In Vivo Methods for Measuring the Glycemic Index

Subjects: Biochemistry & Molecular Biology

Contributor: Yongmei Sun, Chao Zhong, Tim Langrish

The concept of Glycemic Index (GI) was suggested by Jenkins to classify carbohydrate-containing foods. GI is “an expression of the percentage of the area under the blood glucose response curve when taking the same amount of carbohydrate as glucose”. It is a physiological way to explain how dietary carbohydrate impacts blood glucose. The GI value has a range between 1 and 100. Glucose, as the reference material, has a GI value of 100. A food with a lower GI value (≤54) raises blood glucose more slowly.

Keywords: in vitro digestion ; glycemic index

1. Introduction

The concept of Glycemic Index (GI) was suggested by Jenkins to classify carbohydrate-containing foods. GI is “an expression of the percentage of the area under the blood glucose response curve when taking the same amount of carbohydrate as glucose” [1]. It is a physiological way to explain how dietary carbohydrate impacts blood glucose. The GI value has a range between 1 and 100. Glucose, as the reference material, has a GI value of 100. A food with a lower GI value (≤54) raises blood glucose more slowly [2].

Low-GI diets help with the management of obesity, diabetes, and cardiovascular disease [3][4][5][6]. Low-GI foods must be identified by the method of ISO 26642:2010 for labeling purposes [7][8][9]. The ISO 26642:2010 test is an in vivo method that involves many voluntary participants, and the in vivo method is time consuming [10]. Ethical clearance is also necessary and may be another barrier for rapid trial and error testing for some foods during their development stages.

Researchers have investigated some in vitro methods for GI measurements of single foods. Single foods refer to non-processed foods, such as banana and carrot, which are the focus of in vivo methods for GI measurement. The in vitro digestion results for carbohydrates have been associated with GI values [11][12]. However, the correlations between in vivo and in vitro measurements are not consistently high [13][14], and other physiological factors, including the glucose tolerance of different individuals, and meal factors, such as the physical forms of the foods, can confound the relationship [15][16][17]. The current in vitro method is only employed for food product development, but not for food labeling purposes [18][19].

2. In Vivo Methods for GI Measurement

2.1. ISO 26642:2010 Method

An official method for measuring GI was issued by the International Organization for Standardization (ISO) in 2010 [20] after development and update [21][22]. The ISO method has been calibrated by three independent laboratories, Sydney University, Australia, and GI labs in Toronto, Canada, and Biofortis Merieux NutriSciences in Saint-Herblain, France. Using the 2010 ISO method is precise enough to differentiate a low-GI food from a high-GI food with a high probability (97–99%) [23].

The in vivo method of GI measurement is summarized in **Table 1**. Participant recruitment [23], test sample preparation [20], blood sample collection [20], and data analysis [24][25] are key steps for this ISO method.

Table 1. Description of the in vivo method for GI (Glycemic Index) measurement using the ISO (International Organization for Satandardization) 2010 method.

Key Steps	Test Design	Reference
Participants	More than 10 people; No known food allergy; 18–35 years old; Non-smokers; Healthy (8 data/range of criteria).	[23]
Test samples	Reference food: 50 g glucose; Test food: 50 g carbohydrate containing; 250 mL water served.	[20]
Blood samples	Take blood samples at −10, −5, 15, 30, 45, 60, 90, 120 min.	[20]
Data analysis	Spectrophotometry or electrochemical detection-coupled enzyme systems.	[24]

Prior to in vivo tests for GI measurement, test foods are usually analyzed to meet stringent nutritional criteria for energy (kJ or kcal), carbohydrate, saturated fats, sodium, and (in certain foods) fibre and calcium [7][8][9].

2.2. The Opportunities for Using Alternative Methods

The in vivo method of GI measurement has high accuracy and precision [22][23]. At the same time, it requires extra effort to manage the participants and obtain ethics clearance [20]. The cost of the in vivo test is relatively high [10], especially for food formulae, which are still under development. Other researchers have explored alternative methods to determine the GI values of foods, mainly in vitro methods. The GI value determined by an in vitro method is sometimes incorrect when classifying a low-GI food, and to label a high-GI food as a low-GI category is potentially harmful for people with diabetes [18]. So far, the GI measurement of single foods is still determined by in vivo methods [18].

