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Carbohydrate-Based Foods under Agroecosystems: Review on A Journey from Soil to *In Vitro* Engineered Digestion Models

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SOIL is a vital component in the agroecosystem that can control the forming and decomposition of carbohydrates through soil microbial activity. Carbohydrates are an essential part of our diet that can supply our bodies with more than half of human needs from energy. Carbohydrates also contribute to solving the global food crisis by supplying humans and animals with carbohydrate-based foods under different agroecosystems. This review focuses on the fantastic journey of carbohydrates in the agroecosystem, which starts from the soil as a leadingcentral pool for carbon sequestration and carbohydrates forming by plants, the practical microbial activities on carbohydrates, and the role of carbohydrates against climate change. This journey continues after forming carbohydrates by cultivated plants or their microbial decomposition till their consumption by humans/animals using the *in vitro* engineered digestion models. This journey can also show some applications of carbohydrates in different sectors such as food, ecology, pharma, therapeutics, and agriculture. Due to the importance of carbohydrate-based foods for human health, it is a crucial issue to present *in vitro* digestion models of such macro-molecules. Further studies on carbohydrates are needed on many global issues, including climate change, such as loss of soil fertility, soil erosion, and carbohydrate-based agro-biotechnology.

Keywords: Digestive model, agricultural systems, human health, hydrogels, in vitro digestion, climate change, carbon sequestration, pharma.

1. Introduction

Carbohydrates are t, accountingfor 55 to 80% of total daily energy (Tan et al., 2023). Carbohydrate-based foods are components, additives, and ingredients acting as prebiotics, having nutritional value andorganoleptic properties (Gerschenson et al., 2022). The primary carbohydrate sources are vegetables, fruits, grains, and animal sources, including dairy products, including yogurt, cheese, and milk (Rozi et al., 2023). There are two groups of non-digestible carbohydrates: lignin, cellulose, hemicellulose, and pectin, whereas the digestible group involves non-fiber carbohydrates, starch, and organic acids (Kaushik et al., 2022). Concerning the horticultural commodities, the Carb content differs from less than 1.0 to up to more than 60%. This previous content in fruits and vegetables can contribute to and control these commodities color, flavor, nutritional value, and texture (Yahia et al., 2019). Several fruits and vegetables have nutritional and health benefits due to many dietary components along with Carbs such as fiber, ascorbic acid (vitamin C), and flavonoids (Yahia et al., 2019).

Carbohydrates are organic compounds containing carbon derived from plants and animal foods in different agroecosystems. The flow of varying carbohydrate sources is governed by the microbial metabolism and enzyme activities within and between these agroecosystems (Low et al., 2023). Chemical and biological processes of this flow are controlled by the

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carbohydrate-active enzymes (CAZymes), which may include biosynthesis/ glycosylation, photosynthesis, digestion/ saprotrophy for improving C-sequestration, and soil fertility (Low et al., 2023). CAZymes can be classified into five different enzyme classes: carbohydrate esterases, polysaccharide lyases, glycoside hydrolases, glycosyl transferases, and auxiliary activities (Wardman et al., 2022). Many studies focused on these enzymes from different points of view, such as fermented dairy and vegetable products (Liang et al., 2023), animal feed (Plouhinec et al., 2023), mycorrhizal symbioses (Gong et al., 2023), composting (Chen X et al., 2023; Santos-Pereira et al., 2023), and agro-wastes (Ramanaiah et al., 2023; Singh et al., 2023).

Carbohydrates can be digested through a breakdown in the mouth by salivary amylase, then throughout the digestive system, and finally, the monosaccharides are absorbed into the human bloodstream, increasing the sugar level in the blood. What is the carbohydrate digestive model? Why do these models need to be used in many studies? The carbohydrate digestive model is a method by which the human digestive process could be explored, predicted, and analyzed by simulating fluid flow and absorption processes of glucose in the human small intestine (Karthikeyan et al., 2021). Generally, ed by studying different items, mainly the physical and composition form of the human digestive process. There are three main methods for analyzing the digestive process in food products involving an *in vivo* feeding approach using human volunteers (Karthikeyan et al., 2021), advanced computational models (Caillet et al., 2023), and *in vitro* models (Luo et al., 2024).

