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Review Article

An overview on the dry heat treatment (DHT) for starch modification: Current progress and prospective applications

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ABSTRACT

Starch plays a pivotal role in numerous applications, making the enhancement of its functionality through physical processes increasingly important. Dry heat treatment (DHT) is a straightforward and eco-friendly technique that significantly improves starch characteristics and boosts food quality. This method has emerged as a focal point in starch modification research in recent years. This paper reviews current studies on the DHT of starches from various botanical sources, presenting key concepts and methodologies while delving into the impacts and mechanisms of DHT on the structural and physicochemical properties of starches. Furthermore, it elaborates on how additional components, such as ionic gums, amino acids, and sugars, can enhance the functionality of starches modified by DHT. Additionally, this review discusses the practical applications of dry heat-modified starches in the food industry, aiming to offer valuable insights for ongoing research and potential applications in enhancing food quality and functionality through innovative starch modifications.

1. Introduction

Starch, the second most abundant polysaccharide in plants after cellulose, is a key energy source for humans (Gul et al., 2021; Zhu et al., 2023). It consists of linear amylose and branched amylopectin, which form semicrystalline structures through hydrogen bonding (Gul et al., 2021). The structure of starch granules, described by Vandeputte and Delcour (2004), shows amylopectin arranged in crystalline and amorphous layers, with semi-crystalline growth rings varying in order (Fig. 1). These rings have thicknesses ranging from 100 to 400 nm, with the crystalline layers approximately 9–10 nm thick (Li et al., 2022). Zhu and Wang (2014) found that high amylose content can lead to interactions between amylose and amylopectin chains. Natural starch, with its poor resistance to heat, shear, and acid, and tendency to retrograde, often requires chemical additives for quality enhancement in food processing. However, concerns about the potential health risks of these additives have shifted focus to physical modification methods. One of the key physical modification methods for starch is dry heat treatment (DHT), which involves heating starch at elevated temperatures (typically between 130 °C and 200 °C) with low moisture content (below 10%) for varying durations. This process alters the physicochemical properties of starch without significantly affecting its granular structure, making it a widely preferred method in both food science and materials engineering (Ruths, 2024; Liu, 2023; Gong et al., 2021). DHT has been shown to enhance starch's solubility, gelatinization, and rheological properties, all of which are critical for its applications in food products and other industries (Rao et al., 2022a; Oh et al., 2018a; La Fuente et al., 2023a). One of the primary effects of DHT is the alteration of the starch's gelatinization properties. Studies have demonstrated that DHT can lead to changes in the thermal behavior and pasting characteristics of starches, which are essential for their functionality in food systems. For instance, dry heating can increase the viscosity of starch pastes, as observed in the interactions between starch and hydrocolloids like xanthan gum (Ji et al., 2017a; Su et al., 2018a). This interaction not only enhances the shear stability of the pastes but also contributes to the formation of a more robust gel network, which is beneficial for various culinary applications (Ji et al., 2017a; Su et al., 2018a). Furthermore, DHT has been reported to increase the resistant starch (RS) content in certain starches, which is advantageous for health-related applications, particularly in managing postprandial glycemic responses (Kanagaraj et al., 2019a; Muninathan, 2024). The mechanism behind this involves the rearrangement of starch chains and the formation of new

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intermolecular associations during the heating process, which can lead to a reduction in the digestibility of starch (La Fuente et al., 2023a; Muninathan, 2024). This property is particularly valuable in the development of functional foods aimed at improving metabolic health. In addition to its effects on gelatinization and digestibility, DHT also influences the morphological and structural properties of starch granules. For example, the treatment can cause partial disruption of the granule structure, leading to increased surface area and enhanced interaction with water, which can improve the overall solubility of the starch (Rao et al., 2022a). This is particularly evident in studies involving quinoa starch, where DHT resulted in increased solubility and altered rheological properties (Rao et al., 2022a). Moreover, the application of DHT in conjunction with other additives, such as pectin or organic acids, has been explored to further enhance the properties of starch. For instance, the combination of DHT with pectin has been shown to modify the gelatinization properties of sweet potato starch, leading to improved functional characteristics (Liu et al., 2020a; Chen et al., 2017). Such synergistic effects highlight the versatility of DHT as a modification technique. Drawing on a comprehensive review of the literature, this paper discusses the use of DHT to enhance the processability of starch. It concentrates on the principles and techniques of DHT in starches, examines the effects of DHT on the structural and functional properties of starches from various plants, and the effects of DHT when used with other food ingredients on starch functionality and digestibility. Additionally, the uses of dry heat-modified starches in the food industry are summarized. By analyzing the main challenges in this study and considering future research directions, this work aims to provide insights and references for the research and development of dry heat modification in starches.

2. Dry heat treatment: principles and methods

A thermal process known as DHT entails the thermal processing of starch in a "dry" state. Typically, the starch has a hydration content of 7%–13% and is processed at temperatures ranging from 110 °C to 170 °C. DHT modifies the starch without causing pyrolysis, thereby enhancing the functional properties and preserving the structural integrity of the starch granules. The fundamental principle of DHT is the modulation of starch properties through thermal energy in the absence of significant moisture, without the induction of gelatinization or pyrolysis. At temperatures ranging from 110 °C to 170 °C, the amorphous regions of starch endure a phase transformation. The limited water content of starch molecules enhances their molecular mobility, which acts as a plasticizer and allows for changes in the granular structure without resulting in gelatinization (Chandanasree et al., 2016). The thermal energy applied during DHT causes the disruption and reorganization of hydrogen bonds within the starch granules, which leads to modifications in both crystalline and amorphous regions. This enhances properties such as enzymatic digestibility, solubility, and pasting behavior. In contrast to high-temperature pyrolysis, which involves the cleavage of glycosidic bonds and the significant degradation of starch molecules, DHT is intended to elicit controlled degradation (Schafranski et al., 2021). This controlled degradation process generates minor structural modifications that improve the functional properties of the starch without causing charring or fragmentation. The moisture content in DHT is maintained at a level that is insufficient for gelatinization to prevent the excessive enlargement or loss of birefringence of starch granules. This preserves granular integrity while permitting internal molecular rearrangements (Schafranski et al., 2021). Food ingredients, including ionic gums (xanthan gum, guar gum, carboxymethyl cellulose, sodium alginate, whey protein isolate, etc.) and amino acids, can be disseminated in the aqueous phase at a specific mass concentration prior to the introduction of DHT (Chandanasree et al., 2016). In order to optimize the efficacy of the starch treatment, it may be processed using DHT after being immediately mixed, vigorously stirred, and dried at low temperatures to maintain a moisture content below 10%. The typical conditions and parameters for DHT are summarized in Table 1, which includes the methodologies used to analyze the treated starch, temperature, moisture content, time, and cycling times. Studies have evaluated the influence of continuous versus repeated DHT on starch characteristics, revealing that starch is particularly susceptible to continuous DHT, which substantially alters its physical properties (Zhang et al., 2021a; Liang et al., 2021a). In contrast, the starch's resistance to digestion and the content of RS are more effectively increased by repeated DHT administrations (Liang et al., 2021a). Furthermore, the integration of DHT with other starch modification techniques has increased the potential applications and flexibility of this method in starch modification (Chi et al., 2019; Lima et al., 2021).

3. Mechanisms and impact of DHT on starch properties

3.1. Granular morphology

The properties of starches altered through DHT have been rigorously examined using a variety of sophisticated structural analysis techniques, as detailed in Table 1. These techniques predominantly involve microscopic methods aimed at studying the morphology of starch granules, such as light microscopy, scanning electron microscopy, and confocal laser scanning microscopy. Research conducted by Lei et al. (Lei et al., 2020) and Miao et al. (Miao et al., 2021) observed that DHT did not substantially change the granular morphology of corn starch, with the granules maintaining their integrity even after treatment at temperatures between 140 and 200 °C for 2 h. This suggests that DHT primarily facilitates the migration and elimination of water molecules rather than inducing gelatinization or retrogradation processes (Lei et al., 2020). Similarly, another study further emphasized that the morphology of the faba bean starch granules remained largely unaltered, demonstrating that DHT can enhance specific functional properties without compromising the structural integrity of the granules (Fasakin et al., 2024). Contrarily, other studies have reported that DHT can impact the structural integrity of starch granules. Zhang et al. (Zhang et al., 2021a) noted the development of wrinkles or grooves on the surfaces of normal wheat

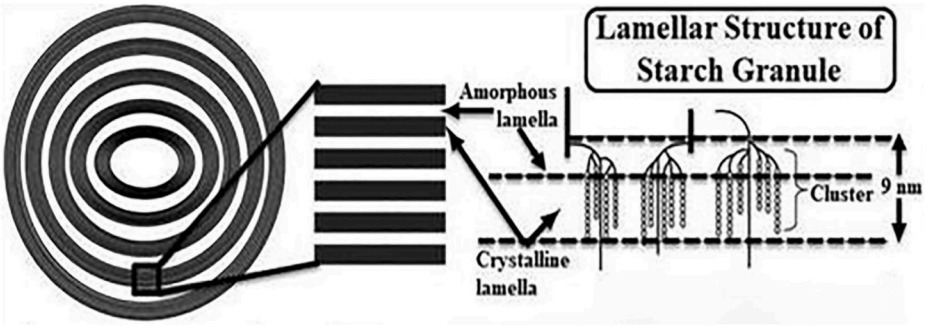

Fig. 1. Illustrates a schematic representation of the lamellar structure of a starch granule, adapted from Vandeputte and Delcour (Vandeputte and Delcour, 2004).

Table 1
Conditions and parameters of dry heat-modified starches and its identification methods.

Starch source	DHT conditions temperature (°C)	Moisture content (%)	Time (h)	Cycling times	Identification methods granular morphology	Crystalline and helical structure	Molecular feature	Reference
Normal and waxy wheat	130	<10	3	2–6	SEM, CLSM	XRD	HPLC	Zhang et al. (Zhang et al., 2021a)
Wheat	130	<10	2–4	1	PLM		FTIR, GPC	Maniglia et al. (Maniglia et al., 2020a)
Corn	140	<10	8–20	1–5	SEM	XRD	FTIR	Zou et al. (Zou et al., 2020)
Corn	130	<10	2–4	1	SEM	–	–	Sun et al. (Sun et al., 2013)
Corn	140–200	7	2	1	SEM	XRD	SEC	Lei et al. (Lei et al., 2020)
Waxy corn	140	<10	4–20	1–5	SEM	XRD	FTIR	Zou et al. (Zou et al., 2019)
Rice	130	7	2–4	1	SEM	XRD	FTIR	Qiu et al. (Qiu et al., 2015a)
High-amylose rice	110–150	<10	1–4	1	–	XRD	–	Oh et al. (Oh et al., 2018b)
Blue highland barley	150–180	<10	2–4	1	SEM, CLSM	XRD	FTIR	Liu et al. (Liu et al., 2023)
Highland barley	160	<10	2	1	SEM	XRD, SAXS	GPC, FTIR, NMR	Bian et al. (Bian et al., 2020)
Proso millet	130	8	2–4	1	SEM	XRD	FTIR	Sun et al. (Sun et al., 2014)
Buckwheat	120–170	7	0.5	1	SEM	XRD	FTIR	He et al. (He et al., 2022)
Mung bean	130	9.2	3	2–6	SEM	XRD	HPLC, FTIR	Liang et al. (Liang et al., 2021a)
Red adzuki bean	130	–	1–9	1	SEM, PLM, CLSM	XRD	HPLC, FTIR, HPAEC	Ge et al. (Ge et al., 2021)
Potato	130	<10	3–9	1	SEM, CLSM	XRD	HPLC, HPAEC	Zhang et al. (Zhang et al., 2023a)
Potato	130	<10	2	1	–	XRD, SAXS	FTIR, GPC	Chi et al. (Chi et al., 2019)
Waxy potato	110	<10	0.5–2.5	1	SEM, PLM	XRD	–	Liu et al. (Liu et al., 2019)
Sweet potato	110	<10	3	6	SEM, LM, CLSM	XRD	FTIR	Gou et al. (Gou et al., 2019)
Cassava	130	6.8	2–4	1	LM, PLM	XRD	GPC	Maniglia et al. (Maniglia et al., 2020b)
Taro	130	<10	2–4	1	–	–	–	Pramodrao and Riar (Pramodrao and Riar, 2014)
Chestnut	140	<10	4–8	1	SEM	XRD	–	Liu et al. (Liu et al., 2022a)
Quinoa	140	<10	4	5	SEM	XRD	FTIR	Zhou et al. (Zhou et al., 2021a)

DHT: dry heat treatment; SEM: scanning electron microscopy; CLSM: confocal laser scanning microscopy; PLM: polarized light microscopy; LM: light microscopy; XRD: X-ray diffraction; SAXS: small angle X-ray scattering; NMR: nuclear magnetic resonance; HPLC: high performance liquid chromatography; HPAEC: high-performance anion-exchange chromatography; GPC: gel permeation chromatography; FTIR: Fourier transform infrared spectroscopy. ”– “implies that identification methods are not involved in the literature.

