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Oat as a Source of Resistant Starch: A Review

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ASTRACT

Oats are recently gaining attention for their composition and various benefits and it is widely used for various purposes including in the food industry and human health. Oats are composed of mainly starch made of amylose and amylopectin with several distinctive chemical, physical, and structural properties. The difference in amylose and amylopectin ratio directly affects the properties of starch, including gelatinization, textural, pasting, functional, rheological, and retrogradation. The characteristics of oat starch also affect its interaction with other food components which substantially affect the food products. In addition, the oat starch is also high in resistant starch content which improves human health (e.g. prevention of colon cancer, cholesterol, and reducing blood sugar). This review summarizes the oat starch as a resistant starch with various chemical compositions and characteristics with various applications.

KEYWORDS: Oat, Resistant Starch, starch, Oat starch characteristics, Oat starch health benefit

HIGHLIGHTS

Oat starch is the main carbohydrate component in oats composed of amylose and amylopectin affecting the amount of resistant starch.

Oat starch has various physical, chemical, and structural properties affecting its properties and functionality

Resistant starch is a major component of oats and it prevents diseases including cholesterol and diabetes.

INTRODUCTION

Recently, the trend of oat consumption has been increasing. Oat is frequently used in food production, including oat flakes, porridge, cereal bars, biscuits, noodles, breads, yogurt, and oat milk and beverages (Yang et al., 2023). Oat starch is used in various food and non-food products, including to replace fat, soup/sauce/gravy/ingredients, and dessert ingredients (Arendt & Zannini, 2013). Oat, or Aneva sativa, is produced from the plant Poaceae grass family. The oats have been manufactured in various forms with differences in texture, flavor, and cooking period time (Zhang et al., 2021). Oat groats are the least processed type of oat, followed by steel-cut oats and rolled or old-fashioned oats. Furthermore, some oats are experienced in pre-cooked methods to reduce the cooking time, such as oats, quick oats, and instant oats. Due to this effectiveness and nutritional value, oats have become a popular breakfast cereal worldwide. Oats are famously consumed by people trying to lose weight and improve gut microbial activity (Shehzad et al., 2023). Moreover, the high content of water and soluble fibers can control the hunger level by consuming oats (Rebello et al., 2016).

Oats have a balanced nutritional profile, high β-glucan concentration, low glycemic starch, essential amino acids, unsaturated fatty acids, and phenolic compounds. Moreover, oats are listed as the only cereal considered a health food by the World Health Organization and have various potentials to be modified into functional foods or food additives (Mao et al., 2022). Additionally, it is a versatile grain for food and has unique qualities compared to other cereal grains. The oat starch is also an essential raw ingredient, and it is widely used in the food industry as it has high nutritional value and broad technological functionality (Punia et al., 2020). While previous research has acknowledged oats' potential as a rich source of resistant starch, there has not been a thorough analysis of the field's current research in this particular area. The exact types and amounts of resistant starch present receive less emphasis in research, with the majority concentrating on the overall nutritional value of oats. Researchers still do not fully grasp the variables, like oat types, processing methods, and cooking procedures, that affect the resistant starch content of oats due to the gap in the research. More research is needed to determine how these factors affect the bioavailability and health advantages of oats-resistant starch.

Resistant starches (RS) are non-digestible carbohydrates that are generally defined as any starch that is not digested in the small intestine but passes through to the large intestine. RS is a good substrate for fermentation, which increases the short-chain fatty acid production and the abundance of intestinal bacteria (Zhu et al., 2020). The interesting properties of oats are commonly discussed in many literature. This paper will delve deeper into the chemical properties of oats as a resistant starch and aims to inform the properties of oats as a resistant starch including their properties, specifically its chemical properties, interaction with other components, types of resistant starches, its mechanism of action, and effects on the human body.

Oat Properties

Chemical Properties of Oat

Oats are notable for their high nutritional content, specifically starch, protein, fat, and dietary fiber, particularly soluble β-glucan content, and are rich in lipids and protein compared to other grain types.