Therefore, this review will concentrate on carbohydrate-based foods, how and where they can be formed, the starting processes of these compounds, the role of soil during these processes, carbohydrates and the global food crisis, and carbohydrate-based foods in agro-ecosystems. Carbohydrate-based foods and human health will also be discussed, referring to how-carbohydrate diet and many human diseases. The carbohydrate-based food matrix, human digestive system, and in vitro digestion models are of great concern in the current study.

2. Carbohydrates and soil

Why are carbohydrates essential compounds? Why these organic constituents are and necessary for all living organisms? Does the forming of carbohydrates start from the soil? What is the crucial role of carbohydrates in soil carbon sequestration? Carbohydrates are organic compounds widespread in the biosphere, and consist of mainly C, O, and H atoms in proportions, according to the standard empirical formula $(CH_2 o)_n$, where n = 3 or more (**Figure 1**). The central carbohydrate-based plants include several vegetables, fruits, legumes, and cereal grains, which could be broadly classified as sugars and non-sugars (Kaushik et al., 2022). Depending on the number of C-atoms in the molecule, these sugars are divided into mono-, di-, tri-, tetra-, and poly-saccharides (Gerschenson et al., 2022). What is the relationship between soil and carbohydrates? There are direct and indirect impacts of soil on the forming and decomposition of carbohydrates t through soil microbial activity (Reuter et al., 2023).

What is the main impact of soil carbon on the global climate change? Carbon in soil, and its behaviour, different transformations, and general cycle are needed to answer this question. Soil carbon is a critical global issue due to its suggested impacts on climate change and vice versa (Puche et al., 2023). This interplay between soil carbon and climate change was emphasized in several studies which reported included the role of soil carbon sequestration for mitigation of climate change (Don et al., 2023), carbon farming (Paul et al., 2023), and their microbial decomposition (Mukhtar et al., 2023). The soil carbon might impact climate changes through the change inatmospheric CO_2 concentration and soil organic carbon (SOC), as presented in **Table 1**. It is worth that there is an urgent need for “tailoring farming practices” to maintain agricultural production and safeguardprotect soil carbon stocks (Puche et al., 2023). It is reported that the C-sink and source function of different vegetations depend on soil type, C-sources, tree species composition, soil micro-organisms, and macrofauna (Devi and Lepcha 2023).