and waxy wheat starch granules following DHT exposure. Similarly, DHT application on waxy corn starch resulted in erosion, leading to the formation of surface fissures and openings as identified by Zou et al. (Zou et al., 2019). Additionally, Vashisht et al. (2017) found that exposure to 130 °C for 2 and 4 h caused the shattering of *Dioscorea* starch granules. Some researchers propose that amylose leakage during DHT could contribute to these structural changes (Chandanasree et al., 2016), though this theory does not fully explain the observed surface erosion in waxy starch granules following DHT (Zhang et al., 2021a). Furthermore, DHT has been shown to induce clumping of starch granules, altering their characteristics. The contradictory findings may be due to differences in the specific conditions of the DHT, such as temperature, duration, and moisture content, as well as the type of starch used. Gong et al. (Gong et al., 2021) noted that DHT has less effect on the starch granule structure while significantly changing its physicochemical properties. Ru et al. (Ru et al., 2015) reported that dry heat-treated corn starch displayed granule adhesion when observed under an electron microscope (Fig. 2). These granules, polygonal in shape with multiple planes and edges, exhibited a compact structure and smooth edges. At a treatment temperature of 60 °C, the distribution of starch granules remained relatively uniform, with a largely intact particle state, although some exhibited small apertures (Ru et al., 2015). On the other hand, this temperature is not within the established range for DHT. At 120 °C for 1 h, there was notable bonding between granules, suggesting that dry heat brought the starch molecules closer together. At 150 °C, fragments of starch granules adhered to the surface of others, potentially due to amylose precipitation around the starch granules (Ru et al., 2015). The research on DHT of proso millet flour and its starch at 130 °C for 2 or 4 h revealed cluster aggregation (Sun et al., 2014). The higher degree of aggregation observed in proso millet flour was mainly attributed to interactions between non-starch components on the granule surface. Moreover, the effect of repeated DHT on the morphology of chickpea starch is influenced by the specific treatment conditions, including temperature and duration. Research has shown that as the duration of repeated DHT increased, the starch granules remained largely intact during the heat treatment (Zhang et al., 2024). However, the gelatinization process progressively extended from the outer layers to the interior of the starch granules as treatment time increased. At the same time, the surface of the granules became rougher, and the degree of gelatinization became more pronounced, leading to

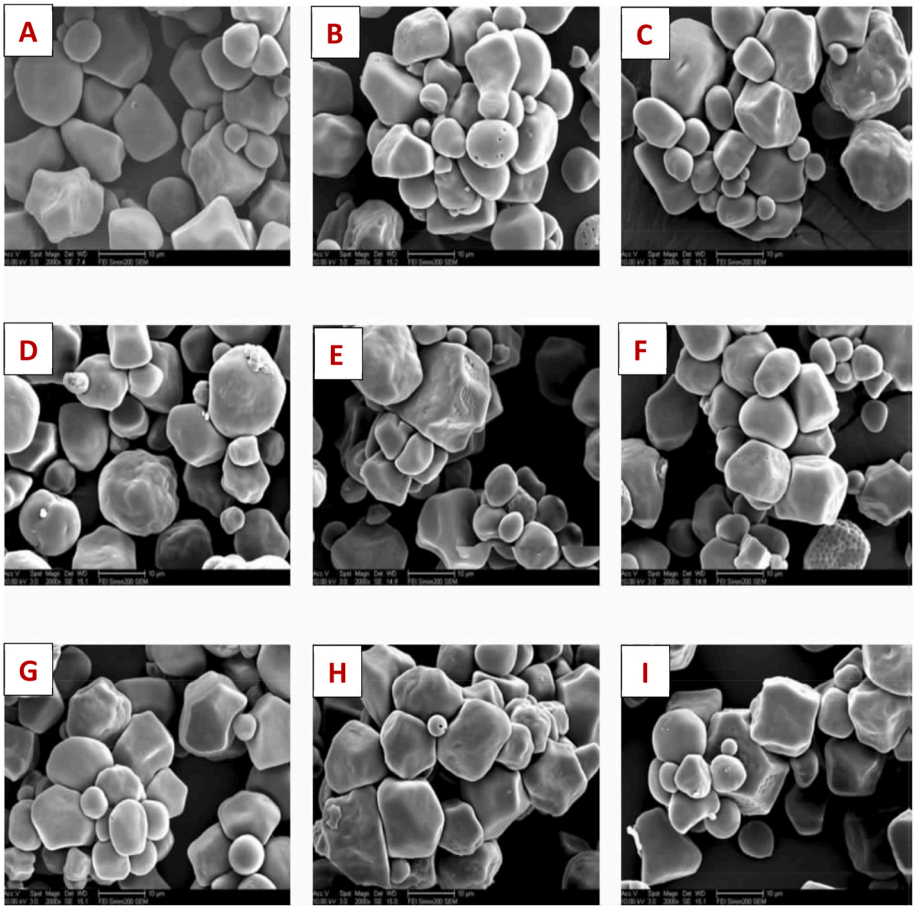

Fig. 2. SEM images of corn starch granules treated under dry-heated treatment. (A) Native corn starch; (B) and (C) corn starch treated at 60 °C for 1 and 4 h respectively; (D) and (E) corn starch treated at 90 °C for 1 and 4 h respectively; (F) and (G)corn starch treated at 120 °C for 1 and 4 h respectively; (H) and (I) corn starch treated at 150 °C for 1 and 4 h respectively, were adapted from Ru et al. (Ru et al., 2015).

the formation of larger granules as a result of starch granule aggregation (Zhang et al., 2024). Although the studies reviewed primarily provide insights into the external morphology of starch granules, it is plausible that the DHT process also significantly affects their internal structure. Therefore, further research is necessary to determine the internal morphological changes in starch granules following DHT. These studies collectively suggest that DHT affects starch granule morphology through mechanisms involving changes in crystallinity, amylose and amylopectin content, and physicochemical properties, which are influenced by the specific conditions of temperature and duration of the treatment. The variations in findings across different starch types and treatment conditions underscore the complexity of starch granule morphology and the need for tailored approaches in starch modification. Overall, DHT is an effective method for modifying the granular morphology of starch, with the optimal temperature range typically between 130 °C and 200 °C (Aaliya et al., 2021; Gong et al., 2022; RUTHS et al., 2024). The treatment duration can vary from 1 to 20 h, depending on the starch type and the desired modifications (Liu et al., 2020a; Aaliya et al., 2021; RUTHS et al., 2024). While shorter treatment times of 1–4 h are sufficient for some applications, longer durations may be necessary for more significant structural changes (Aaliya et al., 2021; Ganesh et al., 2020a). These findings highlight the flexibility of DHT in tailoring starch properties, with the specific conditions needing to be adjusted based on the starch source and intended application.

3.2. Crystalline and molecular structure characterization

The optimal temperature range for DHT to induce significant changes in the X-ray diffraction patterns of starch varies depending on the type of starch and the specific conditions of the treatment. For potato starch, DHT at 120 °C resulted in a transition from type B to type C diffraction patterns, along with a decrease in relative crystallinity, indicating significant structural changes (de Oliveira Maior et al., 2024). In contrast, blue highland barley starch maintained its "A"-type crystalline structure even at higher temperatures of 150 °C and 180 °C, although other physicochemical properties were altered (Liu et al., 2023). Infrared dry heat treatment (IR-DHT) at 200 °C did not lead to irreversible amorphization of potato starch, but it did affect the crystallinity when exposed to water at elevated temperatures (Voroshnina et al., 2024). For rice starch, dry heating at 130 °C altered the X-ray diffraction pattern, with changes in peak intensity observed (Lee et al., 2017a). Additionally, dry heating of corn starch at 190 °C led to a 7.3% reduction in relative crystallinity, demonstrating significant structural transformation (Peng et al., 2024). Similarly, the relative crystallinity of chickpea starch decreased following DHT (Zhang et al., 2024). Native starch, which initially had a crystallinity of 42.62%, dropped to 39.35% and 38.38% after specific heating durations. These findings suggest that while lower temperatures around 120 °C can induce changes in some starches, higher temperatures up to 200 °C are often necessary to achieve more pronounced modifications in the X-ray diffraction patterns, particularly for starches with more stable crystalline structures. The specific temperature and duration of treatment should be tailored to the starch type and desired modification, as excessive heat can lead to undesirable degradation (Bidzińska et al., 2015). The effects of DHT on the crystalline structure of starch molecules present a complex and sometimes contradictory landscape in the literature. While some studies

suggest that DHT leads to a decrease in crystallinity and disruption of the crystalline structure, others indicate that it can also promote recrystallization or the formation of new crystalline structures. On one hand, several studies report that DHT results in a reduction of crystallinity in starch. For instance, Liu et al. (Liu et al., 2022b) observed that DHT can lead to a decrease in the effective water content of starch, which subsequently affects the gel network structure and reduces the swelling and water absorption capacity of starch granules. This aligns with findings from Aaliya et al. (Aaliya et al., 2021), who pointed out that DHT causes a rupture of the crystalline structure and a disruption of the double-helix structure, indicating a significant alteration in the crystalline arrangement of starch. Conversely, other studies highlight that DHT can lead to the formation of new crystallites or the perfection of existing crystalline regions. Qiu et al. (Qiu et al., 2015a) reported that DHT might contribute to the formation of new crystallites or recrystallization, suggesting that some crystalline regions may become more ordered as a result of the treatment. This is further supported by the work of Zheng et al. (Zheng et al., 2020), which indicates that thermal treatment can lead to complex processes involving conformational changes and chain alignment, potentially enhancing the crystalline structure in certain contexts. Moreover, the findings of Jin and Wang (2020) suggest that while amorphous regions are primarily affected during heat treatment, the crystalline regions may require higher thermal energy for disruption, indicating that some crystalline structures could remain intact or even become more stable under specific conditions. These variations can be explained by the differential impact of DHT on the molecular conformation and hydrogen bonding within starch, which are crucial for maintaining its crystalline structure. Heating disrupts the double-amylose helix and increases intramolecular hydrogen bonds, leading to changes in the crystalline region (Zhiguang et al., 2022). Additionally, the specific conditions of DHT, such as temperature and duration, play a significant role in determining the extent and nature of these structural changes, as seen in the contrasting effects of DHT and annealing on black highland barley starch (Liu et al., 2024). Therefore, the molecular mechanism behind these contradictory findings lies in the diverse structural modifications induced by DHT, which are influenced by the starch type and processing parameters. Therefore, DHT is an effective technique for modifying the crystalline structure of starch, with the optimal temperature and time parameters varying based on the starch type and desired modifications. Typically, moderate temperatures ranging from 120 °C to 200 °C and treatment durations of 2–15 h can effectively alter starch crystallinity and enhance its functional properties, while minimizing excessive degradation (Liu et al., 2023; de Oliveira Maior et al., 2024; Voroshnina et al., 2024; Peng et al., 2024; Hui et al., 2024). DHT generally leads to a reduction in the molecular weight of starch due to the breakdown of starch molecular chains, as observed in corn starch where a significant decrease in molecular weight was noted, resulting in the formation of soluble amylopectin and nano-aggregates that stabilize emulsions (Peng et al., 2024). Similarly, in wheat starch, DHT promotes the breakdown of molecular chains, enhancing starch-lipid interactions and forming V-type crystalline structures, which also results in a lower molecular weight (Zheng et al., 2024). However, the extent of these changes can vary based on the starch source and DHT conditions. For instance, cassava starch showed increased mechanical properties and decreased water permeability after DHT, indicating structural rearrangements rather than simple degradation (La Fuente et al., 2022). In black highland barley starch, DHT increased the RDS content while decreasing RS, suggesting a shift in molecular structure rather than a uniform reduction in molecular weight (Liu et al., 2024). The variability in outcomes is further exemplified by taro starch, where DHT led to increased amylose content and solubility, but decreased crystallinity and molecular weight, highlighting the role of temperature and duration in determining the specific structural changes (Hui et al., 2024). Additionally, the type of crystalline structure and the presence of other components, such as lipids, can influence the molecular weight changes, as seen in potato starch where cyclic DHT increased RS content despite a decrease in crystallinity (de Oliveira Maior et al., 2024). These findings underscore that the effects of DHT on starch are multifaceted, influenced by the interplay of treatment conditions, starch type, and the presence of other interacting molecules, leading to diverse structural and functional outcomes. Some studies suggest that DHT promotes the leaching of amylose, increasing its solubility (Liu et al., 2022c). This is attributed to the disruption of the starch granule structure and the weakening of the interactions between amylose and amylopectin (Liu et al., 2022c). However, other studies indicate that DHT can enhance the complexation between amylose and lipids, which may restrict the leakage of amylose (Lee et al., 2017a; Garcia and Franco, 2014). Regarding the effects on amylopectin, some research reports that DHT can increase the thermal stability of amylopectin by enhancing hydrogen bond interactions (Qiu et al., 2015a). In contrast, other studies suggest that DHT can lead to the degradation of amylopectin, affecting the gelation and rheological properties of the starch (Peng et al., 2024). The contradictory findings may be due to differences in the starch sources, moisture content, and specific conditions of the DHT process (Sui et al., 2016; Zavareze et al., 2010). For instance, the extent of changes in the amylose and amylopectin proportions during DHT has been found to depend on the moisture content and starch source (Sui et al., 2016; Zavareze et al., 2010). Additionally, the presence of other components, such as lipids and proteins, can also influence the effects of DHT on the chain length distribution of amylose and amylopectin (Lee et al., 2017a; Yang et al., 2022). The findings indicate that elevated temperatures, specifically between 180 °C and 200 °C for durations of 10–30 min, effectively induce substantial molecular weight decrease and structural alterations in amylose and amylopectin across different starch varieties (Liu et al., 2023; Peng et al., 2024; Hui et al., 2024; Mao et al., 2023; Tomomi et al., 2016). Nevertheless, the ideal temperature and duration may necessitate modification according on the starch source and the intended use.