Besides the glycemic effect, the in vitro method also covers the understanding of food nutrition and formulas, food digestibility and other health benefits by mimicking food digestion in living bodies. Many studies have focused on the chemical analysis of the food digestion process [26][27][28][29]. The chemical analysis, either for physical models or for mathematical models [30][31][32][33][34], has not always considered shear stresses and shear rates when mimicking the digestion process [35]. A comprehensive review of all digestion models is covered by a related paper [35]. Recent digestion models focus on mimicking the kinetics of food movement in the digestive system, as well as the physical processes during the peristaltic movement of digestion system. It is worthwhile to understand food digestion (especially carbohydrate digestion) from engineering perspectives to pave the way for an improved in vitro methods of GI measurement.

3. Food Digestion and Process

3.1. Carbohydrates

Starch is the majority carbohydrate in plants and is deposited in granules in most green plants. Its hydrolysis provides 40–80% of the total human energy intake [21][36]. It is found in many types of plant tissues and organs, such as seeds (e.g., cereal grains), roots (e.g., sweet potato), tubers (e.g., potato), stems (e.g., sago), leaves (e.g., tobacco), fruits (e.g., banana), and even pollen [37][38]. Starch is the dominant component of cereal grains, pluses, and tuber and root crops [37]. For instance, milled rice kernels contain up to 90% starch on a dry basis [39], maize kernels contain up to 80% starch [40], and potatoes contain 60–80% starch [41]. Besides starch-rich crops, pulse grains, such as legumes, have up to 53% starch [42]. Starch is a biopolymer. It contains two major components: amylose and amylopectin. Amylose is a mainly linear polysaccharide, which contributes up to 15–35% of the granules. Amylopectin, however, is a highly branched polysaccharide [37][38][43]. Amylose, containing α-1,4-linked d-glucopyranose and a few branches of α-1,6 linkages, has different properties to amylopectin with α-1,4-linked linear chains of different lengths, connected by about 5% α-1,6 branch linkages [38][44][45][46]. Amylose tends to produce tough gels and strong films, while amylopectin produces soft gels and weak films. It has been reported that a high amylose content in starch may help reduce the glycemic response and increase the blood glucose level slowly [47].

Recent studies have advanced the understanding of the starch features and the fine structure of amylose and amylopectin [37][48]. The importance of plant cell walls and the cellulose tissue structure have been noticed by several works [49][50][51], and these features have also been discussed in the studies of carbohydrate digestion [52][53][54]. The cell wall may be an important mass-transfer resistance from a mass transfer point of view. Starch granules transfer through the broken cell wall before its hydrolysis with digestive enzymes during the digestion processes. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.2. Digestion Process

Studying human digestion was initiated in the medical field for diagnostic purposes [55]. Nowadays, it is an essential factor in the development of novel food products, as well as the testing of new pharmaceutical products [56][57].

The process of food digestion generally includes oral digestion, esophageal transit, gastric digestion, small intestinal digestion, and large intestinal fermentation. Oral digestion is the initial process to produce a bolus, which is a mass of chewed food [58][59]. The bolus has small particle sizes for safe swallowing [60][61]. Once a bolus is swallowed, it moves by esophageal peristalsis, as well as by the simple force of gravity when not lying down [62]. Then, the bolus passes into the stomach. The stomach plays the role as a food container, mixer, grinder, and sieve [63]. The majority of food breakdown happens in the stomach, where the bolus blends with gastric acid as well as digestive enzymes. The speed of food breakdown in the stomach is important to determine other digestion processes, such as gastric emptying, as well as nutrient absorption [57]. Food moves into the small intestine after it moves out of the stomach. Further food breakdown happens in the small intestine. The partially digested food from the stomach is broken down into small molecules to be absorbed and carried into the bloodstream. The large intestine is colonized by microorganisms, which ferment food particles that have not been digested completely. Only water and fermentation by-products are absorbed in the large intestine [62].