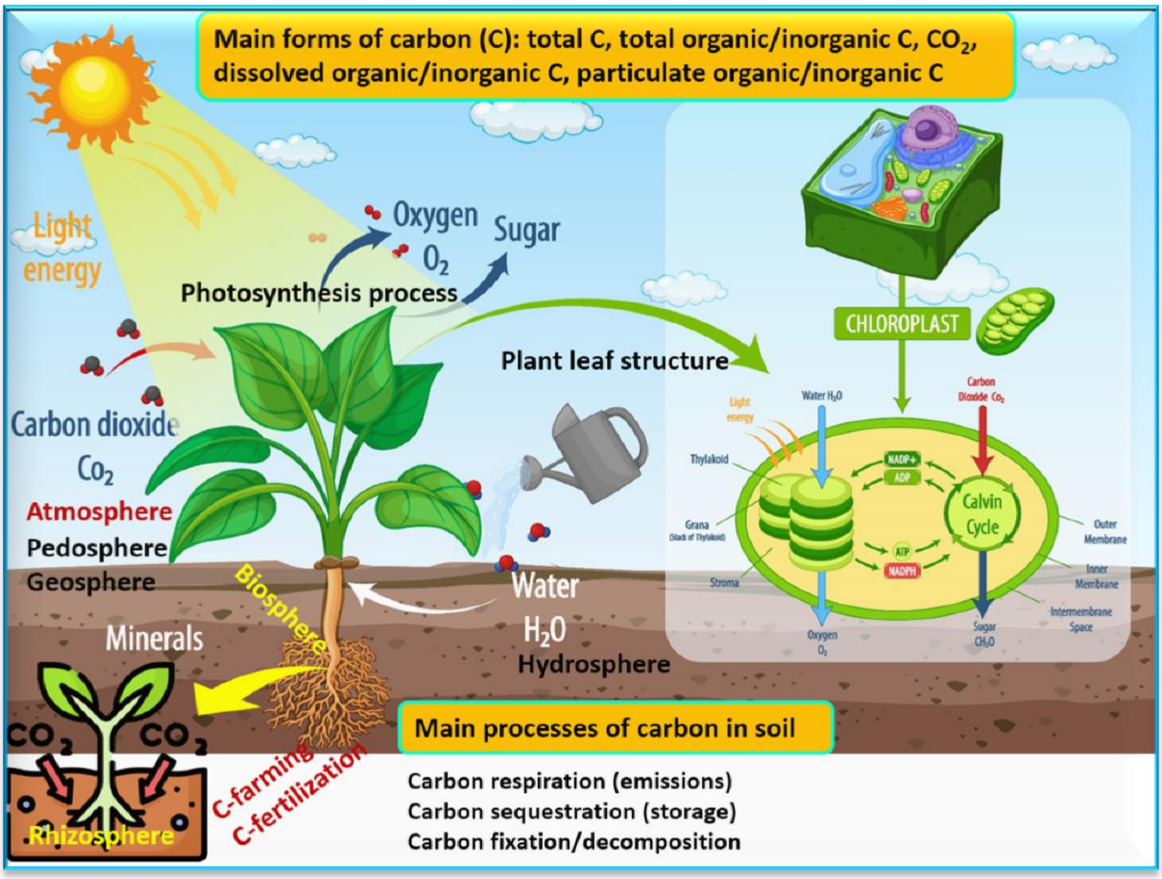

Fig. 1. Carbon is an essential element for all living organisms through building many crucial compounds like carbohydrates. The main processes that happen to soil carbon include respiration, carbon sequestration, and carbon decomposition. The photo from https://www.freepik.com/free-vector accessed on December 13, 2023.

Table 1. Different studies on the interplay between soil carbon and climate change.

Soil conditions or cultivation system	The main findings of the study	Region or country	Refs.
Soil carbon stocks under grasslands	A slight increase in temperature led to an increase in grassland productivity and reduced soil organic carbon (SOC) stocks.	France	Puche et al. (2023)
Soil microbial community functioning and structure	Elevated CO_2 has different impacts on the structure of soil microbial community (mainly fungi/bacteria ratio) with potential interaction to mitigate or enhance each other's effects.	General study	Mukhtar et al. (2023)
Soil carbon sequestration	Terms of soil C sequestration, harmful emissions, SOC loss mitigation, SOC storage, and climate change mitigation should be revised among scientists and stakeholders again.	General study	Don et al. (2023)
Soil carbon farming	Increasing SOC stocks in agricultural soil can remove CO_2 from the atmosphere to mitigate climate change.	Germany	Paul et al. (2023)
Soil organic carbon in dryland	The buffering role of biocrust-forming lichens in modulating climate change by enhancing the accumulation of soil C	Spain	Díaz-Martínez et al. (2023)
Microbial C-use efficiency (CUE) in grassland	Deep-soil organic carbon and its availability can control microbial CUE under climate change across the soil profile by driving terrestrial biogeochemical cycles.	China	Zhang Q et al. (2023)
Soil carbon and nitrogen fractions in the tropics	Soil C & N fractions and their ratios can control soil emissions of N_2O, and the natural forest conversion significantly decreased emissions of soil N2O. In contrast, this conversion to a paddy field had no effects.	China	Zhu et al. (2023)
Potential of soil organic carbon sequestration	Climate change is suggested to increase the loss in soil organic carbon 8.1 and 6.0 Mg C ha^{-1} for the business-as-usual and a crop rotation change scenario, respectively, by 2038, which is promoted by rotation of annual crops with perennial grasses.	Denmark	Gutierrez et al. (2023)
SOC sequestration under grasslands	The management of SOC-sequestration had ,more substantial impacts compared to soil type and climate under using 24 sites of grasslands by increasing fertilizer input and field traffic	Germany	Filipiak et al. (2023)
Carbon sequestration rate and CO_2 flux in forests	The main factors that control C sink and its source function in forests include climatic variables, forest types, and edaphic factors; increased temperature and rainfall may change soil quality.	India	Devi and Lepcha (2023)
Soil microbial activity under polar deserts and tundra	Under polar deserts, soil microbial activities were more sensitive to temperature and moisture changes compared to soil C and N storage, which are not uniformly predictable there	Antarctica	Khan and Ball (2024)

