosity decreased as the treatment time of the samples increased (Figure 2). This behavior is more prominent in the continuous treatments, with the CDHT9 sample showing the lowest viscosity. This can be attributed to the limitation of starch granule expansion caused by the treatment (Liu et al., 2022). The decrease in breakdown indicates that after the treatment, the starches became more resistant to shear and high temperatures, showing greater gel stability and lower chances of retrogradation, as evidenced by the lower setback values (Gou et al., 2019; Maniglia et al., 2020).

In general, continuous treatment proved to be more efficient in reducing the starch paste viscosity, as observed in studies with sweet potato starch and chestnut starch subjected to DHT (Gou et al., 2019; Liu et al., 2022). This could be attributed to the structural changes in the starch particles during the cyclic treatment, resulting in a lower amount of energy required for paste formation and hence lower viscosity (Liu et al., 2022).

3.3 Differential scanning calorimetry

An aqueous starch suspension, when subjected to heating, undergoes a process called gel formation, also known as gelatinization, which can be observed through DSC (Differential Scanning Calorimetry). It is characterized by three distinct temperatures, where T_o or T_{onset} is related to the onset of the gelatinization process. The peak temperature of the event is represented by T_p, and finally T_c represents the temperature at which the gelatinization event is completed and the starch suspension is fully gelatinized, with all the granules swollen. The gelatinization temperature range is represented by the

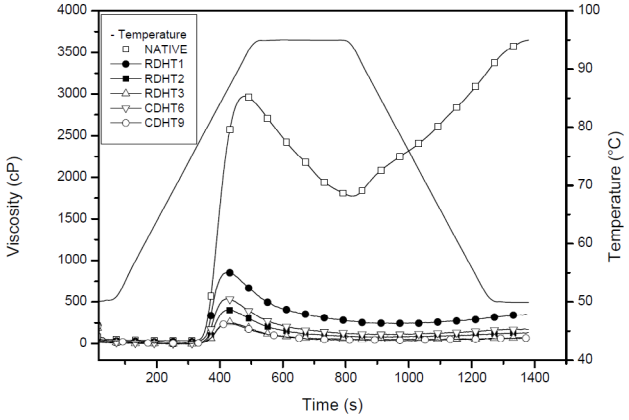

Figure 2. Viscoamylographic profile of native and DHT-treated samples. RDHT1, RDHT2, and RDHT3 represent treatment by repetition under 1, 2, and 3 cycles, respectively. CDHT6 and CDHT9 represent continuous treatment for 6 and 9 h, respectively.

Table 1. Differential scanning calorimetry (DSC) and relative crystallinity (RC) of green banana starch samples.

Sample	Ti /°C	Tp /°C	Tf /°C	Tf-Ti /°C	ΔH_{gel} /J.g $^{-1}$	RC%
Native	$70.1^{a} \pm 0.1$	$74.7^{a} \pm 0.0$	$79.4^{ab} \pm 0.1$	$9.3^{b} \pm 0.2$	$11.6^{b} \pm 0.4$	$32.08^{ab} \pm 1.22$
RDHT1	$67.7^{e} \pm 0.1$	$73.0^{a} \pm 0.0$	$76.5^{c} \pm 0.1$	$8.7^{b} \pm 0.1$	$11.39^{b} \pm 0.3$	$32.28^{ab} \pm 0.38$
RDHT2	$68.7^{b} \pm 0.1$	$69.8^{a} \pm 5.8$	$80.6^{a} \pm 1.0$	$11.9^{a} \pm 1.0$	$6.1^{d} \pm 0.3$	$32.09^{ab} \pm 1.03$
RDHT3	$68.4^{c} \pm 0.1$	$73.1^{a} \pm 0.1$	$74.3^{d} \pm 0.1$	$5.9^{c} \pm 0.1$	$8.29^{c} \pm 0.3$	$33.24^{a} \pm 0.47$
CDHT6	$68.9^{de} \pm 0.1$	$73.71^{a} \pm 0.0$	$79.3^{b} \pm 0.2$	$11.4^{a} \pm 0.3$	$13.3^{a} \pm 0.6$	$29.67^{b} \pm 0.00$
CDHT9	$67.9^{d} \pm 0.1$	$73.27^{a} \pm 0.0$	$77.4^{c} \pm 0.1$	$9.5^{b} \pm 0.1$	$11.09^{b} \pm 0.1$	$26.51^{c} \pm 0.83$

To: onset temperature; Tp: peak temperature; Tc: conclusion temperature; ΔHgel: gelatinization enthalpy. Values are presented as mean ± standard deviation. Values followed by the same letter in the same column are not significantly different according to the Tukey's test ($p < 0.05$). RDHT1, RDHT2, and RDHT3 represent DHT treatment by repetition with 1, 2, and 3 cycles, respectively. CDHT6 and CDHT9 represent continuous DHT modification for 6 and 9 h, respectively.