3.3. Chain length distribution of amylopectin

The effects of DHT on amylopectin chain length distribution are influenced by several molecular mechanisms, including hydrogen bonding and van der Waals forces, although their dominance varies depending on the context. DHT, as explored in various studies, leads to significant structural changes in starch, including amylopectin, primarily through hydrolysis and rearrangement of molecular interactions within the starch granules. For instance, the hydrolysis of amylopectin in the amorphous regions of starch granules during DHT results in a convergence of molecular sizes, indicating a breakdown of larger chains into smaller ones (Tomomi et al., 2016). This process is facilitated by the disruption of hydrogen bonds, which are crucial in maintaining the structural integrity of starch granules. The disruption of these bonds increases the susceptibility of starch to water absorption, enhancing swelling and solubility, as observed in time-dependent heat treatments (Banerjee and Kumar, 2024). Additionally, van der Waals forces play a significant role in stabilizing complex biomolecular structures, including starch, by contributing to the overall energetic balance that maintains structural integrity (Rossi et al., 2015). However, the specific impact of van der Waals forces in the context of DHT on amylopectin is less directly addressed in the literature compared to hydrogen bonding. The interplay of these forces, along with other factors such as moisture content and temperature, ultimately influences the physicochemical properties of starch, including its crystallinity and molecular weight distribution (Bidzińska et al., 2015; Hoover, 2010). Therefore, while both hydrogen bonding and van der Waals forces are integral to the structural changes observed in amylopectin during DHT, hydrogen bonding appears to have a more direct and observable impact on the chain length distribution due to its role in facilitating hydrolysis and molecular rearrangement. The impact of DHT on the chain length distribution of amylopectin is not universally consistent across different starch sources. However, the general trend is that DHT can lead to a

decrease in the proportion of short amylopectin chains (Qiu et al., 2015a; Jiranuntakul et al., 2012; Varatharajan et al., 2010). The degree of change in the amylopectin chain length distribution seems to be influenced by factors such as the moisture content, treatment temperature, and duration of the DHT (Liu et al., 2022c; Jiranuntakul et al., 2012; Varatharajan et al., 2010; Gu et al., 2017). Harsher dry heat conditions (higher temperature, longer duration) tend to result in more pronounced changes in the amylopectin structure (Liu et al., 2022c; Gu et al., 2017). Specifically, DHT at 120 °C for 24 h has been shown to decrease the amount of long amylopectin chains (DP $\geq$ 37) in normal corn starch (Jiranuntakul et al., 2012). Similarly, in wheat starch, DHT at 200 °C led to the hydrolysis of amylopectin in the amorphous regions, resulting in a convergence of molecular sizes for both amylose and amylopectin (Tomomi et al., 2016). Potato starch treated with DHT at 120 °C for durations ranging from 3 to 15 h shows a decrease in relative crystallinity and an increase in RS content, suggesting that cyclic treatments are particularly effective in modifying amylopectin structure (de Oliveira Maior et al., 2024). Taro starch, when subjected to DHT at 130 °C for up to 7 h, exhibits increased amylose content and solubility, with a decrease in molecular weight and crystallinity, indicating a shift in amylopectin chain length distribution (Hui et al., 2024). In contrast, potato and waxy starches treated at temperatures up to 120 °C did not exhibit any changes in the amylopectin chain length distribution (Jiranuntakul et al., 2012; Varatharajan et al., 2010). Similarly, for rice starch, DHT at 120 °C for 16 h did not affect the amylopectin chain length distribution, while microwave treatment displayed increased thermal stability compared to untreated starch (Qiu et al., 2015a). The optimal DHT temperature for altering amylopectin chain length and its subsequent impact on starch functional properties varies depending on the starch source and desired modifications. For instance, DHT at 190 °C significantly transforms corn starch, reducing the relative crystallinity and degrading extra-long amylopectin chains into shorter ones, which enhances the formation of hot-water soluble fractions that stabilize oil-in-water emulsions (Peng et al., 2024). In contrast, taro starch modified at 130 °C for 5 h shows increased amylose content and solubility, while its relative crystallinity and molecular weight decrease, suggesting that moderate temperatures can effectively alter starch properties for specific applications like high-viscosity foods (Hui et al., 2024). Potato starch treated at 120 °C exhibits a transition in X-ray diffraction patterns and a decrease in crystallinity, with cyclic treatments notably increasing RS content, indicating that lower temperatures can also enhance functional properties such as digestibility (de Oliveira Maior et al., 2024). Additionally, blue highland barley starch treated at 150 °C shows decreased amylose content and pasting viscosity, while increasing solubility and water absorption, demonstrating that higher temperatures can significantly modify physicochemical properties (Liu et al., 2023). DHT generally decreases the overall viscosity of starch pastes, making them exhibit shear thinning behavior and "solid-like" gel properties (Lei et al., 2020; Oh et al., 2018b). However, at certain conditions (e.g., 130 °C for 1 h), there can be an increase in gel strength and pasting viscosity (Oh et al., 2018b). As the heating temperature increases, the shear resistance of the starch becomes stronger, approaching a Newtonian fluid behavior (Lei et al., 2020). DHT can make starch gels more fragile and reduce their breaking point, indicating a more brittle texture (Adawiyah et al., 2017). It also enhances paste stability and reduces retrogradation, which is beneficial for food applications (Zhang et al., 2021b). These findings suggest that while higher temperatures like 190 °C can drastically alter amylopectin structure, moderate temperatures around 120–130 °C are effective for enhancing specific functional properties such as viscosity and digestibility, depending on the starch type and application.

3.4. Thermal properties

The thermal properties of starch during DHT are significantly influenced by both temperature and time. DHT modifies the physicochemical characteristics of starch, leading to changes in gelatinization, viscosity, and crystallinity. Temperature plays a crucial role in the gelatinization process of starch. Higher temperatures facilitate the disruption of the crystalline structure of starch granules, leading to increased gelatinization. For instance, Liu et al. (Liu et al., 2022c) demonstrated that DHT at elevated temperatures resulted in decreased gel strength and hardness of chestnut starch, indicating a reduction in crystalline regions and an increase in amorphous areas within the starch granules. Similarly, Chen et al. (Chen et al., 2017) reported that DHT at 130 °C enhanced the gelatinization viscosity of starch blends, suggesting that higher temperatures promote interactions within the starch matrix that affect its thermal properties. The study by Gao et al. (Gao et al., 2021) also supports this, indicating that DHT can improve the freeze-thaw stability of potato starch, which is closely related to its thermal properties. Time is another critical factor that influences the thermal properties of starch. Extended heating times can lead to further degradation of starch chains, affecting their thermal stability. For instance, Fen et al. (Fen et al., 2021a) noted that longer heating times resulted in a decrease in the crystalline regions and crystal strength within starch granules, which directly impacts the thermal parameters such as gelatinization temperature and enthalpy. Additionally, Qiu et al. (Qiu et al., 2015a) found that prolonged DHT significantly altered the pasting properties of starch, indicating that time-dependent changes in starch structure can lead to variations in its thermal behavior. The findings of Zhang et al. (Zhang et al., 2011) also highlight that the duration of heat treatment affects the gelatinization temperature range and the energy required for gelatinization, as measured by differential scanning calorimetry (DSC). Moreover, the interaction between temperature and time is critical in determining the extent of starch modification. For example, the combined effects of high temperature and prolonged treatment times can lead to a significant reduction in the crystallinity of starch, as observed by Zhou et al. (Zhou et al., 2021b) in their study on quinoa starch. This reduction in crystallinity is associated with changes in thermal properties, such as lower gelatinization temperatures and altered enthalpy values, which reflect the energy required to disrupt the hydrogen bonds in the starch structure (Dos Santos et al., 2016). Table 2 shows that DHT impacts the thermal properties of starch, resulting in decreased initial gelatinization temperature (T_o), peak temperature (T_p), final gelatinization temperature (T_c), and the enthalpy change (ΔH) across various sources. Specifically, DHT affected starches from highland barley (Liu et al., 2023), maize (Lei et al., 2020), potato (Chi et al., 2019), waxy potato (Liu et al., 2019), corn (Ru et al., 2015), and buckwheat (He et al., 2022). Furthermore, the extent of this decline became more pronounced as the temperature of DHT increased. In their study, Oh et al. (Oh et al., 2018b) investigated the variations in the gelatinization characteristics of high-amylose rice starch prior to and following DHT treatment. The study found that when the processing time is constant (4 h) and as the processing temperature increases (110–150 °C), T_o (59.4–53.6 °C), T_p (65.2–53.8 °C), and ΔH (9.1–3.6 J/g) of high-amylose rice show a downward trend (Table 2). These results indicate that starches are easier to gelatinize after DHT, and less heat is required for gelatinization. Liu et al. (Liu et al., 2020b) noted that ideal heat treatment conditions can improve the crystal structure of starch by increasing the migration rate of the double helix. Therefore, it is speculated that the destruction of the original weak starch microcrystalline and double helix structure leads to the reduction of T_o, T_p, and T_c, thereby reducing the heat required for gelatinization. Li et al. (Li et al., 2013) attributed the decrease in ΔH associated with these transformations to the structural disruption of starch granules caused by DHT. Some studies indicate that DHT consistently increases gelatinization temperatures. For example, Qin et al. (Qin et al., 2016) reported that the T_p of glutinous rice flour increased significantly after DHT, suggesting enhanced thermal stability. Similarly, Liu et al. (Liu et al., 2022b) observed changes in the thermal properties of chestnut starch due to DHT, although their findings primarily focused on gel strength and hardness rather than direct measurements of gelatinization temperatures. The ΔH associated with

Table 2
Thermal properties of different starches before and after DHT.

Starch source	DHT condition	Thermal property				Reference
		T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)	
High-amylose rice	110–150 °C, <10% moisture, 1–4 h	59.4–53.6↓	65.2–53.8↓	NA	9.1–3.6↓	Oh et al. (Oh et al., 2018b)
Buckwheat	120–170 °C, 7% moisture, 0.5 h	57.62–50.34 ↓	63.74–54.96↓	NA	6.52–3.11↓	He et al. (He et al., 2022)
Corn	90–150 °C, <10% moisture, 0.5–4 h	63.7–62.7↓	70.8–66.8↓	74.9–72.0↓	12.3–10.9↓	Ru et al. (Ru et al., 2015)
Corn	140–200 °C, 7% moisture, 2 h	68.8–61.5↓	71.4–66.3↓	76.5–76.8∼	12.2–6.6↓	Lei et al. (Lei et al., 2020)
Blue highland barley	150–180 °C, <10% moisture, 2–4 h	55.8–51.5↓	59.6–54.5↓	65.6–60.5↓	7.7–6.5↓	Liu et al. (Liu et al., 2023)
Potato	130 °C, <10% moisture, 2 h	61.07–57.23↓	66.95–63.27↓	76.29–76.12 ∼	20.53–17.84↓	Chi et al. (Chi et al., 2019)
Waxy potato	110 °C, <10% moisture, 0.5–2.5 h	68.06–62.59↓	73.27–68.08↓	79.90–74.48↓	14.68–9.87↓	Liu et al. (Liu et al., 2019)

"↑" indicates a greater value; "↓" indicates a lower value; "∼" denotes a similar value; "NA" not available.
T_o: onset gelatinization temperature; T_p: peak gelatinization temperature; T_c: conclusion gelatinization temperature; ΔH: gelatinization enthalpy change; DHT: dry heat treatment.

gelatinization also presents conflicting findings. Some studies report that DHT increases ΔH, indicating that more energy is required to disrupt the starch structure during gelatinization. For example, Zhou et al. (Zhou et al., 2015) found that cross-linked waxy maize starch showed increased melting enthalpy after DHT, suggesting enhanced interactions within the starch granules. The source of starch and the specific conditions of DHT (temperature, duration, and moisture content) also contribute to the observed contradictions. For example, Ganesh et al. (Ganesh et al., 2020a) found that the effects of DHT on *Dioscorea* starch varied, with minor decreases in amylose content and corresponding changes in thermal properties. This suggests that different starches may respond differently to the same treatment conditions, leading to variability in thermal properties. This discrepancy highlights the complexity of the interactions occurring during DHT and how they can vary based on treatment conditions and starch composition. In short, the optimal DHT conditions for achieving the desirable thermal properties in starch are contingent upon the specific starch source and composition, as well as the targeted thermal characteristics. Generally, the thermal properties of starch can be modified by subjecting it to DHT at 120–200 °C for 1–20 h (Liu et al., 2020a, 2022c, 2023; Gong et al., 2022; Mao et al., 2023). However, the precise conditions must be optimized for the specific application.

3.5. Gel strength

DHT can have various effects on the gel strength of starch, depending on the specific starch source and treatment conditions. One potential mechanism for the decrease in gel strength after DHT is the reduction in the effective water content and concentration of starch in the gel network (Liu et al., 2022c). The DHT can affect the swelling and water absorption properties of the starch granules, leading to differences in the viscoelastic properties of the starch gel (Liu et al., 2022c). For taro starch, DHT at moderate temperatures (e.g., 130 °C) for specific durations (e.g., 5 h) increases pasting viscosity and storage modulus, which are indicative of enhanced gel strength (Hui et al., 2024). In potato starch, cyclic DHT (RDHT) at 120 °C for multiple cycles significantly alters the starch's structural properties, reducing paste viscosity but increasing RS content, which can contribute to gel strength (de Oliveira Maior et al., 2024). For high amylose rice starch, 130 °C for 1h produced the strongest gels (Oh et al., 2018b). Cassava starch treated at 130 °C for 4h showed improved gel strength and 3D printability (Maniglia et al., 2020b). Chestnut starch exhibited increased gel strength after DHT, with continuous treatment more effective than repeated treatment (Liu et al., 2022c). Additionally, DHT can induce changes in the starch molecular structure, such as the formation of complexes between amylose and lipids, which may restrict the leakage of amylose into the suspension and result in increased paste clarity but decreased gel strength (Lee et al., 2017a). Similarly, potato starch gels have shown that temperatures ranging from 58 °C to 70 °C promote the formation of stronger gels. However, further temperature increases beyond this range can weaken gel strength, primarily due to alterations in the viscoelastic properties (Torres et al., 2018). In the case of arrowroot starch, gel hardness increases with starch concentration and is maximized at specific temperatures, such as 80 °C, but decreases at temperatures above 100 °C (Lee et al., 2009). On the other hand, some studies have reported that DHT can enhance the gel strength of starch compared to untreated starch (Fen et al., 2021b; Jiang et al., 2022). This is likely due to the reorganization of starch chains and increased molecular interactions, leading to a more stable and stronger gel network (Jiang et al., 2022). The effect of DHT on starch gel strength also depends on the degree of pre-gelatinization or modification of the starch. Partially gelatinized starch samples have been shown to form stronger gels than unmodified starch after reheating, but the gel strength decreases as the degree of pre-gelatinization increases (Fen et al., 2021b). Furthermore, the combination of DHT with other treatments, such as vacuum heat, has been shown to enhance the gel-like behavior of retrograded starches, as seen in Alocasia macrorrhizos starch, which displayed increased storage modulus and thermal stability (Kumar et al., 2024). The contradictory findings may be due to factors such as the starch source, the specific conditions of the DHT process, and the presence of other components like gums or lipids. For instance, the extent of changes in gel strength appears to depend on the amylose content and the degree of starch gelatinization prior to DHT (Qiu et al., 2015a; Lee et al., 2017a; Garcia and Franco, 2014). Generally, optimal conditions for enhancing the gel strength of various starches include moderate to high temperatures (approximately 130–150 °C) and specific durations (typically 4–6 h), although exact parameters should be tailored according to the starch type and intended application (de Oliveira Maior et al., 2024; Hui et al., 2024; Lee et al., 2017b).