Knowledge about the human digestion process may benefit from research in the medical and nutrition fields. However, the fundamental mechanisms are still not completely understood. For instance, Glycemic Index measurement is common in nutritional studies and is conducted by a physiological method [23][64]. The factors related to the glycemic response still require quantitative understanding in terms of the physical and chemical properties of foods. Mass transfer theory may help provide the quantitative analysis by understanding the processes of mass transfer and chemical reaction during food digestion processes. Such engineering perspectives may contribute to the fundamental understanding of food digestion.

3.3. Starch Digestion

The digestion process of starch can be partially quantified by the rate of starch loss, the rate of glucose appearance, and the rate of appearance of various oligosaccharides [65]. It has been stated that “Understanding the factors influencing starch digestion is best done through a causal, mechanistically based approach through the following paradigm: biosynthesis → growth and processing conditions → structure of starch and of starch-containing substances → digestion properties” [65].

In the human digestive system, starch is catalyzed by salivary amylase and pancreatic amylase, which are both α-amylases (Enzyme Commission number is 3.2.1.1) [66]. Salivary amylase is the first enzyme for starch hydrolysis in the mouth [57][67]. This process occurs over a relatively short time (within one minute). When the bolus of food moves into the stomach, the action of α-amylase slows down and the acid hydrolysis of starch increases. The hydrolysis of starch in the stomach may also be affected by the residual activity of salivary amylase, and the acidity of the stomach is likely to partly reduce the activity of the salivary amylase [68]. From the stomach to the duodenum, the bolus encounters α-amylase the pancreatic secretion, which contains sodium hydrogen carbonate and α-amylase. Sodium hydrogen carbonate neutralizes the acidic fluid from the stomach to a pH of about 8 [69]. The continues the catalysis of starch into disaccharides and oligosaccharides. The oligosaccharides, such as α-limit dextrins, small linear oligomers, and larger α-glucans are not absorbed into the blood stream until their further hydrolysis to glucose. In the small intestine, enzymes, including mucosal maltase–glucoamylase and sucrase–isomaltase, catalyze the oligosaccharides into single glucose [65][68].

After a meal, the peak plasma glucose response usually occurs within the first hour, and the glucose level increase seldom lasts more than two hours. This observation puts a clear emphasis on the mouth, salivary fluids, and the stomach as features that may be very important in the glycemic response. At the same time, the pancreas secretes insulin and inhibits the release of glucagon, so that the glucose is normally taken up by muscle and fat tissue. Plasma glucose levels have a range between 3.3 and 8.3 mmol/L, providing body energy for the organs and tissues. However, high postprandial glucose levels are related to the development of Type 2 diabetes and/or cardiovascular disease in susceptible persons [3][70][71]. People with diabetes have a high blood glucose level (hyperglycemia) due to deficiencies in insulin secretion or in insulin action [15][71]. The current in vivo method to determine the glycemic response of a meal/food is to measure small numbers of blood samples from the finger over a period of two hours. The Glycemic Index is then calculated to classify carbohydrate-rich foods [23]. Understanding starch digestion and absorption of starch-derived glucose may help in the maintenance of stable plasma glucose levels.