How can carbohydrates reach the soil? The primary sources of carbohydrates in the soil involve the rhizodeposition or via manure, compost, or plant biomass in litter (**Figure 2**). Under terrestrial ecosystems, the decomposition of carbohydrates is important for C-sinks and water sources, which depend on microbiome abundance, soil properties, CAZyme abundance, and enzyme gene pathways (Xiong et al., 2023). This decomposition of carbohydrates could be achieved by certain CAZymes which involve the degradation of hemicellulose and glucan, besides many soil enzymes such as alpha-L-arabino-furanosidase, endo-beta 1,4-xylanase, and alpha-L-fucosidase (Xiong et al., 2023). Soil microbes can transform/degrade carbohydrates in soil organic matter (SOM) through their respiration and proliferation. Root exudates are an essential sourceof carbohydrates in the soil rhizosphere because root exudates consist mainly of organic acids, and amino acids besides carbohydrates (Low et al., 2023).

3. Carbohydrates and the global food crisis

The global population reached around 8.1 billion people in 2023, which is expected to be more than 8.5 billion by 2030. The terrible increase in global population should meet the global food demand, which tends to rise faster than the global food supply. Global food needs are expected to increase from 42% to 70% in 2030 and 2050, respectively (FAO, IFAD, UNICEF, WFP, and WHO 2021). The Global food crisis, it is a real problem that led to an increase in global hunger levels, which was extremely high in 2021, including around 193 million people in 53 countries under severe food insecurity (Rozi et al., 2023). Thus, there is an urgent global need to strengthen global food security by increasing the production of staple food carbohydrates (Lin and Gómez-Maqueo 2023). Many reports were published on food crises in different places worldwide, such as Indonesia (Rozi et al., 2023), Singapore (Lin and Gómez-Maqueo 2023), Seri Lanka (Sooriyaarachchi and Jayawardena 2023), and Lebanon (Nakat et al., 2023).

Along with other macronutrients (proteins and fats), carbohydrates have a crucial role in food security. Producing food carbohydrates using limited natural resources could be supported through the following methods: emerging novel foods, revalorization of by-products, alternative crops, and food production using innovative technology (Lin and Gómez-Maqueo 2023). Traditional and non-conventional sources of carbohydrates in the human diet are a global issue that researchers attempt to find alternatives to carbohydrate sources, including novel dietary carbohydrates (Traughber et al., 2021), microalgae bioactive carbohydrates (Gouda et al., 2022), an alternative to unconventional grain crops such as millet, amaranth, and quinoa (Lin and Gómez-Maqueo 2023), as presented in **Figure 3**.

Many alternative carbohydrates have an acceptable potential for human consumption, such as monkey jack (*Artocarpus lakoocha* Roxb.), breadfruit (*Artocarpus altilis* S. Park. Fosb), wood apple (*Limonia acidissima* L.), gumihan (*Artocarpus sericarpus*), marang fruit (*Artocarpus odoratissimus*), and nam-nam (*Cynometra cauliflora*) (Lin and Gómez-Maqueo 2023). The carbohydrate quality can be evaluated through the four main criteria: whole grain intake (content), dietary fiber intake, free sugar intake, and glycemic index (Tan et al., 2023). There is a need for a dietary guideline scoring system regarding carbohydrate food quality (Drewnowski et al., 2022). Based on the available natural resources (water, soil, etc.), the production of carbohydrates might differ in different countries worldwide.