3.6. Pasting properties

The rapid viscosity analyzer (RVA) is capable of assessing and evaluating the pasting temperature and viscosity of grain and grain-processed products, as well as measuring the viscosity of starch at various temperatures. The RVA viscosity curve provides the following information: peak viscosity (PV), setback (SB), final viscosity (FV), breakdown (BD), and pasting temperature (PT). The manner in which DHT affects the viscosity properties of starch is dependent on the starch's botanical origin and treatment conditions (Table 3). Several studies have indicated that DHT can lead to a reduction in PV across various starch sources. Specifically, the PV of corn starch was lowered as reported by Ru et al. (Ru et al., 2015), as well as in blue highland barley (Liu et al., 2023), buckwheat (He et al., 2022), proso millet (Sun et al., 2014), quinoa (Rao et al., 2022b), and potato (Zhang et al., 2023a). Additionally, Oh et al. (Oh et al., 2018b) discovered that the pasting characteristics of high-amylose rice starch are significantly influenced by the conditions under which DHT is applied. When the treatment temperature is 110 °C, the pasting characteristic curve significantly shifts upward, and the PV increases by 43%. When subjected to DHT at 130 and 150 °C, the PV reached their maximum values after 1 h of treatment. As the heating time prolonged, the PV value of the starch

Table 3
Pasting properties of different starches before and after DHT.

Starch source	DHT condition	Pasting parameters					Reference
		PT (°C)	PV	BD	SB	FV	
Rice	130 °C, 7% moisture, 2–4 h	66.5–66.5 ~	2579–3096↑	1565–1913↑	323–322 ~	1305–1505↑	Qiu et al. (Qiu et al., 2015a)
Waxy rice	130 °C, <10% moisture, 4 h	69.4–68.6 ↓	295.9–369.4↑	124.0–175.4↑	NA	183.0–224.6↑	Su et al. (Su et al., 2018b)
High-amylose rice	130 °C, <10% moisture, 4 h	82.4–78.8↓	190.3–176↓	28.3–42↑	NA	226.1–193.3↓	Su et al. (Su et al., 2018b)
Corn	90–150 °C, <10% moisture, 0.5–4 h	76.42–72.43↓	4175–2619↓	1468–1962↑	1491–460↓	4198–1117↓	Ru et al. (Ru et al., 2015)
Blue highland barley	160 °C, <10% moisture, 2 h	78.6–73.4↓	3719–1025↓	2120–2765↑	1858–388↓	3457–1137↓	Liu et al. (Liu et al., 2023)
Buckwheat	120–170 °C, 7% moisture, 0.5 h	73.32–66.95↓	5200–50↓	2430–30↓	1910–130↓	4900–690↓	He et al. (He et al., 2022)
Proso millet	130 °C, 8% moisture, 2–4 h	76–74.6↓	2822–2536↓	1854–1062↓	501–742↑	1470–2266↑	Sun et al. (Sun et al., 2014)
Potato	130 °C, <10% moisture, 3–9 h	72.20–73.05 ~	6154–368↓	3282–99↓	402–108↓	3274–378↓	Zhang et al. (Zhang et al., 2023a)
Quinoa	150–200 °C, <10% moisture, 2 h	73.05–64.5↓	5120–1740↓	468–157↓	452–657↑	5104–2240↓	Rao et al. (Rao et al., 2022b)
Chestnut	130 °C, <10% moisture, 2–4 h	81.7–81.8 ~	3402–4327↑	1980–2798↑	2748–3423↑	4171–4952↑	Gul et al. (Gul et al., 2014)
Faba bean	100–150 °C, <10% moisture, 1–5 h	72.63–72.62~	2205–2267↑	567–617↑	1887–1992↑	3524–3642↑	Fasakin et al. (Fasakin et al., 2024)
Chickpea	180 °C, <10% moisture, 3 h, repeat 2–5 cycles	NA	4358–62↓	1447–2↓	2930–23↓	5841–66↓	Zhang et al. (Zhang et al., 2024)

"↑" indicates a greater value; "↓" indicates a lower value; "~" denotes a similar value; "NA" not available.
PV: pasting temperature; BD:breakdown viscosity; SB: setback viscosity; FV: final viscosity; PT: pasting temperature; DHT: dry heat treatment.

paste decreased. A possible explanation for the observed decrease in PV from DHT is that DHT may lead to shortening of molecular chains and disruption of glycosidic bonds in starch molecules, causing a significant drop in PV, as suggested by Sun (Sun et al., 2023). In contrast, research has shown that DHT actually increases the PV in other types of starch, such as normal rice (Qiu et al., 2015a), waxy rice (Su et al., 2018b), faba bean (Fasakin et al., 2024), and chestnut (Gul et al., 2014). There is a difference between the starches, mainly in the content of amylose, so the reason for this opposite trend may be related to the main effect of DHT on amylose (Liu et al., 2022c). SB is the difference between PV and trough viscosity, which represents the degree of disintegration of starch granules and reflects the thermal stability of starch paste. DHT can increase the SB of proso millet (Sun et al., 2014), quinoa (Rao et al., 2022b), faba bean (Fasakin et al., 2024), and chestnut (Gul et al., 2014) starches. However, normal rice starch remained relatively unchanged (Qiu et al., 2015a). On the other hand, corn (Ru et al., 2015), blue highland barley (Liu et al., 2023), and buckwheat (He et al., 2022) starches observed a decline in SB. According to Liu et al. (Liu et al., 2022a), the physical condition of amylose was greatly affected by DHT, which also reduced the leaching of free amylose molecules. FV represents the stability of starch cold paste, reflecting the polymerization phenomenon of starch molecules during the cooling process. Maize (Ru et al., 2015), high-amylose rice (Su et al., 2018b), blue highland barley (Liu et al., 2023), buckwheat (He et al., 2022), and potato (Zhang et al., 2023a) starches treated with DHT showed a decrease in FV compared to their respective control starches. On the other hand, FV increased in rice (Qiu et al., 2015a), waxy rice (Su et al., 2018b), proso millet (Sun et al., 2014), faba bean (Fasakin et al., 2024), and chestnut (Gul et al., 2014) starches. According to Liu et al. (Liu et al., 2023), alterations in FV are predominantly associated with changes in crystalline structure and short amylopectin during DHT. The BD value represents the difference between the highest and lowest viscosities. DHT increased the BD of rice (Qiu et al., 2015a), waxy rice (Su et al., 2018b), maize (Ru et al., 2015), blue highland barley (Liu et al., 2023), faba bean (Fasakin et al., 2024), and chestnut (Gul et al., 2014) starches. On the other hand, DHT decreased the BD of buckwheat (He et al., 2022), proso millet (Sun et al., 2014), potato (Zhang et al., 2023a), and quinoa (Rao et al., 2022b) starches. According to the authors, the alteration of the amorphous region of the granules might be the cause of the change in the BD. The reduction in the BD following DHT indicates that the starch exhibited increased resistance to higher temperatures and mechanical stress, and vice versa (Sun et al., 2014). PT represents the temperature at which the viscosity begins to increase. DHT can decrease the PT of some different types of starch (Table 3), but it did not change significantly for rice (Qiu et al., 2015a), potato (Zhang et al., 2023a), faba bean (Fasakin et al., 2024), and chestnut (Gul et al., 2014). DHT reduces the hydrogen bonding forces within or between starch molecules during the pasting test process, making it easier for water molecules to penetrate into starch particles and cause expansion, resulting in a decrease in the pasting temperature. The contradictory findings may be due to factors such as the starch source, the presence of other components (e.g., lipids, hydrocolloids), and the specific conditions of the DHT process (e.g., temperature, duration, moisture content). For instance, the extent of changes in pasting properties appears to depend on the amylose content and the degree of starch gelatinization prior to DHT (Su et al., 2018b). In one example, the viscosity of native chickpea starch was 4358, but after undergoing repeated DHT, it dropped dramatically to just 60 (Zhang et al., 2024) (Table 3). This suggests that the treated starch became significantly thinner and less sticky. The study also found that as the duration of repeated DHT increased, the BD value decreased. This implies that prolonged exposure to dry heat makes the starch more stable, as it breaks down less when heated. Additionally, the study showed that with more dry heat cycles, the SB value decreased, indicating that the treated starch retains greater stability when it cools down (Zhang et al., 2024). The findings suggest that moderate DHT temperatures, typically between 120 °C and 150 °C for 2–4 h, effectively enhance the viscosity of various starches. However, the optimal temperature and duration may vary depending on the starch type and treatment conditions. This process promotes interactions between starch molecules, which strengthens the starch paste structure and increases its viscosity (Gong et al., 2022; Qin et al., 2016; Ji et al., 2017b).

3.7. Swelling power, solubility and oil absorption capacity

DHT significantly influences the swelling power and solubility of starch, with varying effects depending on the specific conditions of treatment, such as temperature and duration, as well as the type of starch being modified. The swelling power of starch refers to its ability to absorb water and expand upon heating. Research indicates that DHT can lead to both increases and decreases in swelling power, depending on the treatment conditions. For instance, Rao et al. (Rao et al., 2022b) found that DHT increased the solubility of quinoa starch, with maximum solubility observed at 200 °C, suggesting that higher temperatures can enhance the ability of starch to swell by promoting the leakage of amylose from the granules. For taro starch, DHT at 130 °C for varying durations resulted in decreased swelling power, with the most significant changes observed at higher temperatures and longer treatment times (Hui et al., 2024). Moreover, the swelling power of both native

and dry-heated faba bean starch increases with temperature, particularly between 50 and 60 °C, indicating starch gelatinization (Fasakin et al., 2024). However, higher temperatures (70–90 °C) have little effect on swelling power. Both higher dry heat temperatures and longer heating durations result in greater swelling power, with starch heated at 150 °C showing superior results compared to that heated at 100 °C (Fasakin et al., 2024). However, several studies have reported that DHT leads to a decrease in swelling power of starch including those from millet, wheat (both normal and waxy), corn, waxy rice, waxy corn, highland barley, sweet potato, potato, quinoa, chestnut, and taro (Table 4), indicating that excessive heat or prolonged treatment can lead to structural changes that inhibit swelling. Additionally, Liu et al. (Liu et al., 2022b) noted that DHT could reduce the effective water content of starch, which in turn affects its swelling capacity. This reduction in swelling power may be attributed to the formation of stronger intermolecular interactions among starch chains, which limits the granules' ability to absorb water. The solubility of starch generally increases with DHT, particularly at elevated temperatures. For example, Shi et al. (Shi et al., 2018) observed that as the temperature increased during DHT, the solubility of starch also increased, suggesting that the crystalline structure of starch becomes disrupted, allowing for greater water interaction with the starch molecules. Similarly, Mu et al. (Mu et al., 2013a) reported that enzymatically hydrolyzed heat-treated starches exhibited increased solubility due to the breakdown of granule structure, which facilitates water absorption. However, the relationship between solubility and swelling power is complex. While solubility may increase, swelling power can decrease if the structural integrity of the starch granules is compromised. For instance, Zięba et al. (Zięba et al., 2020) found that the solubility of starch increased with roasting, but the swelling power decreased as the temperature rose. This indicates that while starch may become more soluble, it may not necessarily swell as effectively due to changes in its physical structure. The contradictory findings may be due to factors such as the starch source, the specific conditions of the DHT process (e.g., temperature, duration, moisture content), and the presence of other components (e.g., lipids, hydrocolloids) that can interact with the starch during the treatment. For instance, Liu et al. (Liu et al., 2022c) suggested that the decrease in gel strength of chestnut starch after DHT could be due to the reduced effective water content and the changes in the swelling and water absorption performance of the starch granules. In contrast, Lee et al. (Lee et al., 2017a) found that DHT of pregelatinized rice starch enhanced the complexation between amylose and lipids, which may have restricted the leakage of amylose and increased the paste clarity. Additionally, the extent of changes in swelling power and solubility appears to depend on the amylose content and the degree of starch gelatinization prior to DHT (Dong and Digestion, 2024). Therefore, while the specific optimal conditions can vary, a general trend suggests that moderate temperatures around 90 °C and shorter durations, such as 2 h, may be effective in maximizing the swelling power of starch across different types (Sobowale et al., 2022; Pratama, 2018). The influence of DHT on the oil absorption capacity of starch is an important aspect of starch modification that affects its functionality in food applications. Research indicates that varying the conditions of DHT, such as temperature and duration, can lead to significant changes in the oil absorption capacity of starch (Table 4). Liu's study on blue highland barley starch demonstrated that both the temperature and duration of DHT significantly affected oil absorption capacity. Specifically, as the treatment temperature increased from 150 °C to 180 °C and the duration extended, the oil absorption capacity increased from 1.74 g/g to 2.22 g/g (Liu et al., 2023). This suggests that higher temperatures and longer treatment times enhance the ability of starch to absorb oil, likely due to the disruption of the starch granule structure, which exposes more hydrophobic regions of the amylose-lipid complex. The increase in oil absorption capacity can be attributed to structural changes within the starch granules. Sujka et al. (Sujka et al., 2015) discussed the mechanisms of oil absorption, noting that it involves the physical entrapment of oil and the affinity of non-polar protein side chains for lipids. As DHT alters the crystalline structure of starch, it can enhance the exposure of these hydrophobic regions, leading to improved oil absorption. The presence of other components, such as lipids or hydrocolloids, can also influence the oil absorption capacity of starch. Wang et al. (Wang et al., 2020a) reported that the destruction of the starch structure during treatment could expose more hydrophobic portions, thereby increasing oil absorption. Similarly, Chung et al. (Chung et al., 2010) noted that the interactions between starch and hydrocolloids during DHT could enhance oil absorption capacity by modifying the starch's structural properties. Therefore, the optimal temperature range for maximizing oil absorption capacity in various starches through DHT is likely between 120 °C and 190 °C, with controlled treatment durations, depending on the starch type and the desired structural modifications. This range

Table 4
Swelling power, solubility and oil absorption capacity of different starches before and after DHT.