Table 1. Nutritional Content of Oat

Name	Amount
Starch	60%
Protein	14%
Fat	7%
Dietary fiber	4%

It is exceptionally high in potassium when it comes to micronutrients and it contains other insignificant substances like phenolics (Zhang et al., 2021). Aside from that, oats are a good source of phenolic compounds and antioxidants such as phytic acid, flavonoids, sterols, etc, which can decrease inflammation and help to guard the cells from free-radical oxidation reactions (Paudel et al., 2021). The high content of β-glucan soluble fiber, high protein, and fat content in oats help to minimize the risk of coronary heart disease. In addition, oats also contain several essential vitamins and minerals like phosphorus, iron, zinc, polyphenols, and selenium (Chen et al., 2021).

Characteristics of Oat Starch

The oat starch has several unique characteristics, including gelatinization, textural, functional, pasting, physicochemical, morphological, and rheological properties (Kaur et al., 2022). The gelatinization properties occur when the starch and water are exposed to heat above the critical temperature. Gelatinization results in the starch granules swelling, the crystallite melts, loss of birefringence, increasing viscosity of the food product, and solubilization. A high degree of crystalline behavior raises the transition temperature, providing structural stability and making granules resistant to gelatinization. In addition, the higher amount of amylose will lower the melting point of crystallites, which initiates the gelatinization process. The increase in viscosity can also be used to observe the pasting properties. The swelling of starch granules will eliminate the molecular order, the granules will undergo mechanical stress, and shear will lead to disruption of granules, and amylose and amylopectin will leach out. This process will form a paste. Moreover, as this process alters starch's structural and physical properties, it is highly related to the processing and palatability of oat food. Many factors influence the rheological properties of starch paste and gel, including the chemical structure of starch, pasting conditions (e.g., temperature, shear rate, and heating rate), starch concentration, and storage conditions (temperature and time) (Punia et al., 2020).

Interaction of Starch with Different Components

Oat starch is widely used in food applications such as soup, sauces, baked products, milk products, snacks, and noodles. It also increases the viscosity of food products. Oat starches contain high protein content, high digestibility, and high amounts of dietary fiber (Yang et al., 2023). In addition, the oat starch is also influenced by interactions with other components, namely protein, starch, lipid, and polyphenol (Kaur et al., 2022). Kumar et al. (2018) stated that the quality of food products made from oat starch is also affected by the concentration and composition of starch and protein. Moreover, Punia et al. (2020) also mentioned that reducing the fat in food products can affect the amylose-lipid complex, which may alter the starch swelling and gelatinization properties.

Resistant Starch

Types of RS

Type 1 resistant starch (RS1). Because the starch is physically confined within the food matrix, this form of starch is resistant. Physical barriers prevent enzymes from accessing the starch. Foods can have their starch released through milling or grinding, which makes it more palatable and accessible (Kraithong et al., 2022).

Type 2 resistant starch (RS2). Because of the way the starch granules are made, this kind of starch is naturally resistant. Unripe bananas, for example, or maize starch with a high amylose content, which does not gelatinize when cooked, are examples of foods where RS2 can develop (Snelson et al., 2019).

RS3, or resistant starch type 3. When gelatinized starch is heated and cooled, this kind of starch results. It can happen naturally during routine food processing (such as when potatoes are cooked and chilled), or it can happen when RS-rich items are made (Butardo & Sreenivasulu, 2016).

Type 4 resistant starch (RS4). This form of starch is made by adding chemical linkages to the starch polymer that prevent the digestive amylases from working properly. The kind and degree of bonding determine the inhibition. Dextrinization, etherification, esterification, oxidation, and cross-linking with difunctional reagents are among the chemistries that hinder amylolysis. These chemistries can significantly alter the food engineering functionality that the RS contributes to the food, such as solubility and process tolerance (Dhakal & Dey, 2022). In addition to resisting heating and amylase enzyme hydrolysis, RS5 offers steady processing qualities that minimize the swelling of starch granules. The ability of starch to paste is also impacted by the development of amylose-lipid complexes (Faridah et al., 2021).