References

1. Jenkins, D.J.; Wolever, T.M.; Taylor, R.H.; Barker, H.; Fielden, H.; Baldwin, J.M.; Bowling, A.C.; Newman, H.C.; Jenkins, A.L.; Goff, D.V. Glycemic index of foods: A physiological basis for carbohydrate exchange. Am. J. Clin. Nutr. 1981, 34, 362–366.
2. Atkinson, F.S.; Foster-Powell, K.; Brand-Miller, J.C. International tables of glycemic index and glycemic load values: 2008. Diabetes Care 2008, 31, 2281–2283.
3. Ludwig, D.S. The glycemic index: Physiological mechanisms relating to obesity, diabetes, and cardiovascular disease. JAMA 2002, 287, 2414–2423.
4. Brand-Miller, J.; Foster-Powell, K.; Holt, S. The New Glucose Revolution Complete Guide to Glycemic Index Values; Marlowe & Company: Boston, MA, USA, 2003.
5. Warren, J.M.; Henry, C.J.K.; Simonite, V. Low glycemic index breakfasts and reduced food intake in preadolescent children. Pediatrics 2003, 112, e414.
6. Thomas, D.E.; Brotherhood, J.R.; Brand, J.C. Carbohydrate feeding before exercise: Effect of glycemic index. Int. J. Sports Med. 1991, 12, 180–186.
7. Baghurst, K.I. Dietary guidelines: The development process in Australia and New Zealand. J. Am. Diet. Assoc. 2003, 103 (Suppl. S12), 17–21.
8. Brand-Miller, J.; McMillan-Price, J.; Steinbeck, K.; Caterson, I. Dietary glycemic index: Health implications. J. Am. Coll. Nutr. 2009, 28 (Suppl. S4), 446s–449s.
9. Garsetti, M.; Vinoy, S.; Lang, V.; Holt, S.; Loyer, S.; Brand-Miller, J.C. The glycemic and insulinemic index of plain sweet biscuits: Relationships to in vitro starch digestibility. J. Am. Coll. Nutr. 2005, 24, 441–447.
10. Barclay, A.W.; Flood, V.M.; Brand-Miller, J.C.; Mitchell, P. Validity of carbohydrate, glycaemic index and glycaemic load data obtained using a semi-quantitative food-frequency questionnaire. Public Health Nutr. 2008, 11, 573–580.
11. Englyst, K.; Vinoy, S.; Englyst, H.; Lang, V. Glycaemic index of cereal products explained by their rapidly and slowly available glucose. Br. J. Nutr. 2003, 89, 329–340.
12. Jenkins, D.J.A.; Wolever, T.M.S.; Collier, G.; Ocana, A.; Rao, V.; Buckley, G.; Lam, Y.; Mayer, A.; Thompson, L. Metaboliceffects of low-glycemic-index diet. Am. J. Clin. Nutr. 1988, 46, 968–975.