Starch source	DHT condition	Temperature (°C)	SP (g/g)	S (%)	OAC (%)	Reference
Finger Millet	120 °C, <10% moisture, 4 h	60	10.3–8.21↓	1.3–1.9↑		Gautam et al. (Gautam et al., 2023)
		70	13.8–11.9↓	2–2.6↑		
		80	16.3–14.8↓	3–4.1↑		
		90	16.54–16.1↓	4.3–5.4↑		
Potato	130 °C, <10% moisture, 3–9 h	50	1.92–2.04↑	0.34–0.88↑		Zhang et al. (Zhang et al., 2023a)
		60	9.20–7.94↓	4.26–7.34↑		
		70	23.25–17.69↓	4.70–25.91↑		
		80	26.04–24.16↓	5.00–29.12↑		
		90	38.72–29.52↓	5.24–35.74↑		
Blue highland barley	160 °C, <10% moisture, 2 h	–			1.44–2.22↑	Liu et al. (Liu et al., 2023)
Sweet potato	110 °C, <10%moisture, 3 h, repeat 6 cycles	50	2.24–2.25 ~	0.22–0.50↑		Gou et al. (Gou et al., 2019)
		60	2.26–2.33↓	0.31–0.97↑		
		70	3.65–2.69↓	0.89–2.39↑		
		80	19.31–17.55↓	6.31–22.54↑		
		90	26.61–22.72↓	9.30–26.56↑		
Water chestnut	130 °C, <10% moisture, 2–4 h	–			1.22–1.53↑	Gul et al. (Gul et al., 2014)
Chestnut	140 °C, <10%moisture, 3 h, repeat 4 cycles	50	1.95–1.34↓	0.15–0.75↑		Liu et al. (Liu et al., 2022b)
		60	2.22–1.61↓	0.26–0.92↑		
		70	3.85–2.96↓	1.01–2.17↑		
		80	12.84–7.61↓	5.61–16.30↑		
		90	22.59–11.28↓	7.79–23.69↑		
Rice	120 °C, <10% moisture, 2 h	–			0.7–3.0↑	Zhou et al. (Zhou et al., 2019)

"↑" indicates a greater value; "↓" indicates a lower value.
SP: Swelling power; S: solubility; OAC:oil absorption capacity; DHT: dry heat treatment.

effectively balances the enhancement of oil absorption properties while preserving the integrity of the starch granules (Liu et al., 2023; Peng et al., 2024; Wu et al., 2024; Tabara et al., 2014).

3.8. Syneresis

DHT can have varying effects on the syneresis of starch, depending on the specific starch source and treatment conditions. One potential mechanism for the decrease in syneresis after DHT is the disruption of the ordered structure of starch molecules, which can lead to a more stable gel network and reduced water expulsion (Liu et al., 2022c; Mu et al., 2013b). The DHT can affect the retrogradation and crystallization behavior of starch, thereby influencing the syneresis (Mu et al., 2013b; Dobosz et al., 2018). On the other hand, some studies have reported an increase in syneresis after DHT, particularly for starches with higher amylose content (Zhang et al., 2011; Dobosz et al., 2018). This could be due to the enhanced retrogradation and crystallization of amylose during the DHT (Zhang et al., 2011; Dobosz et al., 2018). The effect of DHT on starch syneresis also depends on the degree of pre-gelatinization or modification of the starch. Partially gelatinized starch samples have been shown to have lower syneresis compared to unmodified starch after reheating, but the syneresis increases as the degree of pre-gelatinization increases (Mu et al., 2013b). The duration of DHT significantly influences the syneresis of starch, impacting its structural and functional properties, which are crucial for food processing applications. Prolonged DHT generally leads to a decrease in the relative crystallinity and swelling power of starch, as observed in various studies on different starch types, including potato, barley, and taro starches (Liu et al., 2023; de Oliveira Maior et al., 2024; Hui et al., 2024). This reduction in crystallinity is often accompanied by a decrease in gelatinization temperature and enthalpy, indicating a less ordered molecular structure, which can affect the water retention capacity and syneresis of starch gels (Liu et al., 2023; de Oliveira Maior et al., 2024; Hui et al., 2024). For instance, in potato starch, cyclic DHT increased RS content, which is beneficial for reducing syneresis in food products that require stable gel structures (de Oliveira Maior et al., 2024). Similarly, in taro starch, extended DHT increased solubility and decreased swelling power, which can lead to reduced syneresis in applications requiring high viscosity and gel stability (Hui et al., 2024). The morphological changes, such as the appearance of dents and cracks on starch granules, further contribute to these effects by altering the interaction of starch with water (Sun et al., 2023). These modifications are advantageous in food processing, where reduced syneresis can enhance the texture and shelf-life of products like sauces, soups, and gels. Additionally, the increased solubility and altered pasting properties due to DHT can improve the functional performance of starch in various food formulations, making it a valuable technique for developing low-glycemic index foods and enhancing the nutritional profile of starchy foods (Hui et al., 2024; Liu et al., 2022d). These findings suggest that moderate temperatures around 120–130 °C with treatment durations ranging from 4 to 15 h are generally effective in minimizing syneresis across various starch types. However, specific conditions may need to be tailored based on the starch source and the desired end-use properties of the product (de Oliveira Maior et al., 2024; Liu et al., 2022c; Kang et al., 2020).

3.9. In vitro digestibility

Starch digestibility plays a critical role in health, impacting metabolic diseases, diabetes management, and satiety. It can be categorized into three nutritional fractions: RDS, SDS, and RS. RS and SDS are particularly valued for their potential to stabilize glucose metabolism, prevent diabetes, and enhance satiety. Therefore, managing RS intake is crucial for preventing metabolic disorders, colon cancer, and type 2 diabetes. The effect of varying temperature and time on the in vitro digestibility of starch during DHT is multifaceted, impacting both the structural and physicochemical properties of starch. High temperatures and extended treatment times generally lead to a decrease in amylose content and crystallinity, which in turn affects digestibility (Table 5). For instance, in blue highland barley starch, DHT at 150 and 180 °C for 2–4 h increased the content of RDS while decreasing SDS and RS content, indicating enhanced digestibility with higher temperatures and longer durations (Liu et al., 2023). A similar trend was observed with chickpea starch, where DHT treatments led to an increase in RDS content (Zhang et al., 2024). This increase is attributed to structural changes in the starch granules, which enhanced their susceptibility to digestive enzymes. The study found that RDS levels generally increased with additional cycles or extended treatment durations, reflecting enhanced digestibility. In contrast, SDS and RS levels decreased as the DHT treatment intensified. Specifically, SDS values declined with more repeated cycles or longer continuous treatments, reaching their lowest in the most extensively treated samples (Zhang et al., 2024), indicating that the structural integrity of the starch was compromised, leading to a reduction in RS content. Similarly, potato starch subjected to continuous and repeated DHT at 120 °C showed a decrease in paste viscosities and gelatinization enthalpy, with cyclic treatments notably increasing RS content by 18.26%, suggesting that cyclic heating can enhance RS formation and thus modify digestibility (de Oliveira Maior et al., 2024). Corn starch dried at high temperatures, such as 130 °C, showed increased digestibility due to partial gelatinization, which made it more susceptible to enzymatic action (Malumba et al., 2014). Moreover, temperature differences in treatment, such as high temperature followed by low temperature, can enhance molecular rearrangement, increasing RS content and altering digestibility (Feng et al., 2024). IR-DHT at 200 °C also demonstrated increased solubility and digestibility due to structural changes in starch granules (Voroshnina et al., 2024). Liu et al. (Liu et al., 2019) observed that DHT increased RDS and SDS levels in waxy potato starch while decreasing RS levels, indicating a shift towards more rapidly digestible properties. This change is likely due to molecular rearrangements and increased structural disorder from DHT, which reduces the starch's resistance to enzymatic hydrolysis. Zhang et al. (Zhang et al., 2021a) also noted similar effects in wheat starch, where repeated DHT cycles increased RDS and SDS but decreased RS levels. This enhancement in digestibility might be attributed to the disruption of starch granules and the formation of a porous structure, facilitating easier enzymatic access. Conversely, DHT has been found to increase SDS and reduce RDS and RS in corn starch, aligning with observations in red adzuki bean starch (Zou et al., 2020; Ge et al., 2021). These results indicate that DHT modifies the structural arrangement and possibly forms a protective barrier around amylase's active sites, slowing or inhibiting hydrolysis in some cases (Chi et al., 2019). Studies by Yang et al. (Yang et al., 2021) and Liu et al. (Liu et al., 2022a) reported that DHT decreased RDS and increased SDS and RS in waxy rice starch and chestnut starch, respectively, showcasing properties conducive to slow digestion. Similarly, Gong et al. (Gong et al., 2021) found that compared to OSA-modified starch, the RDS content decreased while the RS content increased significantly after DHT, which they attributed to the structural disintegration of starch granules and the loss of crystallinity. Kanagaraj et al. (Kanagaraj et al., 2019a) reported that DHT of rice and barnyard millet starches increased the RS content, suggesting the conversion of digestible starch into RS. These variations underscore how different DHT conditions can significantly affect starch digestibility. Moreover, exposure of high-amylose rice starch to increasing temperatures (110, 130, and 150 °C) and durations (0, 1, 2, and 4 h) resulted in decreased RDS and SDS levels and increased RS content, highlighting an enhancement in the starch's resistance to digestion. These changes could be due to an increase in amylose content, alterations in crystal form, and a reduction in crystallinity, all of which contribute to improved anti-digestive properties. The stability and structure of amylose are closely linked with RS. Thus, the in vitro digestibility characteristics of starch can vary significantly among different types, largely dependent on the internal molecular rearrangement that occurs during DHT, influenced by amylose content and specific DHT parameters. Therefore, the optimal

Table 5
In vitro digestibility of different starches before and after DHT.

Starch source	DHT condition	Digestion characteristics			Reference
		RDS (%)	SDS (%)	RS (%)	
Waxy potato	110 °C, <10% moisture, 0.5–2.5 h	23.85–32.16↑	24.58–25.51↑	51.56–42.33↓	Liu et al. (Liu et al., 2019)
Wheat	130 °C, <10% moisture, 3 h, repeat 6 cycles	21.35–25.62↑	0.76–1.16↑	77.88–73.21↓	Zhang et al. (Zhang et al., 2021a)
Corn	140 °C, <10% moisture, 4–20 h, repeat 5 cycles	40.41–37.91↓	53.05–60.50↑	6.54–1.58↓	Zou et al. (Zou et al., 2020)
Red adzuki bean	130 °C, <10% moisture, 1–9 h	63.63–61.40↓	23.47–28↑	12.90–10.60↓	Ge et al. (Ge et al., 2021)
Waxy rice	120 °C, 8% moisture, 4 h	22.9–19.5↓	14.0–16.1↑	63.1–64.3↑	Yang et al. (Yang et al., 2021)
Chestnut	140 °C, <10% moisture, 4–8 h	21.14–15.10↓	21.27–23.13↑	57.59–61.77↑	Liu et al. (Liu et al., 2022a)
High-amylose rice	110–150 °C, <10% moisture, 1–4 h	42.2–36.8↓	17.7–13.1↓	42.0–50.6↑	Oh et al. (Oh et al., 2018c)
Potato	130 °C, <10% moisture, 3–9 h	32.43–30.65↓	6.91–5.55↓	60.66–63.80↑	Zhang et al. (Zhang et al., 2023a)
Quinoa	140 °C, <10% moisture, 4 h, repeat 5 cycles	43.74–54.91↑	34.67–22.31↓	21.58–22.77↑	Zhou et al. (Zhou et al., 2021a)
Chickpea	180 °C, <10% moisture, 3 h, repeat 2–5 cycles	16.1–20.0↑	2.1–1.3↓	2.1–1.3↓	Zhang et al. (Zhang et al., 2024)

"↑" indicates a greater value; "↓" indicates a lower value; "~" denotes a similar value.
RDS: rapid digestible starch; SDS: slow digestible starch; RS: resistant starch; DHT: dry heat treatment.

DHT conditions to enhance in vitro starch digestibility appear to involve a temperature range of 130 °C–180 °C, with a treatment time of 2–4 h (Liu et al., 2023; Rao et al., 2022b; Jiang et al., 2020a). Overall, higher temperatures and longer treatment times generally enhance starch digestibility by altering its structural properties, although specific outcomes can vary depending on the starch source and treatment method.