Structure of resistant starch

To improve the physiological qualities and increase the content of resistant starch, the molecular structure of oat starch has been modified using several ways. Various studies have found that resistant starch of various sizes has variable physicochemical and functional features. The size of the surface area of starch granules, for example, would affect enzyme digestion. Due to the varied particle sizes of resistant starch granules, the surface area of enzyme action was also diverse, which directly affected enzyme digestion (Xia et al., 2023). However, the main properties of starch depend on the composition of amylose and amylopectin. Amylose and amylopectin are both the main components of starch which accounts for approximately 98–99% of oat starch granules (Punia et al., 2020). The resistant starch is influenced by the ratio of amylose and amylopectin and generally, the RS content of starch is strongly correlated with the amylose level as well as the ratio of amylopectin/amylose content, as the higher the number, the larger the content of resistant starch is. This is due to the fact that amylose is more resistant to digestion, thus giving the properties of resistant starch. Amylose has a relatively smaller structure chain which is easy to reorient in solution and to regenerate. It is a polysaccharide composed of α-D-glucose units, bonded to each other through α(1→4) glycosidic bonds with a low degree of polymerization and a branching frequency with a low α-1, 6 linkage frequency. Amylopectin, on the other hand, tends to have a higher degree of polymerization and a higher α-1, 6 linkage frequency (Tian & Sun, 2020). Many studies have reported the total amount of amylose in oat starch, however, those numbers vary from 19.4 - 22.7% to 27.5–29.5% (Raigond et al., 2014).

Resistant starch mechanism

The largest concentrations of resistant starch (RS), quickly digestible starch (RDS), and slowly digestible starch (SDS) were found in the oat bran group, the -glucan group, and the control group, respectively (Zhu et al., 2020). By giving a full feeling, oats may lower cholesterol and blood sugar levels and aid with appetite control. Oat bran may function by preventing the intestines from absorbing elements that can cause diabetes, high cholesterol, and heart disease. When applied to the skin, oats appear to lessen edema (Paudel et al., 2021). The component of starch known as resistant starch is not digested in the small intestine and is instead fermented by bacteria in the colon. This process produces short-chain fatty acids, which may have certain metabolic consequences (Bojarczuk et al., 2022).

To increase the intake of resistant starch, a good food to add to the diet is cereal-based foods. Resistant starch could be present naturally in cereal grains as a result of encapsulation of starch in cell or protein matrix. Resistant starch could also be incorporated into cereal-based food, as it has been studied to have evidence of health benefits in both conditions (Nguyen et al., 2022).

Adding oats to one's diet is one of the most convenient ways to add resistant starch, simply by cooking the oats and letting them cool down, such as the RS2 starches. After the starch cools, the RS3 starches form due to the recrystallization of gelatinized starch. Oats have a high antioxidant content, therefore, when the cooked oats are cooled down, the level of resistant starch could increase even further, such as in overnight oats (Raigond et al.,2018).

Whole oat food (WO) is considered to be a resistant starch type 2 (RS2), in research done by Zhu et al. (2020), oat products consist of 0.4 to 12.8% of oat resistant starch (ORS). Oat products that contain higher levels of ORS are known to improve IR and glucose tolerance for individuals with diabetes. The oat dietary fibers that are not digested by the gastrointestinal digestive system would be fermented in the large intestine in the gut microbiome. Resistant starch which is present in the raw form of oats is also known as RS2 starch and in research done by Zhang et al. (2021), RS2 starch makes up 29.31% of starch content in raw oats. RS2 slows down digestion as it has a compact structure of starch granules which makes it difficult for it to be broken down by the enzymes. In the same study, it was found that the high lipid content in oats – 3-7%, maybe another factor for the high level of RS in oats, as the amylose-lipid complex is more resistant to the enzymatic breakdown. RS starches that are less susceptible to enzymatic breakdown are also known as RS5 starches. The RS5 starches are not only more resistant to enzymes, it also change the gut microbiota content.