Table 2. RVA profile results of native and DHT-treated green banana starch samples.

Sample	Pasting temperature /°C	Viscosity peak /mPa s	Breakdown /mPa s	Setback /mPa s	Final viscosity /mPa s
Native	$78.60^{a} \pm 0.29$	$3003.00^{a} \pm 0.71$	$1246.00^{a} \pm 1.41$	$1905.00^{a} \pm 0.71$	$3662.50^{a} \pm 0.71$
RDHT1	$78.55^{a} \pm 0.42$	$859.30^{b} \pm 1.06$	$620.50^{b} \pm 0.71$	$106.80^{b} \pm 1.06$	$345.75^{b} \pm 0.35$
RDHT2	$80.25^{a} \pm 0.21$	$403.50^{d} \pm 0.71$	$325.30^{d} \pm 0.35$	$54.50^{d} \pm 0.71$	$131.50^{d} \pm 0.71$
RDHT3	$80.95^{a} \pm 0.92$	$257.30^{e} \pm 1.77$	$209.80^{e} \pm 1.06$	$24.00^{f} \pm 1.41$	$71.50^{e} \pm 0.71$
CDHT6	$79.23^{a} \pm 0.46$	$537.50^{c} \pm 0.78$	$428.50^{c} \pm 0.71$	$66.50^{c} \pm 0.71$	$175.50^{c} \pm 0.71$
CDHT9	$80.35^{a} \pm 1.34$	$243.50^{f} \pm 0.71$	$208.80^{e} \pm 0.35$	$33.00^{e} \pm 1.41$	$66.00^{f} \pm 1.41$

mPa s: milliPascal-seconds. Values are presented as mean ± standard deviation. Values followed by the same letter in the same column are not significantly different according to the Tukey's test ($p < 0.05$). RDHT1, RDHT2, and RDHT3 represent DHT treatment by repetition with 1, 2, and 3 cycles, respectively. CDHT6 and CDHT9 represent continuous DHT modification for 6 and 9 h, respectively.

degree of heterogeneity of the crystallites (T_c-T_o) (Cheng et al., 2023; Dornelles et al., 2023).

Figure 3 shows the DSC curves for the samples characterized in this study. The samples presented a typical gelatinization pattern, with endothermic events observed during the excessive heating of starch in the presence of water. This phenomenon occurs due to the breaking of hydrogen bonds between the molecules and the consequent disruption of the structural micellar organization of the granules (Lei et al., 2020). Overall, there is a decrease in the gelatinization temperatures for the modified samples compared to the native green banana starch, which is consistent with the onset temperatures found for these samples (Table 1).

The thermal transition parameters of the botanical source studied are summarized in Table 1. For starches treated with DHT in repetition, a more significant decrease in T_o was observed for RDHT1 (67.7°C). As the cycles and modification times increase, T_p is not significantly influenced. The final gelatinization temperature (T_c) showed an effective decrease for all treatments, although it was more significant for three cycles of DHT treatment (74.3°C). These observations may indicate that the gelatinization temperature range becomes wider than that of native starch, and the homogeneity of the double-helix crystallites present in the starch is increased after DHT treatment (Lei et al., 2020).

The gelatinization enthalpy (ΔH_{gel}) is related to the loss of the double helical order rather than the loss of crystallinity inside the granules (Maior et al., 2021). When a high value of ΔH_{gel} is observed, it implies that the interactions between the double helices (which are grouped) in the crystalline regions may be better dispersed due to longer chains in the amylopectin (Bet et al., 2018). Thus, the treatment applied to the RDHT2 sample was more effective compared to the others, as it showed the lowest T_p (69.8°C) and the lowest ΔH_{gel} (6.1 J.g^{-1}).

As significant changes in the gelatinization enthalpy variations (ΔH_{gel}) were observed among the samples (Table 1), it is suggested that the modification was sufficient to completely break some of the double helices present in the amorphous and crystalline regions of the granules (Xu et al., 2021).