13. Urooj, A.; Puttaraj, S. Glycaemic responses to cereal-based Indian food preparations in patients with non-insulin-dependent diabetes mellitus and normal subjects. Br. J. Nutr. 2000, 83, 483–488.
14. Vinoy, S.; Normand, S.; Meynier, A.; Sothier, M.; Louche-Pelissier, C.; Peyrat, J.; Maitrepierre, C.; Nazare, J.-A.; Brand-Miller, J.; Laville, M. Cereal processing influences postprandial glucose metabolism as well as the GI effect. J. Am. Coll. Nutr. 2013, 32, 79–91.
15. Jenkins, D.J.; Kendall, C.W.; Augustin, L.S.; Franceschi, S.; Hamidi, M.; Marchie, A.; Jenkins, A.L.; Axelsen, M. Glycemic index: Overview of implications in health and disease. Am. J. Clin. Nutr. 2002, 76, 266S–273S.
16. Dona, A.C.; Landrey, K.; Atkinson, F.S.; Miller, J.C.B.; Kuchel, P.W. 1H NMR spectroscopy for the in vitro understanding of the glycaemic index. Br. J. Nutr. 2013, 109, 1934–1939.
17. Ek, K.L.; Wang, S.; Copeland, L.; Brand-Miller, J.C. Discovery of a low-glycaemic index potato and relationship with starch digestion in vitro. Br. J. Nutr. 2014, 111, 699–705.
18. Brand-Miller, J.; Holt, S. Testing the glycaemic index of foods: In vivo, not in vitro. Eur. J. Clin. Nutr. 2004, 58, 700–701.
19. Louie, J.C.Y.; Moshtaghian, H.; Boylan, S.; Flood, V.M.; Rangan, A.M.; Barclay, A.W.; Brand-Miller, J.C.; Gill, T.P. A systematic methodology to estimate added sugar content of foods. Eur. J. Clin. Nutr. 2015, 69, 154–161.
20. International Organization for Standardization. 26642:2010; Food products—Determination of the Glycaemic Index (GI) and Recommendation for Food Classification. ISO: Geneva, Switzerland, 2010.
21. Nantel, G. Carbohydrates in human nutrition. Food Nutr. Agric. 1999, FNA/ANA 24, 6–10.
22. Brouns, F.; Bjorck, I.; Frayn, K.N.; Gibbs, A.L.; Lang, V.; Slama, G.; Wolever, T.M.S. Glycaemic index methodology. Nutr. Res. Rev. 2005, 18, 145–171.
23. Wolever, T.M.S.; Meynier, A.; Jenkins, A.L.; Brand-Miller, J.C.; Atkinson, F.S.; Gendre, D.; Leuillet, S.; Cazaubiel, M.; Housez, B.; Vinoy, S. Glycemic index and insulinemic index of foods: An interlaboratory study using the ISO 2010 method. Nutrients 2019, 11, 2218.
24. Kunst, A. UV-methods with hexokinase and glucose-6-phosphate dehydrogenase. Methods Enzym. Anal. 1984, VI, 163–172.