Oat's main components are amylose and amylopectin, which account for the content of resistant starch in them. The amount of amylose in oats is relatively high, as RS has a high-level content of amylose. This is due to the fact that amylose has a helical structure as well as the presence of hydrogen bonds linking in the glucose chain, which makes it less digestible for enzyme breakdown (Li et al., 2020). According to Ashwar et al. (2015), amylose has been recognized as the main factor of resistant starch formation. The retrogradation of amylose results in a higher amount of resistant starch after heating and cooling. Resistant starches also form from amylopectin during retrogradation due to the increase in molecule entanglement in the gel network which increases the molecular order of helix formation of the outer short chains. Amylopectin debranching produces low-molecular-weight polymers which promote the retrogradation process and thus it can increase the content of RS (Zaman & Sarbini, 2016).

Oats consist of not only resistant starch which slows down the digestion process, it also β-Glucans (βG). β-Glucans are a form of soluble fiber which dissolves in water and gelatinizes in the digestive tract. As a result, the β-Glucans slow down the digestion process and assist in the absorption of nutrients (Binou et al., 2020).

Heat treatment effect on resistant starch

Exposure to high temperatures might alter the composition of resistant starch inside oats. Gelatinization commonly occurs when starch is exposed to heat in which the starch granules can absorb water and swell (Donmez et al., 2021). As a result, the resistant starch will be more digestible in the intestine since the structure is changed (Romano & Kumar et al., 2019). During the gelatinization, the starch stored in the oats is normally in the form of semi-crystalline. However, this structure is disturbed by the heat, making the starch more accessible to react with water and enzymes, hence, the granules will be weakened and ruptured (Yussof et al., 2013). If the heating process is continued, then, the amylose and amylopectin might reach out to the solution in the form of a short-chain molecule, thus creating a gelling network that increases the viscosity of the whole solution. Typically, the starch starts to gelatinize around 110ºC up to 130ºC (Yacu, 2020).

On the other hand, the cooling in which the temperature is decreasing will reform the semi-crystal formation, thus, the content of resistant starch increases (Shah et al., 2016). The process is called retrogradation where the amylose and amylopectin are reassembled creating an ordered structure that is similar to its original. As a result of retrogradation, the oat's texture will also be altered, commonly becoming firmer, bulkier, and having a gritty texture (Pahwa et al., 2020). Moreover, retrogradation also impacts the resistance to digestion. Due to the reform of resistant starch, it can prevent the oat from being completely digested by the small intestine although the resistant starch is not the same as in the raw oat (Patel et al., 2017).

Overnight Oats Vs. Cooked

The amount of heat used during cooking is a contributing component; the lower the heat, the more nutrients are available. Cooking the oats by soaking them overnight is a way to cook oats without heat, and even though the process takes considerably longer, it has more nutrients than the cooked form (Chun, 2023). Overnight oatmeal has more resistant starch than cooked oats, because when starchy meals are chilled, their structure is once more reorganized, making it harder for the digestive enzymes to break them down (Abdulmageed et al., 2023). More "resistant starch," which is fiber since it is not broken down, is now present in the food (O'Neil et al., 2015).

Digestion of resistant starch in the human body

Short-chain fatty acids (SCFAs), such as acetate, propionate, and butyrate, are mainly produced when RS enters the colon through fermentation by bacteria in the gut microbiota (Bach Knudsen et al., 2018). While both acetate and propionate may have adverse effects on health, butyrate is the SCFA that is most influenced by RS consumption and has been specifically linked to health benefits. By lowering inflammation, reducing the incidence of colon cancer, and enhancing gut barrier integrity, butyrate contributes significantly to human gut health (Geirnaert et al., 2017).