4. Functionality of dry heat-modified starches by food ingredients

4.1. Thermal properties

The thermal properties of starch can be significantly influenced by the addition of various additives during DHT. The thermal properties of dry heat-modified starches are significantly influenced by varying glucose concentrations, as the interactions between starch and glucose can alter the physicochemical characteristics of the starch. In the presence of glucose, the thermal stability of starch can be affected due to the formation of complexes between glucose and the starch molecules. These complexes can hinder the gelatinization process, which is the irreversible transformation of starch granules into a viscous gel upon heating in water. Studies have shown that the addition of glucose can lead to an increase in the gelatinization temperature and enthalpy of starch, indicating enhanced thermal stability (Oh et al., 2018a; Su et al., 2018a). For instance, the interaction between glucose and amylose can result in a more stable crystalline structure, which may require higher temperatures to disrupt during gelatinization (Oh et al., 2018c). Dry heating of potato starch combined with glucose has obviously shown higher T_o, T_p, T_c, and ΔH when compared with that of single DHT (Table 6). The inclusion of glucose during the process of dry heating is likely to have a significant impact on facilitating the organization of starch molecules and preventing the degradation of starch granules. Applying dry heat to potato starch and adding glucose can help retain the non-crystalline portion of the granules, thus inhibiting starch molecular motion. The reduction in chain mobility and the interaction between starch and glucose may help prevent structural disintegration during dry heating (Singh et al., 2019). The influence of amino acids on the thermal properties of dry heat-modified starches is a complex interaction that can significantly alter the physicochemical characteristics of starch. When starch is subjected to DHT, the presence of amino

Table 6
Changes in the thermal properties of different kinds of modified starch by dry heating with food ingredient.

Starch source	Food ingredients (addition level)	DHT condition	Thermal property				Reference
			T_o (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)	
Potato	–	130 °C, <10% moisture, 2 h	54.4	58.5	65.9	9.6	Lee et al. (Lee et al., 2021)
	Glucose (0.3%)	130 °C, 10% moisture, 2 h	55.1↑	59.2↑	66.4↑	9.8↑	
Corn	–	130 °C, 10% moisture, 4 h	53.09	57.68	61.93	8.55	Ji et al. (Ji et al., 2016)
	Lysine (0.04%)	130 °C, 10% moisture, 4 h	54.89↑	59.52↑	64.38↑	8.40 ↓	
Rice	–	130 °C, <10% moisture, 2 h	71.2	79.80	84.57	11.41	Lutfi et al. (Lutfi et al., 2021)
	Sodium alginate (1%)	130 °C, <10% moisture, 2 h	74.32↑	80.54↑	86.72↑	10.11 ↓	
Corn	–	130 °C, <10% moisture, 2 h	67.89	71.51	76.19	11.19	
	Sodium alginate (1%)	130 °C, <10% moisture, 2 h	70.21↑	72.34↑	78.65↑	10.32 ↓	
Waxy rice	–	130 °C, <10% moisture, 4 h	62.5	67.4	74.7	11.2	Li et al. (Li et al., 2013)
	Xanthan gum (0.03%)	130 °C, <10% moisture, 4 h	63.4↑	68.8↑	76.7↑	9.0 ↓	
Cassava	–	130 °C, <10% moisture, 4 h	60.49	69.44	79.86	0.96	Chandanasree et al. (Chandanasree et al., 2016)
	CMC (0.4%)	130 °C, <10% moisture, 4 h	57.61 ↓	66.59 ↓	73.74 ↓	0.66 ↓	
Water chestnut	–	130 °C, <10% moisture, 4 h	69.46	78.54	85.2	17.3	Gul et al. (Gul et al., 2014)
	CMC (1%)	130 °C, <10% moisture, 4 h	31.26 ↓	78.06 ↓	84.3 ↓	29.9↑	
Potato	–	120 °C, <10% moisture, 3 h	63.25	69.91	85.62	2.761	Gao et al. (Gao et al., 2019)
	Pectin (3%)	120 °C, <10% moisture, 3 h	61.47 ↓	68.49 ↓	85.35 ↓	2.504 ↓	
Sweet potato	–	130 °C, <10% moisture, 2 h	66.31	71.07	82.07	1.88	Zhang et al. (Zhang et al., 2020)
	Short-chain inulin (0.25%)	130 °C, <10% moisture, 2 h	67.20↑	73.21↑	82.21↑	1.61 ↓	
	–	130 °C, <10% moisture, 4 h	65.61	71.90	81.09	1.65	
	Short-chain inulin (0.25%)	130 °C, <10% moisture, 4 h	66.54↑	72.80↑	81.21↑	1.42 ↓	
Rice	–	130 °C, <10% moisture, 6 h	60.04	65.75	70.65	8.26	Zhu et al. (Zhu et al., 2020)
	Whey protein isolate (3%)	130 °C, <10% moisture, 6 h	60.46↑	66.05↑	70.75↑	9.88↑	

"↑" indicates a greater value; "↓" indicates a lower value.
T_o: onset gelatinization temperature; T_p: peak gelatinization temperature; T_c: conclusion gelatinization temperature; ΔH: gelatinization enthalpy change.
DHT: dry heat treatment; CMC: carboxymethylcellulose.

acids can modify its thermal behavior, gelatinization properties, and pasting characteristics due to the formation of interactions between the starch molecules and the amino acids. Amino acids, particularly those with charged side chains, can enhance the binding ability to starch chains, leading to increased entanglement during the cooling process. This phenomenon has been observed in studies where charged amino acids were shown to elevate the swelling behavior of starch pastes, likely due to electrostatic interactions among the starch chains mediated by the amino acids (Sakauchi et al., 2010). Such interactions can result in higher gelatinization temperatures and altered thermal stability, as the presence of amino acids can stabilize the starch structure against thermal degradation (Jiang et al., 2020b). In addition to the direct interactions between amino acids and starch, the thermal treatment itself can further modify these properties. For example, the application of DHT in conjunction with amino acids can lead to the formation of new bonds, such as ester linkages, which can enhance the thermal stability of the modified starch (Jiang et al., 2020b). The resulting starch-amino acid complexes may exhibit improved resistance to retrogradation, a common issue in starch-based products that can affect their shelf life and texture (Wan et al., 2017). Ji et al. (Ji et al., 2016) reported that corn starch treated with lysine-assisted DHT exhibited higher gelatinization temperatures (T_o = 54.89 °C, T_p = 59.52 °C, T_c = 64.38 °C) than corn starch treated solely with DHT (T_o = 53.09 °C, T_p = 57.68 °C, T_c = 61.93 °C) (Table 6). This could be attributed to weak electrostatic interactions between starch and lysine, as well as esterification reactions facilitated by DHT, which alter the starch's gelatinization properties. Conversely, the inclusion of amino acids like L-aspartic acid and L-lysine without DHT led to decreased T_o, T_p, T_c, and ΔH values in maize starch, suggesting a potential weakening in the internal structure of starch granules and the disruption of amylopectin double helices (Jiang et al., 2020a; Qiu et al., 2015b). Hydrocolloids significantly influence the thermal properties of dry heat-modified starches by altering their gelatinization and pasting characteristics. The addition of hydrocolloids such as xanthan gum, guar gum, and carboxymethyl cellulose (CMC) can modify the gelatinization temperature and enthalpy of starches, often leading to a decrease in these parameters due to reduced water availability and increased viscosity, which affects the thermal transitions of starches (Megusar et al., 2022; Bet et al., 2018). For instance, xanthan gum and hydroxypropyl methyl cellulose (HPMC) have been shown to increase the gelatinization temperature and viscoelasticity of starch systems, indicating a more stable gel network (Megusar et al., 2022). Similarly, the incorporation of hydrocolloids like guar gum enhances the thermal stability of starches, as observed in common vetch seed starch, where the addition of guar gum increased thermal stability, unlike CMC, which decreased it (Bet et al., 2018). DHT itself modifies the thermal properties of starches by altering their crystalline structure and reducing gelatinization enthalpy, as seen in potato starch, where DHT led to a transition from type B to type C crystallinity and a decrease in relative crystallinity (de Oliveira Maior et al., 2024). The combination of hydrocolloids with DHT can further enhance these effects, as demonstrated in water chestnut starch, where the addition of CMC during dry heating reduced the gelatinization temperature and altered pasting properties (Gul et al., 2014). Similarly, other hydrocolloids like pectin may decrease the gelatinization temperature and ΔH of starch, potentially through charge interactions that inhibit starch-water interactions and reduce thermal transitions (Chandanasree et al., 2016; Gao et al., 2019). In contrast, sodium alginate, xanthan gum, and short-chain inulin have been shown to increase the gelatinization temperature and ΔH of starch (Table 6), possibly due to their hygroscopic nature, which limits water mobility and competes with starch molecules for water (Li et al., 2013; Lutfi et al., 2021; Zhang et al., 2020). These hydrocolloids likely strengthen the intermolecular forces between themselves and starch, requiring more energy to disrupt the starch structure. Therefore, the optimal conditions for heat modification of starches in the presence of hydrocolloids depend on the specific interactions between the starch and the hydrocolloids, the desired functional properties, and the processing parameters such as temperature and moisture content. Overall, hydrocolloids, when used in conjunction with dry heat modification, can significantly tailor the thermal properties of starches, making them suitable for various industrial applications by enhancing their stability and modifying their gelatinization behavior (Gul et al., 2014; Shahzad et al., 2019). Whey Protein Isolate (WPI)-assisted DHT has been shown to significantly influence the thermal properties of starch, particularly in terms of increasing the gelatinization temperature and the ΔH change associated with the gelatinization process. The interaction between WPI and starch during DHT can lead to structural modifications that enhance the thermal stability of the starch matrix. Research indicates that the presence of WPI during DHT can lead to the aggregation of starch granules, which may initially seem counterintuitive as aggregation typically implies a reduction in the effective surface area for water absorption. However, this aggregation can actually stabilize the starch granules, resulting in an increase in both the gelatinization temperature and ΔH value (Kumar et al., 2022; Zhu et al., 2020). Specifically, the thermal analysis of starches treated with WPI has demonstrated a significant increase in peak gelatinization temperatures, suggesting that the protein-starch interactions create a more robust structure that requires higher energy input to disrupt during gelatinization (Kumar et al., 2022; Zhu et al., 2020). Interestingly, WPI-assisted DHT has been found to increase the gelatinization temperature and ΔH value of rice starch (Zhu et al., 2020) (Table 6). This increase might be due to the hydrophobic groups within the protein becoming more exposed upon denaturation at high temperatures, enhancing the protein's hydrophobicity and thus decreasing the starch granules' ability to absorb water. This results in a delayed gelatinization process and an increase in gelatinization temperatures, demonstrating the complex interplay of molecular interactions in starch modification.

4.2. Pasting properties

When starch is subjected to DHT in the presence of glucose, several changes in pasting properties can be observed. The addition of glucose tends to enhance the PV of starch pastes. This increase can be attributed to the formation of starch-glucose complexes, which stabilize the starch granules and promote greater water retention during gelatinization (Lee et al., 2017a). The presence of glucose can also lead to an increase in the swelling power of starch granules, which is essential for achieving higher viscosities during the pasting process (Renzetti et al., 2022). Moreover, glucose can affect the breakdown viscosity of starch pastes. Studies have shown that the presence of glucose can reduce the breakdown viscosity, indicating that the granules are less prone to rupture during heating and cooling cycles (Rao et al., 2022a). This effect is particularly important in applications where maintaining the integrity of the starch paste is crucial, such as in sauces and gravies. The stabilization of starch granules by glucose may result from the formation of hydrogen bonds between the hydroxyl groups of glucose and the hydroxyl groups on the starch molecules, which can enhance the cohesiveness of the starch paste (Ganesh et al., 2020b). Additionally, the interaction between glucose and starch can lead to changes in the thermal properties of the starch, which in turn influences its pasting behavior. For instance, glucose can increase the gelatinization temperature and ΔH (enthalpy change) of starch, suggesting that more energy is required to disrupt the starch-glucose complexes during heating (Tian et al., 2021). This increase in thermal stability can result in a more viscous paste, as the starch granules are better able to withstand the heating process without significant degradation. The introduction of hydrocolloids during DHT also significantly modifies the pasting characteristics of starch (Table 7). For instance, the inclusion of hydrocolloids such as sodium alginate and pectin in DHT processes with starch has been found to decrease pasting viscosities and increase pasting temperatures (Gao et al., 2019; Lutfi et al., 2021). This effect may stem from the hydrocolloids altering the starch's interstitial structure, enhancing intermolecular forces, and thus compacting the particle's

Table 7
Changes in the pasting profile of different kinds of modified starch by dry heating with food ingredient.