25. Sepulveda, J.L. Chapter 9—Challenges in routine clinical chemistry testing analysis of small molecules. In Accurate Results in the Clinical Laboratory, 2nd ed.; Dasgupta, A., Sepulveda, J.L., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 101–140.
26. Li, H.; Dhital, S.; Gidley, M.J.; Gilbert, R.G. A more general approach to fitting digestion kinetics of starch in food. Carbohydr. Polym. 2019, 225, 115244.
27. Woolnough, J.W.; Monro, J.A.; Brennan, C.S.; Bird, A.R. Simulating human carbohydrate digestion in vitro: A review of methods and the need for standardisation. Int. J. Food Sci. Technol. 2008, 43, 2245–2256.
28. Minekus, M.; Alminger, M.; Alvito, P.; Ballance, S.; Bohn, T.; Bourlieu, C.; Carrière, F.; Boutrou, R.; Corredig, M.; Dupont, D.; et al. A standardised static in vitro digestion method suitable for food-an international consensus. Food Funct. 2014, 5, 1113–1124.
29. Goff, H.D.; Repin, N.; Fabek, H.; el Khoury, D.; Gidley, M.J. Dietary fibre for glycaemia control: Towards a mechanistic understanding. Bioact. Carbohydr. Diet. Fibre 2018, 14, 39–53.
30. Guerra, A.; Etienne-Mesmin, L.; Livrelli, V.; Denis, S.; Blanquet-Diot, S.; Alric, M. Relevance and challenges in modeling human gastric and small intestinal digestion. Trends Biotechnol. 2012, 30, 591–600.
31. Bordoloi, A.; Singh, J.; Kaur, L. In vitro digestibility of starch in cooked potatoes as affected by guar gum: Microstructural and rheological characteristics. Food Chem. 2012, 133, 1206–1213.
32. Dartois, A.; Singh, J.; Kaur, L.; Singh, H. Influence of guar gum on the in vitro starch digestibility—rheological and microstructural characteristics. Food Biophys. 2010, 5, 149–160.
33. Gidley, M.J. Hydrocolloids in the digestive tract and related health implications. Curr. Opin. Colloid Interface Sci. 2013, 18, 371–378.
34. Liu, D.; Dhital, S.; Wu, P.; Chen, X.-D.; Gidley, M.J. In vitro digestion of apple tissue using a dynamic stomach model: Grinding and crushing effects on polyphenol bioaccessibility. J. Agric. Food Chem. 2020, 68, 574–583.
35. Zhong, C.; Langrish, T. A comparison of different physical stomach models and an analysis of shear stresses and strains in these system. Food Res. Int. 2020, 135, 109296.
36. Li, H.; Gidley, M.J.; Dhital, S. High-amylose starches to bridge the “fiber gap”: Development, structure, and nutritional functionality. Compr. Rev. Food Sci. Food Saf. 2019, 18, 362–379.
37. Ai, Y.; Jane, J.-L. Chapter 3—Understanding Starch Structure and Functionality. In Starch in Food: Structure, Function and Applications, 2nd ed.; Woodhead Publishing Series in Food Science, Technology and Nutrition; Woodhead Publishing: Sawston, UK, 2018; pp. 151–178.
38. Pérez, S.; Bertoft, E. The molecular structures of starch components and their contribution to the architecture of starch granules: A comprehensive review. Starch Stärke 2010, 62, 389–420.
39. Zhou, Z.; Robards, K.; Helliwell, S.; Blanchard, C. Compositionand functional properties of rice. Int. J. Food Sci. Technol. 2002, 37, 849–868.
40. Orman, B.A.; Schumann, R.A. Comparison of near-infrared spectroscopy calibration methods for the prediction of protein, oil, and starch in maize grain. J. Agric. Food Chem. 1991, 39, 883–886.
41. Robertson, T.M.; Alzaabi, A.Z.; Robertson, M.D.; Fielding, B.A. Starchy carbohydrates in a healthy diet: The role of the humble potato. Nutrients 2018, 10, 1764.
42. Wang, N.; Daun, J.K. Quality of Western Canadian Pulse Crops—2006; Canadian Grain Commission: Winnipeg, MB, Canada, 2006.
43. Preiss, J. Chapter 1—Plant starch synthesis. In Starch in Food, 2nd ed.; Sjöö, M., Nilsson, L., Eds.; Woodhead Publishing: Sawston, UK, 2018; pp. 3–95.
44. Takeda, Y.; Shitaozono, T.; Hizukuri, S. Structures of sub-fractions of corn amylose. Carbohydr. Res. 1990, 199, 207–214.
45. Hizukuri, S. Polymodal distribution of the chain lengths of amylopectins, and its significance. Carbohydr. Res. 1986, 147, 342–347.
46. Hizukuri, S.; Takeda, Y.; Yasuda, M.; Suzuki, A. Multi-branched nature of amylose and the action of debranching enzymes. Carbohydr. Res. 1981, 94, 205–213.
47. Li, H.; Dhital, S.; Slade, A.J.; Yu, W.; Gilbert, R.G.; Gidley, M.J. Alteringstarch branching enzymes in wheat generates high-amylose starch with novel molecular structure and functional properties. Food Hydrocoll. 2019, 92, 51–59.
48. Manners, D.J.; Matheson, N.K. The fine structure of amylopectin. Carbohydr. Res. 1981, 90, 99–110.