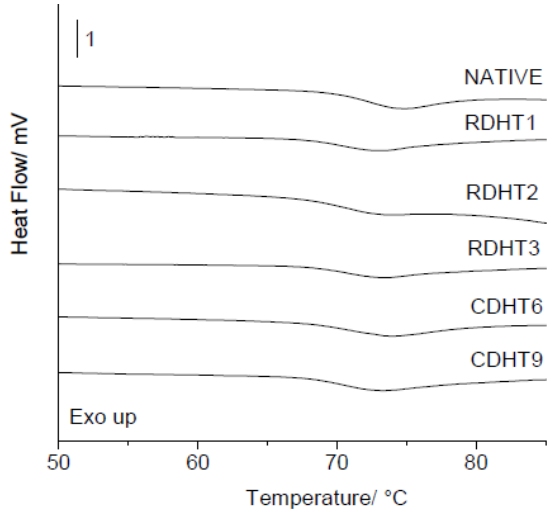

Figure 3. DSC curves of native and treated starch samples. RDHT1, RDHT2, and RDHT3 represent treatment by repetition under 1, 2, and 3 cycles, respectively. CDHT6 and CDHT9 represent continuous treatment for 6 and 9 h, respectively.

3.4 Field emission gun scanning electron microscopy

In general, untreated starch granules showed varied sizes and shapes, including oval, spherical, and rod-like forms, with a smooth surface and a slight rough layer on some granules (Figure 4), similar to those observed by Wu et al. (2020) and

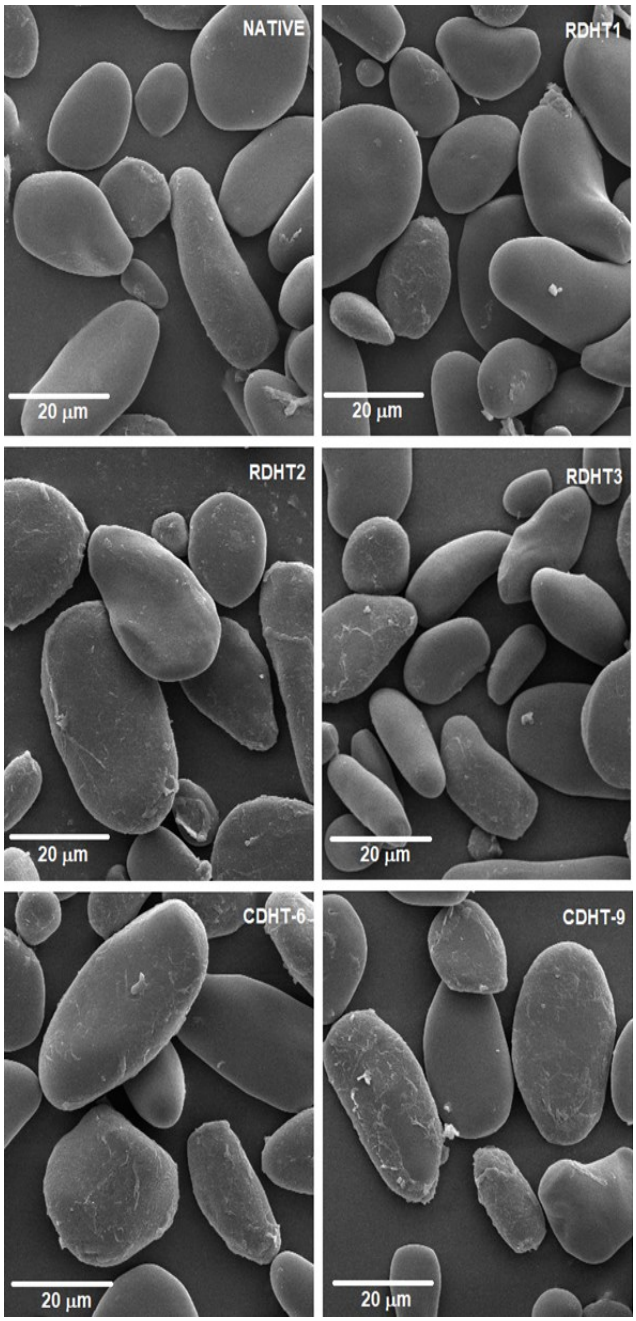

Figure 4. Microimages of native and treated starch samples. RDHT1, RDHT2, and RDHT3 represent treatment by repetition under 1, 2, and 3 cycles, respectively. CDHT6 and CDHT9 represent continuous treatment for 6 and 9 h, respectively.

Yang et al. (2022) in native banana starch using scanning electron microscopy.

After the treatments, it can be observed that some granules showed slight deformations and flattening, as well as an increase in the rough layer, particularly in the RDHT2, CDHT6, and CDHT9 samples. Furthermore, the sample treated with 9 h of repetitive treatment (RDHT3) showed a higher number of elongated and smaller granules, with less surface roughness. In a study conducted with mung bean starch (Liang et al., 2021), no changes were observed in the starch granules after RDHT and CDHT treatments, neither among themselves nor compared to the native starch. In another study, with waxy potato starch (Liu et al., 2019), holes were found in the superficial granules. The generation of these potholes was not necessary due to the transfer or rearrangement of central molecules and the weakening of the tissue structure in the starch granules. However, in another study with quinoa starch, the surface of the starch changed from a smooth structure to a porous structure with the appearance of holes after treatment with DHT (Zhou et al., 2021). Therefore, the DHT did not significantly alter the structure of green banana starch granules, aligning with the findings of Maniglia et al. (2020), who subjected cassava starch to DHT for 2 and 4 h.