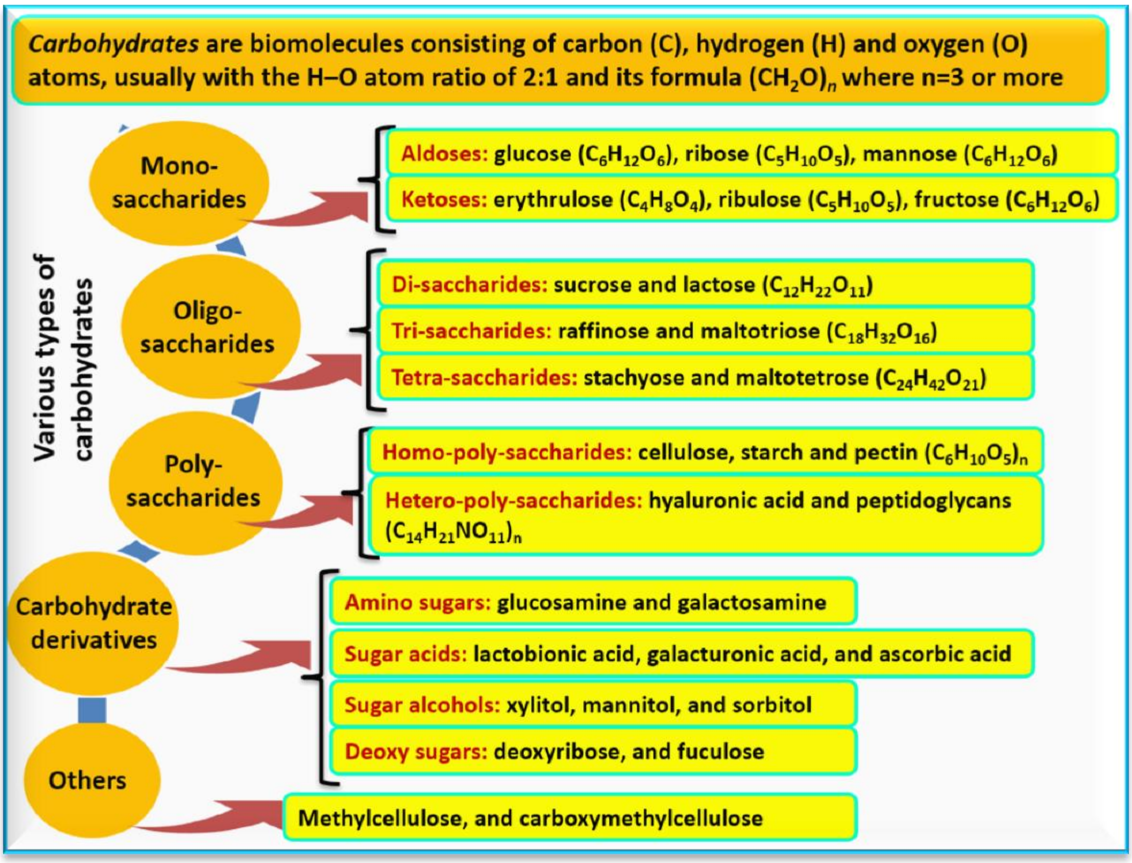

Fig. 2. Definition of carbohydrates and different types supplying with some examples (adapted from Ramaprabha et al. 2024).