49. Berglund, J.; Mikkelsen, D.; Flanagan, B.M.; Dhital, S.; Gaunitz, S.; Henriksson, G.; Lindström, M.E.; Yakubov, G.E.; Gidley, M.J.; Vilaplana, F. Wood hemicelluloses exert distinct biomechanical contributions to cellulose fibrillar networks. Nat. Commun. 2020, 11, 11–16.
50. Singh, A.; Lal, U.R.; Mukhtar, H.M.; Singh, P.S.; Shah, G.; Dhawan, R.K. Phytochemical profile of sugarcane and its potential health aspects. Pharmacogn. Rev. 2015, 9, 45–54.
51. Holland, C.; Ryden, P.; Edwards, C.H.; Grundy, M.M.L. Plant cell walls: Impact on nutrient bioaccessibility and digestibility. Foods 2020, 9, 201.
52. Dhital, S.; Bhattarai, R.R.; Gorham, J.; Gidley, M.J. Intactness of cell wall structure controls the in vitro digestion of starch in legumes. Food Funct. 2016, 7, 1367–1379.
53. Dhital, S.; Baier, S.K.; Gidley, M.J.; Stokes, J.R. Microstructural properties of potato chips. Food Struct. 2018, 16, 17–26.
54. Liu, D.; Lopez-Sanchez, P.; Gidley, M.J. Cellular barriers in apple tissue regulate polyphenol release under different food processing and in vitro digestion conditions. Food Funct. 2019, 10, 3008–3017.
55. Beaumont, B.; Plattsburgh, M.D. Experiments and observations on the gastric juice and the physiology of digestion. Dublin J. Med. Chem. Sci. 1835, 22, 49–69.
56. Keppler, S.; O'Meara, S.; Bakalis, S.; Fryer, P.J.; Bornhorst, G.M. Characterization of individual particle movement during in vitro gastric digestion in the Human Gastric Simulator (HGS). J. Food Eng. 2020, 264, 109674.
57. Bornhorst, G.; Singh, R. Gastric digestion in vivo and in vitro: How the structural aspects of food influence the digestion process. Annu. Rev. Food Sci. Technol. 2014, 111, 32.
58. Gavião, M.B.; Bilt, A. Salivary secretion and chewing: Stimulatory effects from artificial and natural foods. J. Appl. Oral Sci. Rev. FOB 2004, 12, 159–163.
59. Bilt, A. Oral physiology, mastication and food perception. In Designing Functional Foods: Measuring and Controlling Food Structure Breakdown and Nutrient Absorption; Woodhead Publishing: Sawston, UK, 2009; pp. 1–35.
60. Agrawal, K.R.; Lucas, P.W.; Prinz, J.F.; Bruce, I.C. Mechanical properties of foods responsible for resisting food breakdown in the human mouth. Arch. Oral Biol. 1997, 42, 1–9.
61. Yurkstas, A.A. The masticatory act: A review. J. Prosthet. Dent. 1965, 15, 248–260.
62. Griffiths, M. Crash Course: Gastrointestinal System E-Book; Elsevier Health Sciences: Amsterdam, The Netherlands, 2012.
63. Meyer, J.H. Gastric emptying of ordinary food: Effect of antrum on particle size. Am. J. Physiol. Gastrointest. Liver Physiol. 1980, 239, G133–G135.
64. Louie, J.C.Y.; Buyken, A.E.; Brand-Miller, J.C.; Flood, V.M. The link between dietary glycemic index and nutrient adequacy. Am. J. Clin. Nutr. 2012, 95, 694–702.
65. Dona, A.C.; Pages, G.; Gilbert, R.G.; Kuchel, P.W. Digestion of starch: In vivo and in vitro kinetic models used to characterise oligosaccharide or glucose release. Carbohydr. Polym. 2010, 80, 599–617.
66. Taniguchi, H.; Honnda, Y. Amylases. In Encyclopedia of Microbiology, 3rd ed.; Schaechter, M., Ed.; Academic Press: Oxford, UK, 2009; pp. 159–173.
67. Hoebler, C.; Devaux, M.-F.; Karinthi, A.; Belleville, C.; Barry, J.-L. Particle size of solid food after human mastication and in vitro simulation of oral breakdown. Int. J. Food Sci. Nutr. 2000, 51, 353–366.
68. Boron, W.; Boulpaep, E.L. Medical Physiology; Elsevier: Saint Louis, MO, USA, 2016.
69. Foster, T.; Adams, G.; di Bari, V.; Connerton, I.; Gould, J.; Gouseti, O.; Gray, D.; Yakubov, G. Food biotechnology. Curr. Opin. Chem. Eng. 2020, 30, 53–59.
70. Livesey, G.; Taylor, R.; Livesey, H.F.; Buyken, A.E.; Jenkins, D.J.; Augustin, L.S.; Sievenpiper, J.L.; Barclay, A.W.; Liu, S.; Wolever, T. Dietary glycemic index and load and the risk of type 2 diabetes: A systematic review and updated meta-analyses of prospective cohort studies. Nutrients 2019, 11, 1280.
71. Priebe, M.G.; Eelderink, C.; Wachters-Hagedoorn, R.E.; Vonk, R.J. Starch digestion and applications of slowly available starch. In Starch in Food; Elsevier: Amsterdam, The Netherlands, 2018; pp. 805–826.