3.5 In vitro digestibility

The contents of the three starch fractions are presented in Table 3. The contents of RDS, SDS, and RS for green banana starch were 5.73, 4.43, and 89.84%, respectively. After DHT treatment, an increase in the content of SDS and a decrease in RS were observed for all modifications. Starches treated for 6 h under continuous treatment showed a lower RDS value (3.83%) and a more pronounced increase in SDS (14.84%). The treated starches exhibited a 29.85% increase in the SDS fraction and an 8.10% decrease in RS. Similar results were found by Liu et al. (2019) while studying potato starch, and a reduction in the RS content was observed. Maize starch subjected to DHT (Zou et al., 2020) showed a decrease in RS and an increase in SDS, similar to what was observed in this study. The content of SDS is primarily influenced by the proportion and arrangement of the amorphous structure in the granules, while the content of RS is influenced by the presence of a more organized structure in the granules, preferably composed of amylopectin. The structural disintegration caused by DHT can increase starch digestibility, leading to increased levels of digestible starch fractions (Bian et al., 2020). However, González et al. (2020), when modifying wheat flour through DHT, observed that the starch exhibited an increase in RS content, indicating that the botanical source plays a crucial role in the modification characteristic promoted by the treatment.

Table 3. Results of *in vitro* digestibility of native and modified green banana starch samples.

Sample	RDS (%)	SDS (%)	RS (%)
Native	$5.73^{a} \pm 0.05$	$4.43^{d} \pm 0.54$	$89.84^{a} \pm 0.58$
RDHT1	$5.11^{ab} \pm 0.54$	$8.23^{c} \pm 0.57$	$86.66^{b} \pm 0.04$
RDHT2	$6.08^{a} \pm 0.44$	$11.49^{b} \pm 0.73$	$82.44^{c} \pm 0.29$
RDHT3	$5.69^{a} \pm 0.15$	$12.10^{b} \pm 0.05$	$82.21^{c} \pm 0.20$
CDHT6	$3.83^{b} \pm 0.10$	$14.84^{a} \pm 0.01$	$81.34^{c} \pm 0.11$
CDHT9	$6.48^{a} \pm 0.53$	$12.57^{b} \pm 0.72$	$80.96^{c} \pm 1.25$

RDS: rapidly digestible starch; SDS: slowly digestible starch; RS: resistant starch. Values are presented as mean ± standard deviation. Values followed by the same letter in the same column are not significantly different according to the Tukey's test ($p < 0.05$). RDHT1, RDHT2, and RDHT3 represent DHT treatment by repetition with 1, 2, and 3 cycles, respectively. CDHT6 and CDHT9 represent continuous DHT modification for 6 and 9 h, respectively.

DHT modification induces changes in two starch fractions, specifically RS and SDS. Although there is a modification in the RDS fraction for amylomaize treated continuously for 6 h, the effects are more pronounced in the aforementioned fractions. Continuous treatments for 6 and 9 h resulted in the most statistically significant differences, both for SDS and RS.

The digestibility results found in this study point to potential applications in foods aimed at specific consumers who need to reduce their glycemic index after a meal. This is possible because the content of SDS was increased with the continuous use of DHT. In this research, the analyses were conducted on granular starch, so further studies are needed to evaluate the behavior and changes induced by gelatinized starch.

4 CONCLUSION

In this study, DHT under continuous and repeated regimes was used to modify green banana starch. The application of modification resulted in changes in the gelatinization process, and morphology was also affected by the DHT, with a more prominent effect in the samples treated with repeated cycles. The X-ray diffraction pattern remained unchanged, but there was a decrease in RC for both continuously and cyclically treated starches. The use of DHT led to a significant decrease in the paste properties of all treatments, especially in the more drastic modifications, such as 9 h of continuous treatment and 3 cycles of DHT. The *in vitro* digestibility of green banana starch was also altered, with an increase in the slowly digestible fraction and a decrease in the RS fraction.

Starches with low viscosity, as observed in this study, can be applied to food products that do not require high viscosity or products that should not form a gel, for example, dairy drinks and bakery products. Furthermore, starches with reduced ΔH_{gel} require less energy in the industrial food process, resulting in lower production costs. The modification increased the fraction of SDS by 29.85%, suggesting its application in foods geared toward low-sugar diets and functional foods.

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