Starch source	Food ingredients (addition level)	DHT condition	Pasting parameters					Reference
			PV	BD	SB	FV	PT (°C)	
Corn	–	130 °C, <10% moisture, 2 h	1032.7	288	154	898.7	81.3	Lee et al. (Lee et al., 2021)
	Glucose (0.3%)	130 °C, 10% moisture, 2 h	1134.0↑	355.3↑	214.7↑	993.3↑	79.2↓	
Corn	–	130 °C, 10% moisture, 4 h	4156	991	884	5040	65.63	Ji et al. (Ji et al., 2016)
	Lysine (0.04%)	130 °C, 10% moisture, 4 h	4109 ↓	1661↑	−24 ↓	4085 ↓	64.75 ↓	
Rice	–	130 °C, <10% moisture, 2 h	340.80	84.57	187.41	NA	68.40	Lutfi et al. (Lutfi et al., 2021)
	Sodium alginate (1%)	130 °C, <10% moisture, 2 h	290.54 ↓	75.72 ↓	162.11 ↓	NA	73.32↑	
	–	130 °C, <10% moisture, 4 h	294.65	85.91	150.39	NA	67.34	
	Sodium alginate (1%)	130 °C, <10% moisture, 4 h	282.89 ↓	78.54 ↓	126.24 ↓	NA	73.26↑	
Potato	–	120 °C, <10% moisture, 3 h	6672	4020	462	3114	65.6	Gao et al. (Gao et al., 2019)
	Pectin (3%)	120 °C, <10% moisture, 3 h	860 ↓	365 ↓	122 ↓	617 ↓	67.9↑	
Cassava	–	130 °C, 10% moisture, 4 h	4667	2343	2645	4969	70.34	Chandanasree et al. (Chandanasree et al., 2016)
	CMC (0.4%)	130 °C, 10% moisture, 4 h	4912↑	2064 ↓	2527↓	5375↑	68.22 ↓	
Pea	–	130 °C, <10% moisture, 4 h	296.42	86.29	15.71	361.83	71.65	Sun et al. (Sun et al., 2013)
	CMC (1%)	130 °C, <10% moisture, 4 h	267.88 ↓	29.46 ↓	209.67↑	448.46↑	73.10↑	
Corn	–	130 °C, <10% moisture, 4 h	258.7	111.54	82.67	289.79	74.15	
	CMC (1%)	130 °C, <10% moisture, 4 h	188.71↓	28.00↓	45.29↓	206 ↓	75.20↑	
Chestnut	–	140 °C, <10% moisture, 4 h	163	10.3	85.3	238	NA	Liu et al. (Liu et al., 2022a)
	Xanthan gum (0.05%)	140 °C, <10% moisture, 4 h	283↑	6.0 ↓	93 ↑	370↑	NA	
	Xanthan gum (0.2%)	140 °C, <10% moisture, 4 h	532↑	38.7↑	178.3↑	672↑	NA	
Tigernut tuber	–	130 °C, <10% moisture, 2 h	4594	2385	1342	3551	74.8	Miao et al. (Miao et al., 2021)
	Chinese quince seed gum (0.5%)	130 °C, <10% moisture, 2 h	5973↑	2743↑	1921↑	5151↑	77.1↑	
Corn	–	130 °C, <10% moisture, 4 h	3108	1123	1071	3056	73.6	Qiu et al. (Qiu et al., 2015b)
	Soy protein isolate (3%)	130 °C, <10% moisture, 4 h	3703↑	1518↑	1684↑	3869↑	72.6 ↓	

"↑" indicates a greater value; "↓" indicates a lower value; "NA" not available.
PV: pasting temperature; BD:breakdown viscosity; SB: setback viscosity; FV: final viscosity; PT: pasting temperature.
DHT: dry heat treatment; CMC: carboxymethylcellulose.

internal structure, which limits water absorption and expansion, leading to reduced viscosity (Keppler et al., 2018). Further studies, such as those by Chandanasree et al. (Chandanasree et al., 2016), show that cassava starch treated with dry heat and CMC (0.4%) exhibited lower BD, SB, and PT, but higher PV and FV compared to samples without hydrocolloid. Similarly, Sun et al. (Sun et al., 2013) demonstrated that pea starch blended with CMC (1%) and subjected to DHT at 130 °C for 2 h had increased SB, FV, and PT, while PV and BD decreased. These variations indicate that pasting properties can differ based on the type of starch even when the same hydrocolloid (CMC) and concentration are used. Liu et al. (Liu et al., 2022a) observed that adding xanthan gum to chestnut starch during DHT can increase pasting viscosities, particularly when the xanthan gum concentration is raised from 0.05% to 0.2%. Miao et al. (Miao et al., 2021) noted that incorporating Chinese quince seed gum into tigernut tuber starch for DHT resulted in higher pasting viscosities and temperatures. This suggests that interactions between the gum and amylose, coupled with the structural rearrangement of the starch during DHT, contribute to the increased viscosity. Additionally, the breakdown of glycosidic linkages and partial melting of crystals are factors in this phenomenon (Qiu et al., 2015a). Soy Protein Isolate (SPI) similarly affects dry-heated corn starch by lowering pasting temperatures and increasing viscosities (Qiu et al., 2015b) (Table 7). The mechanism here involves SPI-assisted dry heat breaking hydrogen bonds within or between starch molecules, allowing water molecules easier entry into the granules. This facilitates granule expansion at lower temperatures, reducing the pasting temperature. The increase in viscosities likely results from interactions between starch molecules and SPI, specifically through cross-linking between the carboxyl groups of SPI and the hydroxyl groups of starch during the heating process.

4.3. Swelling power and solubility

Hydrocolloids significantly influence the swelling power and solubility of dry heat-modified starches through various mechanisms, including their ability to interact with starch molecules and alter the physical properties of the starch matrix. The incorporation of

hydrocolloids during DHT can lead to changes in the structural integrity of starch granules, which in turn affects their ability to swell and dissolve in water. Studies have noted a reduction in the swelling power of various starches between 60 °C and 95 °C when hydrocolloids and DHT are applied, compared to starches only subjected to DHT (Table 8). This reduction can be attributed to the osmotic pressure generated within the continuous phase of the hydrocolloid, which may restrict the expansion of starch granules (Alam et al., 2020). Such interactions highlight the complex nature of hydrocolloid-starch interactions, where the type and concentration of hydrocolloid can yield varying effects on swelling behavior. Additionally, the increased viscosity of the continuous phase due to hydrocolloids prevents water from penetrating the expanding granules (Pramodrao and Riar, 2014). Su et al. (Su et al., 2018b) examined the influence of xanthan gum-assisted DHT on rice starch types with varying amylose contents (37.85%, 27.55%, and 9.98%). Their findings indicated that for high- and medium-amylose rice starch, the swelling power remained largely unchanged during DHT, regardless of xanthan gum addition ($P > 0.05$). Conversely, for low-amylose rice starch, DHT alone reduced expansibility by 21%, while xanthan gum-assisted DHT further reduced it by 54%. This is due to DHT facilitating the anchoring of xanthan gum on the starch granules' surfaces, reducing their propensity to swell and maintaining their integrity during gelatinization (Su et al., 2018b). In addition to swelling power, hydrocolloids also influence the solubility of dry heat-modified starches. The solubility of starches tends to increase with the addition of hydrocolloids, particularly at elevated temperatures. Nawab et al. (Nawab et al., 2014) found that the solubility of cowpea starch increased with rising temperature, and this trend was consistent across different hydrocolloids used in their study. This increase in solubility can be linked to the disruption of the crystalline structure of starch granules, which is facilitated by the presence of hydrocolloids during DHT. In contrast, studies have also observed a decrease in the solubility of starches treated with dry heat and hydrocolloids between 60 °C and 95 °C (Table 8). This reduced solubility, when compared to starches treated with DHT alone, is linked to the gums' negative charge competing with starch molecules for water. Additionally, the envelopment of starch granules by gums prevents the leakage of amylose (Zhang et al., 2023b). This diminished solubility makes the starch suitable for flavor encapsulation aimed at controlled release, while the reduced swelling power is beneficial for enhancing texture during cooking processes. Moreover, the temperature at which DHT is conducted plays a crucial role in determining the solubility of starches modified with hydrocolloids. Higher temperatures generally facilitate the breakdown of hydrogen bonds within the starch granules, promoting amylose leaching. For example, Sumardiono et al. (Sumardiono et al., 2021) noted that elevated temperatures during DHT could weaken the starch structure, enhancing solubility. However, the presence of xanthan gum may counteract this effect by providing a protective layer around the starch granules, thus limiting the extent of amylose release even at higher temperatures (da Silva Costa et al., 2020). The modification of moth

Table 8
Changes in the swelling power and solubility of different kinds of modified starch by dry heating with food ingredient.

Starch source	Food ingredients (addition level)	DHT condition	Temperature (°C)	SP (g/g)	S (%)	Reference
Sweet potato	–	130 °C, <10% moisture, 4 h	60	15.15	6.32	Pramodrao and Riar (Pramodrao and Riar, 2014)
	Sodium alginate (1%)	130 °C, <10% moisture, 4 h	60	14.90↓	5.75↓	
Taro	–	130 °C, <10% moisture, 4 h	60	12.27	7.27	
	Sodium alginate (1%)	130 °C, <10% moisture, 4 h	60	11.80↓	6.36↓	
Cassava	–	130 °C, 10% moisture, 4 h	90	7.49	17.26	Chandanasree et al. (Chandanasree et al., 2016)
	CMC (0.4%)	130 °C, 10% moisture, 4 h	90	6.54↓	17.05↓	
Water chestnut	–	130 °C, <10% moisture, 2 h	90	7.78	19.6	Gul et al. (Gul et al., 2014)
	CMC (1%)	130 °C, <10% moisture, 2 h	90	7.45↓	19.4 ↓	
Potato	–	130 °C, 10% moisture, 4 h	95	32.7	25.8	Li et al. (Li et al., 2020)
	Xanthan gum (1%)	130 °C, 10% moisture, 4 h	95	27.3↓	16.5↓	
High-amylose rice	–	130 °C, <10% moisture, 4 h	85	17.08	NA	Su et al. (Su et al., 2018b)
	Xanthan gum (1.5%)	130 °C, <10% moisture, 4 h	85	16.43↓	NA	
Waxy rice	–	130 °C, <10% moisture, 4 h	85	24.65	NA	
	Xanthan gum (1.5%)	130 °C, <10% moisture, 4 h	85	14.20↓	NA	
Tigernut tuber	–	130 °C, <10% moisture, 2 h	75	17.8	18.7	Miao et al. (Miao et al., 2021)
	Chinese quince seed gum (0.5%)	130 °C, <10% moisture, 2 h	75	15.8↓	19.7↑	
	–	130 °C, <10% moisture, 2 h	85	27.4	23.3	
	Chinese quince seed gum (0.5%)	130 °C, <10% moisture, 2 h	85	17.7↓	21.8↓	
Moth bean	–	110 °C, <10% moisture, 8 h	95	11.4↓	13.4↑	
	Citric acid (2.5 w/w) + stearic acid (2.5 w/w)	110 °C, <10% moisture, 8 h	95	7.9↓	17↑	

"↑" indicates a greater value; "↓" indicates a lower value; "NA" not available.
SP: Swelling power; S: solubility; DHT: dry heat treatment; CMC: carboxymethylcellulose.

bean starch using a mixture of organic acids under dry heating significantly influences its swelling power and solubility (Table 8), which are critical parameters affecting its functionality in various applications. Research has shown that the swelling power of native moth bean starch is 11.4 g/g (Singh et al., 2019). However, this value decreases when the starch is modified with citric and stearic acid, likely due to the formation of shorter chains and stronger interactions between the starch molecules. The solubility of starches increases after treatment with citric and stearic acid, likely because the modified starch chains have a greater ability to retain water (Singh et al., 2019). However, in some cases, such as with potato starch, solubility may decrease due to structural changes caused by the modification process (Kapelko-Żeberska et al., 2016).

4.4. In vitro digestibility

The modification of moth bean starch using a mixture of organic acids under dry heating has garnered attention due to its potential to enhance the functional properties of starch, making it suitable for various applications in food and pharmaceutical industries. This process typically involves the use of organic acids such as citric acid, which can alter the physicochemical properties of starch, including its digestibility, viscosity, and thermal stability. Research indicates that the modification of moth bean starch can lead to significant changes in its structural and functional characteristics. For instance, Singh et al. (Singh et al., 2019) demonstrated that the application of organic acids under dry heating conditions resulted in a marked increase in the digestibility of moth bean starch, primarily due to the disruption of the crystalline structure, which enhances enzyme accessibility to the starch granules. This is consistent with findings from other studies, which have shown that acid hydrolysis can effectively reduce amylose content and alter the pasting properties of starches, thereby improving their digestibility (Singh et al., 2016). The combination of DHT and amino acids significantly influences the in vitro digestibility of starch, primarily through the formation of RS and changes in the physicochemical properties of starch. According to Table 9, combining DHT-modified corn starch with aspartic acid and lysine results in decreased RDS and increased SDS and RS contents, in comparison to non-heated mixtures (Jiang et al., 2020a). This indicates that DHT positively affects the formation of SDS and RS in the presence of amino acids, making the starch more resistant to α-amylase degradation. The rise in SDS and RS levels following DHT exposure could be due to esterification processes or the formation of cross-linking structures between corn starch and amino acids during DHT (Wang et al., 2021). Another explanation might be the formation of a more intact surface on granules during DHT (Liu et al., 2019), which provides a barrier against starch molecular disruption. Elevating the DHT temperature increases SDS and RS levels while reducing RDS content in amino acid and corn starch combinations. The samples treated at 130 °C for 12 h with aspartic acid or lysine showed the lowest RDS and the highest SDS and RS contents. Kang et al. (Kang et al., 2021) reported that lauric acid-assisted DHT on wheat starch decreases its crystallinity and short-range order, yet minimally impacts its digestibility, potentially due to DHT obstructing the formation of the lauric acid-starch complex. Research indicates that DHT can enhance the formation of RS, which is less susceptible to enzymatic digestion. For instance, studies have shown that DHT increases the RS content in various starches, including corn and rice, by promoting retrogradation and altering the crystalline structure of starch (Oh et al., 2018a; Kanagaraj et al., 2019a). The presence of amino acids, such as lysine, during DHT can further enhance these effects. The interaction between amino acids and starch chains during the heat treatment process stabilizes the starch structure, reducing the accessibility of digestive enzymes and thereby decreasing the overall digestibility of starch (Jiang et al., 2020b; Sudheesh et al., 2020). Moreover, the synergistic effects of charged amino acids combined with DHT have been documented to improve the physicochemical properties of starch, making it more resistant to α-amylase attack. This resistance is attributed to the formation of stable cross-links between starch molecules and amino acids, which effectively hinders enzyme action (Muninathan, 2024; Jiang et al., 2020b). Additionally, the incorporation of amino acids during DHT has been shown to increase the soluble dietary fiber content, which is beneficial for digestive health and glycemic control (Oh et al., 2018a; Liang et al., 2021b). The combination of DHT and hydrocolloids plays a significant role in modulating the in vitro digestibility of starch. One of the primary effects of hydrocolloids in conjunction with DHT is the formation of a continuous network that suspends starch granules within a gel. This network acts as a physical barrier, limiting the access of digestive enzymes to the starch, thereby reducing its digestibility. For instance, Dartois et al. (Dartois et al., 2010) demonstrated that guar gum forms a coherent gel that significantly inhibits starch hydrolysis by creating a barrier against enzymatic attack. Similarly, Saleh et al. (Saleh et al., 2016) noted that the addition of hydrocolloids enhances gel strength, which is attributed to increased hydrogen bonding and immobilization of water molecules, further contributing to the reduction in digestibility. The rheological properties of starch pastes are also significantly affected by the presence of hydrocolloids during DHT. Ji et al. (Ji et al., 2017a) reported that the interaction between hydrocolloids and starch leads to increased paste viscosity and shear stability, which can enhance the structural integrity of the starch gel. This increased viscosity not only contributes to the physical barrier effect but also influences the overall digestibility of starch by altering the flow and mixing characteristics during digestion (Jang et al., 2015). Oh et al. (Oh et al., 2018a) further supported this by showing that DHT of starch-hydrocolloid mixtures results in changes to

Table 9
Changes in digestion profile of different kinds of modified starch by dry heating with food ingredient.