Resistant starch, which is mainly present in oats and is difficult for the small intestine to digest, is a significant component of oats. Instead, it gets to the large intestine, fermented by colonic bacteria as a substrate (Zhu et al., 2020). The ability of these bacteria to metabolize resistant starch is fueled by it. With the complex structure of RS, certain bacteria are needed to initiate the degradation of this semi-crystalline material. The resistant starch is fermented in the large intestine by specific gut bacterial species, Ruminococcus bromii and Bifidobacterium adolescentis, and other related Bifidobacterium species, as well as particular strains of Firmicutes, are currently the known human gut microorganisms with demonstrated RS degrading capabilities (DeMartino & Cockburn, 2020). The resistant starch is broken down by these bacteria into other byproducts, including butyrate, during fermentation. In this fermentation process, butyrate is one of the main byproducts. It is released into the colon, where it provides colonocytes, the cells that line the colon, with their primary energy source and aids in maintaining the integrity of the gut lining (Dobranowski & Stintzi, 2021).

Health effects

Consuming resistant starch has numerous health benefits, including preventing colon cancer, reducing blood sugar levels, reducing cholesterol, and inhibiting fat buildup (DeMartino & Cockburn, 2020). Resistant starch is commonly used to reduce the risk of diabetes and obesity because it can help lower blood sugar, lose weight, and have a low glycemic index (GI). As a result, RS has promising growth prospects and benefits for the functional food processing industry. RS provides similar physiological benefits to dietary fiber but without the drawbacks of dietary fiber's unpleasant taste and flavor. Moreover, the non-digestible fibers in oats are fermented in the large intestine, producing butyrate. Butyrate is a short-chain fatty acid (SCFA) that is known for having various health benefits (Cavaleri & Bashar, 2018). According to Bourassa et al. (2016), butyrate is well known for its wide range of advantages, including strengthening the mucosal barrier to improve gut health, lowering colon inflammation, and preventing problems like leaky gut. Additionally, it regulates bowel movements and might prevent colon cancer. Oats, as one of the more well-known sources of RS, are gaining popularity due to their excellent nutritional content and health advantages in the prevention of obesity and diabetes (Xia et al., 2023).

CONCLUSION

Oats are mainly composed of starch with various amylose and amylopectin ratios, which affect the product's structure, properties, and amount of resistant starch. The oat has resistant starch 2, which will turn into resistant starch 3 after retrogradation. The characteristics of the oat starch will form the properties and functionality of the food product, including gelatinization, which affects the viscosity texture, pasting properties, functionality, physicochemical attributes, and retrogradation of the food products. Moreover, other components such as protein, lipids, and polyphenols also influence the properties of the oat starch. Food products with oat-resistant starch have a broad positive health income, especially in how they influence gut microbiota and butyrate production. It also plays a role in reducing cholesterol, diabetes, and colon cancer.

REFERENCE

1. Abdulmageed, L. H., Hanoush, N. H., & Abdulmajeed, A. H. (2023). The Health Importance of Resistant Starch in Some Agricultural Crops: A Review. *Journal of University of Anbar for Pure Science*, *17*(1), 62–71. https://doi.org/10.37652/juaps.2023.179057
2. Arendt, E. K., & Zannini, E. (2013). Oats. *Cereal Grains for the Food and Beverage Industries*, 243–283e. https://doi.org/10.1533/9780857098924.243
3. Ashwar, B. A., Gani, A., Shah, A., Wani, I. A., & Masoodi, F. A. (2015). Preparation, health benefits and applications of resistant starch—a review. *Starch - Stärke*, *68*(3–4), 287–301. https://doi.org/10.1002/star.201500064
4. Bach Knudsen, K., Lærke, H., Hedemann, M., Nielsen, T., Ingerslev, A., Gundelund Nielsen, D., Theil, P., Purup, S., Hald, S., Schioldan, A., Marco, M., Gregersen, S., & Hermansen, K. (2018). Impact of Diet-Modulated Butyrate Production on Intestinal Barrier Function and Inflammation. *Nutrients*, *10*(10), 1499. https://doi.org/10.3390/nu10101499
5. Binou, P., Yanni, A. E., Stergiou, A., Karavasilis, K., Konstantopoulos, P., Perrea, D., Tentolouris, N., & Karathanos, V. T. (2020). Enrichment of bread with beta-glucans or resistant starch induces similar glucose, insulin and appetite hormone responses in healthy adults. *European Journal of Nutrition*, *60*(1), 455–464. https://doi.org/10.1007/s00394-020-02265-6\
6. Bojarczuk, A., Skąpska, S., Mousavi Khaneghah, A., & Marszałek, K. (2022). Health benefits of resistant starch: A review of the literature. *Journal of Functional Foods*, *93*, 105094. https://doi.org/10.1016/j.jff.2022.105094
7. Bourassa, M. W., Alim, I., Bultman, S. J., & Ratan, R. R. (2016). Butyrate, neuroepigenetics and the gut microbiome: Can a high fiber diet improve brain health? *Neuroscience Letters*, *625*, 56–63. https://doi.org/10.1016/j.neulet.2016.02.009

8. Butardo, V. M., & Sreenivasulu, N. (2016). Tailoring Grain Storage Reserves for a Healthier Rice Diet and its Comparative Status with Other Cereals. *International Review of Cell and Molecular Biology*, *323*, 31–70. https://doi.org/10.1016/bs.ircmb.2015.12.003
9. Cavaleri, F., & Bashar, E. (2018). Potential Synergies of β-Hydroxybutyrate and Butyrate on the Modulation of Metabolism, Inflammation, Cognition, and General Health. *Journal of Nutrition and Metabolism*, *2018*, 1–13. https://doi.org/10.1155/2018/7195760
10. Chen, O., Mah, E., Dioum, E., Marwaha, A., Shanmugam, S., Malleshi, N., Sudha, V., Gayathri, R., Unnikrishnan, R., Anjana, R. M., Krishnaswamy, K., Mohan, V., & Chu, Y. (2021). The Role of Oat Nutrients in the Immune System: A Narrative Review. *Nutrients*, *13*(4), 1048. https://doi.org/10.3390/nu13041048
11. Chun, W. N. (2023). *Benefits of Overnight Oats vs Cooked*. One Pot Wellness.
12. DeMartino, P., & Cockburn, D. W. (2020). Resistant starch: impact on the gut microbiome and health. *Current opinion in biotechnology*, *61*, 66-71.
13. Dobranowski, P. A., & Stintzi, A. (2021). Resistant starch, microbiome, and precision modulation. *Gut Microbes*, *13*(1). https://doi.org/10.1080/19490976.2021.1926842
14. Donmez, D., Pinho, L., Patel, B., Desam, P., & Campanella, O. H. (2021). Characterization of starch–water interactions and their effects on two key functional properties: Starch gelatinization and retrogradation. *Current Opinion in Food Science*, *39*, 103-109. https://doi.org/10.1016/j.cofs.2020.12.018
15. Faridah, D. N., Andriani, I., Talitha, Z. A., & Budi, F. S. (2021). Physicochemical characterization of resistant starch type V (RS5) from manggu cassava starch (Manihot esculenta). *Food Research*, *5*(2), 228–234. https://doi.org/10.26656/fr.2017.5(2).496
16. Geirnaert, A., Calatayud, M., Grootaert, C., Laukens, D., Devriese, S., Smagghe, G., De Vos, M., Boon, N., & Van de Wiele, T. (2017). Butyrate-producing bacteria supplemented in vitro to Crohn's disease patient microbiota increased butyrate production and enhanced intestinal epithelial barrier integrity. *Scientific Reports*, *7*(1). https://doi.org/10.1038/s41598-017-11734-8
17. Kaur, P., Kaur, K., Basha, S. J., & Kennedy, J. F. (2022). Current trends in the preparation, characterization and applications of oat starch—A review. *International Journal of Biological Macromolecules*, *212*, 172-181. https://doi.org/10.1016/j.ijbiomac.2022.05.117
18. Kraithong, S., Wang, S., Junejo, S. A., Fu, X., Theppawong, A., Zhang, B., & Huang, Q. (2022). Type 1 resistant starch: Nutritional properties and industry applications. *Food Hydrocolloids*, *125*, 107369. https://doi.org/10.1016/j.foodhyd.2021.107369
19. Kumar, L., Brennan, M., Zheng, H., & Brennan, C. (2018). The effects of dairy ingredients on the pasting, textural, rheological, freeze-thaw properties and swelling behaviour of oat starch. *Food Chemistry*, *245*, 518-524. https://doi.org/10.1016/j.foodchem.2017.10.125
20. Li, S., Sang, C., Turchini, G. M., Wang, A., Zhang, J., & Chen, N. (2020). Starch in aquafeeds: the benefits of a high amylose to amylopectin ratio and resistant starch content in diets for the carnivorous fish, largemouth bass (Micropterus salmoides). *British Journal of Nutrition*, *124*(11), 1145-1155.
21. Mao, H., Xu, M., Ji, J., Zhou, M., Li, H., Wen, Y., ... & Sun, B. (2022). The utilization of oat for the production of wholegrain foods: Processing technology and products. *Food Frontiers*, *3*(1), 28-45. https://doi.org/10.1002/fft2.120
22. Nguyen, S. N., Drawbridge, P., & Beta, T. (2022). Resistant Starch in Wheat-, Barley-, Rye-, and Oat-Based Foods: A Review. *Starch - Stärke*, *75*(9–10). https://doi.org/10.1002/star.202100251