Starch source	Food ingredients (addition level)	DHT condition	Digestion characteristics			Reference
			RDS (%)	SDS (%)	RS (%)	
Corn	Aspartic acid (0.5%)	130 °C, <10% moisture, 2 h	−5.8	+1.28	+4.52	Jiang et al. (Jiang et al., 2020a)
	Aspartic acid (0.5%)	130 °C, <10% moisture, 12 h	−7.42	+1.14	+6.28	
	Lysine (0.5%)	130 °C, <10% moisture, 2 h	−9.42	+7.49	+2.51	
	Lysine (0.5%)	130 °C, <10% moisture, 12 h	−10.28	+7.5	+3.41	
Chestnut	Xanthan gum (0.01%)	140 °C, <10% moisture, 4 h	−3.21	+2.03	+2.18	Liu et al. (Liu et al., 2022a)
	Xanthan gum (0.01%)	140 °C, <10% moisture, 8 h	−5.92	+2.17	+5.0	
	Xanthan gum (0.2%)	140 °C, <10% moisture, 4 h	−2.46	+0.47	+2.0	
	Xanthan gum (0.2%)	140 °C, <10% moisture, 8 h	−6.23	+0.7	+5.53	
High amylose rice	CMC (0.04%)	130 °C, <10% moisture, 1 h	−4.8	−7.3	+12.1	Oh et al. (Oh et al., 2018c)
	CMC (0.04%)	130 °C, <10% moisture, 4 h	−3.6	−6.4	+10	
	Guar gum (0.04%)	130 °C, <10% moisture, 1 h	−2.3	−0.3	+1.0	
	Guar gum (0.04%)	130 °C, <10% moisture, 4 h	−1.7	−6.1	+5.5	

RDS: rapid digestible starch; SDS:slow digestible starch; RS:resistant starch.
DHT: dry heat treatment; CMC: carboxymethylcellulose.The values are derived by subtracting the fraction content in modified starch through dry heating from the content after incorporating the food ingredient. '+' indicates an increase or improvement in the measured parameter relative to the control, while the '-' denotes a decrease or reduction.

the gel structure, which reduces enzyme susceptibility and enhances the formation of RS. Moreover, the type of hydrocolloid used can significantly impact the digestibility of starch. For instance, chestnut starch's digestibility decreases with higher xanthan gum concentrations or longer heating times at the same temperature, resulting in lower RDS and higher SDS and RS levels (Liu et al., 2022a). A comparative study found that CMC-assisted DHT (130 °C, 4 h) and guar gum-assisted DHT (130 °C, 1–4 h) reduce the RDS content of high-amylose rice starch by 4.8% and increase the RS content by 12.1% compared to CMC-assisted DHT at 130 °C for 1 h (Oh et al., 2018c). The combination of DHT with anionic food gums creates a synergistic effect that enhances the reduction in starch digestibility. This effect also fosters strong bonds between starch and gum, leading to a more compact and structured formation. This structured formation reduces the enzyme-accessible surface area, making enzymatic penetration more difficult and thus slowing starch hydrolysis.

5. Applications of DHT-modified starches

5.1. Improving the processing characteristics of grain raw materials

DHT is utilized to augment the processing features of rice flour. Qiu et al. (Qiu et al., 2015a) observed that prolonging the DHT duration incrementally increased the disulfide bond content in glutinous rice flour, which subsequently led to enhancements in pasting properties, gel hardness, and viscosity. Specifically, the PV rose from 1156 cP to 3381 cP, and the viscosity of cold paste escalated from 394 cP to 3043 cP, illustrating a marked improvement in the processing attributes of glutinous rice flour. Tabara et al. (Tabara et al., 2015) evaluated the oil binding capacity of rice flour after various DHT durations and noted a significant enhancement in oil absorption, especially for flour treated at 120 °C for 120 min, which exhibited a higher oil binding capacity of 6.35 mL/g. Zhou et al. (Zhou et al., 2019) explored the impact of DHT on rice flour's processing traits, finding an increase in oil retention that correlated with the particle size of the flour—the finest particles showed the most significant increase in oil retention (67%), followed by medium (28%) and coarse particles (14%). The research also demonstrated that DHT increased the three-phase contact angle and surface hydrophobicity of proteins in rice flour, suggesting that particle size and DHT are effective in optimizing oil retention in rice flour. DHT also proves beneficial in modifying wheat flour characteristics, enhancing dough handling and suitability for various culinary applications.

5.2. Improvement in quality of grain products

As mentioned earlier, DHT can enhance the processing characteristics of grain starch, which will ultimately improve the quality of grain products. Hong et al. (Hong et al., 2021) found that DHT increased the whiteness value of fresh wet noodles made from wheat flour processing and significantly improved the tensile strength, hardness, and chewiness of cooked fresh wet noodles. This indicates that DHT can improve the quality of fresh, wet noodles. Sudha et al. (Sudha et al., 2016) applied both dry heat (100 °C, 2 h in an air oven) and moist heat (steaming at normal pressure for 30 min) to wheat flour. The DHT resulted in wheat flour with a higher falling number value, without significantly altering the bread's specific volume. Conversely, moist heat treatment considerably reduced the bread's specific volume and led to lower immunogenicity against gliadin. Wang et al. (Wang et al., 2020b) discovered that moderate DHT temperatures (110 °C or 130 °C) extended dough formation time and increased dough stability, whereas higher temperatures (150 °C) adversely affected these characteristics, increasing dough weakness and reducing stability. As these studies indicate, DHT enhances the processing characteristics of grain starch, ultimately improving the quality of grain-based products. Research indicates that DHT can significantly enhance the springiness of pancakes. Cho et al. demonstrated that the application of dry heat to starch and flour fractions results in increased springiness, which is crucial for achieving desirable texture in pancakes (Cho et al., 2019). The mechanism behind this enhancement is attributed to the gelatinization and retrogradation processes that occur during heating, which modify the starch structure and improve its elastic properties. Additionally, the incorporation of specific ingredients, such as xanthan gum, during DHT has been shown to further enhance the springiness of pancake formulations (Su et al., 2018a). Sponge cakes are characterized by their light and airy structure, which is largely dependent on the volume expansion during baking. Ureta et al. (Ureta et al., 2015) highlighted that the baking conditions, including temperature and airflow, significantly affect the volume of sponge cakes. DHT contributes to this volume increase by altering the gelatinization properties of starch, leading to improved gas retention and expansion during the baking process. Furthermore, studies have shown that the specific volume of sponge cakes can be enhanced through the application of DHT, resulting in a more porous and desirable texture (Gentscheva et al., 2022). DHT alters the gelatinization and pasting properties of starch within the flour. This modification can lead to improved water absorption and dough handling characteristics, which are essential for baking applications (Qiu et al., 2015a). For example, the peak viscosity of flour can increase after DHT, indicating enhanced thickening properties (Qiu et al., 2015a). As González et al. (González et al., 2021) reported, increasing DHT temperatures raised wheat flour's starch crystallinity and molecular order, enhancing the SDS content while reducing the RDS content, affecting bread texture positively below 100 °C but increasing hardness and reducing volume above this temperature. DHT effectively reduces the moisture content of flour, which is critical for preventing microbial growth and enzymatic reactions that can lead to spoilage (Bucsella et al., 2016). For instance, heat treatment has been shown to significantly decrease the moisture sorption capacity of flour, thus enhancing its shelf life (Bucsella et al., 2016).

5.3. DHT in 3D food applications

3D food printing is an innovative technology that integrates knowledge from various disciplines including 3D modeling, electromechanical control, and food science. This technique speeds up the transition from raw materials to final products, reduces resource consumption, and cuts production costs. It allows for the creation of foods with precise sizes, sensory qualities, and nutritional values, presenting a new method of food production. Additionally, it offers the potential to improve the nutritional content of foods and customize healthy recipes for specific groups such as patients, the elderly, and children. Maniglia et al. (Maniglia et al., 2020a) applied DHT to enhance the 3D printing properties of wheat starch. Their research showed that while DHT caused a slight increase in the size of the starch granules, it did not alter their shape or surface properties. The functional groups of the starch remained intact post-DHT, indicating minimal oxidation. However, the treatment led to a reduction in the crystalline regions within the starch granules and a slight depolymerization of medium-sized molecules. The hydrogels created from these modified starches were less viscous but exhibited greater structural strength when left undisturbed. After undergoing DHT for 4 h, the wheat starch demonstrated improved performance in 3D printing. Further extending this research, Maniglia et al. (Maniglia et al., 2020b) explored the use of cassava starch for creating hydrogels suitable for 3D printing. The DHT conditions applied to cassava starch were similar to those used for wheat starch, specifically 130 °C for periods of 2 and 4 h. Prolonged DHT resulted in larger granule sizes and an increase in carbonyl content. Consequently, the cassava starch, after DHT, showed enhanced texture and pasting properties, making the hydrogels more suitable for 3D printing applications. This advancement underscores the potential of DHT in improving the functional properties of starches for specialized applications such as 3D food printing.

6. Challenges and future work

DHT has emerged as a significant method for modifying starches, enhancing their functional properties for various applications. This technique involves heating starch at high temperatures (typically between 130 °C and 200 °C) under low moisture conditions, which can lead to substantial changes in the starch's physicochemical properties. However, despite its advantages, DHT also presents challenges that need to be addressed to optimize its application in food science and other industries. One of the primary challenges associated with DHT is the precise control of treatment conditions, such as temperature and duration. Variations in these parameters can lead to inconsistent results in the modification of starch properties. For instance, studies have shown that prolonged exposure to high temperatures can result in the degradation of starch granules, affecting their gelatinization and rheological properties (Liu et al., 2022b; Rao et al., 2022b). Specifically, the decrease in the storage modulus (G′) of starch gels after DHT can be attributed to reduced water content and altered swelling behavior of the starch granules, which impacts the gel network structure (Liu et al., 2022b). Therefore, establishing optimal conditions for DHT is crucial to ensure the desired modifications without compromising the starch's integrity. Furthermore, the interaction of starch with other components during DHT can complicate the modification process. The presence of hydrocolloids, for example, can enhance the structural stability of starch pastes, but may also lead to increased viscosity that complicates processing (Su et al., 2018b; Ji et al., 2017b). Additionally, the formation of RS during DHT is influenced by the starch's amylose content and the specific conditions of treatment, which can vary widely across different starch sources (Kanagaraj et al., 2019b). This variability necessitates a deeper understanding of the underlying mechanisms at play during DHT to tailor the process for specific applications. Looking towards future work, there are several promising avenues for research and application of DHT-modified starches. The development of starches with enhanced functional properties, such as increased solubility and improved digestibility, could lead to innovative food products that cater to health-conscious consumers (Rao et al., 2022b; Muninathan et al., 2024). For instance, DHT has been shown to significantly increase the RS content, which is beneficial for glycemic control and overall health (Muninathan et al., 2024). Moreover, the potential for combining DHT with other modification techniques, such as heat-moisture treatment or chemical modifications, could yield starches with superior characteristics for specific applications (Liang et al., 2021a; La Fuente et al., 2023b).

7. Conclusions

DHT is recognized as a significant technique for the physical modification of starch, gaining considerable interest for its eco-friendly, straightforward, and efficient attributes. DHT can control the alteration of starch-based raw materials or the transformation of starch components throughout processing. Various factors, such as starch source, DHT temperature and time, and food additives, influence the effectiveness of dry heat modification. The impact of these factors on the processing characteristics of dry heat-modified grain starch still needs to be clarified. Relevant research can be in-depth in the following four aspects: 1) conducting research on the correlation between DHT intensity and starch structural properties and gaining a deeper understanding of modification mechanisms; 2) exploring the synergistic effect of new treatment methods such as pulsed electric field, ultrasonic waves, ozone, plasma, etc. with DHT, such as establishing a dual modification method to improve the modification effect and efficiency; 3) target-oriented dry heat modification; 4) Regulation and optimization of DHT are necessary for each starch source to prevent the destruction of starch granules, which can lead to undesired characteristics. In combination with the production process of the target food, the processing characteristics of a certain aspect of starch should be targeted to improve so as to develop a dry heat modification method for special processing ingredients or extend the modification from raw starch to the production of starch-based foods such as noodles, bread, cake, and other products.

CRediT authorship contribution statement

Hong-Ju He: Writing – original draft, Validation, Software, Investigation, Formal analysis, Data curation. **Guanglei Li:** Writing – review & editing, Supervision, Resources. **Mohammed Obadi:** Supervision, Writing – review & editing, Conceptualization. **Xingqi Ou:** Validation, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

No data was used for the research described in the article.

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