23. O'Neil, C. E., Nicklas, T. A., Fulgoni, V. L., & DiRienzo, M. A. (2015). Cooked oatmeal consumption is associated with better diet quality, better nutrient intakes, and reduced risk for central adiposity and obesity in children 2–18 years: NHANES 2001–2010. *Food & Nutrition Research*, *59*(1), 26673. https://doi.org/10.3402/fnr.v59.26673
24. Pahwa, A., Khamrui, K., & Prasad, W. (2020). Influence of oat flour on pasting properties of flour blends, cooking quality and sensory attributes of vermicelli. *The Annals of the University Dunarea de Jos of Galati. Fascicle VI-Food Technology*, *44*(2), 70-84. https://doi.org/10.35219/foodtechnology.2020.2.05
25. Patel, H., Royall, P. G., Gaisford, S., Williams, G. R., Edwards, C. H., Warren, F. J., ... & Butterworth, P. J. (2017). Structural and enzyme kinetic studies of retrograded starch: Inhibition of α-amylase and consequences for intestinal digestion of starch. *Carbohydrate Polymers*, *164*, 154-161. https://doi.org/10.1016/j.carbpol.2017.01.040
26. Paudel, D., Dhungana, B., Caffe, M., & Krishnan, P. (2021). A Review of Health-Beneficial Properties of Oats. *Foods*, *10*(11), 2591. https://doi.org/10.3390/foods10112591
27. Punia, S., Sandhu, K. S., Dhull, S. B., Siroha, A. K., Purewal, S. S., Kaur, M., & Kidwai, M. K. (2020). Oat starch: Physico-chemical, morphological, rheological characteristics and its applications-A review. *International journal of biological macromolecules*, *154*, 493-498. https://doi.org/10.1016/j.ijbiomac.2020.03.083
28. Rasane, P., Jha, A., Sabikhi, L., Kumar, A., & Unnikrishnan, V. S. (2013). Nutritional advantages of oats and opportunities for its processing as value added foods - a review. *Journal of Food Science and Technology*, *52*(2), 662–675. https://doi.org/10.1007/s13197-013-1072-1
29. Raigond, P., Ezekiel, R., & Raigond, B. (2015). Resistant starch in food: a review. *Journal of the Science of Food and Agriculture*, *95*(10), 1968-1978.
30. Rebello, C. J., O'Neil, C. E., & Greenway, F. L. (2016). Dietary fiber and satiety: the effects of oats on satiety. *Nutrition Reviews*, *74*(2), 131-147.Romano, N., & Kumar, V. (2019). Starch gelatinization on the physical characteristics of aquafeeds and subsequent implications to the productivity in farmed aquatic animals. *Reviews in Aquaculture*, *11*(4), 1271-1284. https://doi.org/10.1111/raq.12291
31. Samitinjaya Dhakal, & Dey, M. (2022). Resistant starch type-4 intake alters circulating bile acids in human subjects. *Frontiers in Nutrition*, *9*. https://doi.org/10.3389/fnut.2022.930414
32. Shah, A., Masoodi, F. A., Gani, A., & Ashwar, B. A. (2016). Newly released oat varieties of Himalayan region-Techno-functional, rheological, and nutraceutical properties of flour. *LWT*, *70*, 111-118. https://doi.org/10.1016/j.lwt.2016.02.033
33. Shehzad, A., Rabail, R., Munir, S., Jan, H., Fernández-Lázaro, D., & Aadil, R. M. (2023). Impact of Oats on Appetite Hormones and Body Weight Management: A Review. *Current Nutrition Reports*, *12*(1), 66–82. https://doi.org/10.1007/s13668-023-00454-3
34. Snelson, M., Jong, J., Manolas, D., Kok, S., Louise, A., Stern, R., & Kellow, N. J. (2019). Metabolic Effects of Resistant Starch Type 2: A Systematic Literature Review and Meta-Analysis of Randomized Controlled Trials. *Nutrients*, *11*(8).https://doi.org/10.3390/nu11081833
35. Tian, S., & Sun, Y. (2020). Influencing factor of resistant starch formation and application in cereal products: A review. *International Journal of Biological Macromolecules*, *149*, 424–431. https://doi.org/10.1016/j.ijbiomac.2020.01.264
36. Xia, J., Zhang, Y., Huang, K., Cao, H., Sun, Q., Wang, M., Zhang, S., Sun, Z., & Guan, X. (2023). Different multi-scale structural features of oat-resistant starch prepared by ultrasound combined

enzymatic hydrolysis affect its digestive properties. *Ultrasonics Sonochemistry*, *96*, 106419. https://doi.org/10.1016/j.ultsonch.2023.106419

37. Yacu, W. (2020). Extruder screw, barrel, and die assembly: General design principles and operation. In *Extrusion cooking*(pp. 73-117). Woodhead Publishing. https://doi.org/10.1016/C2020-0-02148-1
38. Yang, Z., Xie, C., Bao, Y., Liu, F., Wang, H., & Wang, Y. (2023). Oat: Current state and challenges in plant-based food applications. *Trends in Food Science & Technology*. https://doi.org/10.1016/j.tifs.2023.02.017
39. Yussof, N. S., Utra, U., & Alias, A. K. (2013). Hydrolysis of native and cross-linked corn, tapioca, and sweet potato starches at sub-gelatinization temperature using a mixture of amylolytic enzymes. *Starch-Stärke*, *65*(3-4), 285-295. https://doi.org/10.1002/star.201200002
40. Zaman, S. A., & Sarbini, S. R. (2016). The potential of resistant starch as a prebiotic. *Critical reviews in biotechnology*, *36*(3), 578-584.
41. Zhang, K., Dong, R., Hu, X., Ren, C., & Li, Y. (2021). Oat-Based Foods: Chemical Constituents, Glycemic Index, and the Effect of Processing. *Foods*, *10*(6), 1304. https://doi.org/10.3390/foods10061304
42. Zhu, Y., Dong, L., Huang, L., Shi, Z., Dong, J., Yao, Y., & Shen, R. (2020). Effects of oat β-glucan, oat resistant starch, and the whole oat flour on insulin resistance, inflammation, and gut microbiota in high-fat-diet-induced type 2 diabetic rats. *Journal of Functional Foods*, *69*, 103939. https://doi.org/10.1016/j.jff.2020.103939