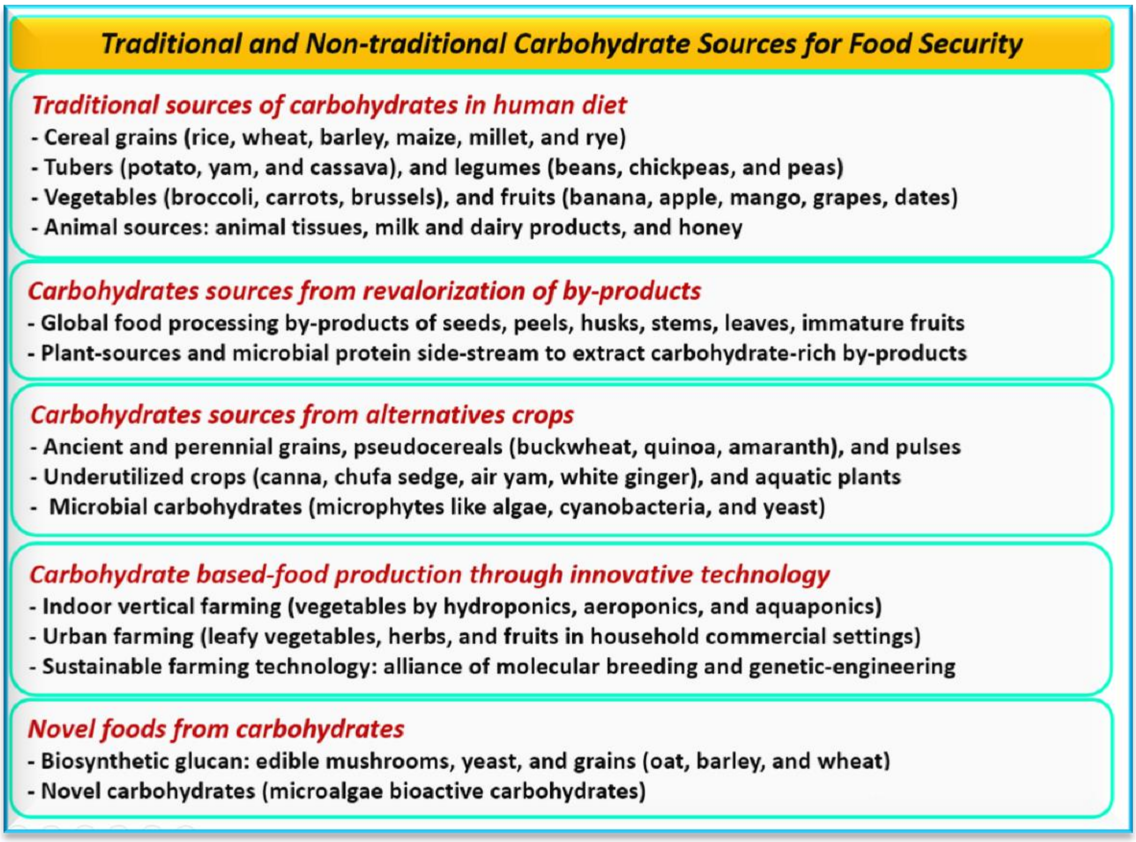

Fig. 3. Suggested strategies for the traditional and non-traditional sources of carbohydrates for food security (sources: Traughber et al., 2021; Gouda et al., 2022; Lin and Gómez-Maqueo 2023; Tan et al., 2023).

4. Carbohydrates flow in agroecosystems

This section presents the carbohydrates in agriculture, forms in soil, flow in different agro-ecosystems, and sources. In soil, there are three primary forms of carbohydrates: (1) the soluble free sugars in the soil solution, (2) the complex polysaccharides (mainly cellulose and hemicellulose) and (3) different sizes and shapes of polymeric molecules, which are attached firmly to colloidal particles of clays and humic substances (FAO 2005). Along with the previous forms of carbohydrates, different sources of carbohydrates in soil are quickly broken down by various soil micro-organisms, including algae, bacteria, fungi, protozoa, and viruses (FAO 2005). Carbon in soil and air in the form of CO_2 can be biosynthesized/adsorbed by plants during the photosynthesis process and metabolically formed into carbohydrates aa a wide array of mono-, oligo-, and poly-saccharides, as well as glycosylated biomolecules (Low et al., 2023). The flow of carbohydrates in the agro-ecosystems is involved in several topics such as (1) carbohydrates-based plant foods, (2) carbohydrates as a link of plant-microbe interactions, (3) carbohydrate-microbe interactions for soil fertility, (4) the role of microbes for conversion carbohydrates by honeybees, (5) dairy products and gut microbiomes, and (6) the consumption of different crop products under crucial decomposition by gut microbes (Butler et al., 2023; Chen Y et al., 2023; Low et al., 2023). Carbohydrates also have a strong interplay with many global issues, including soil carbon sequestration (Filipiak et al., 2023), climate change (Díaz-Martínez et al., 2023), loss of soil fertility (Liu et al., 2023), soil erosion (Jing et al., 2023), United Nations of sustainable development goals (SDGs), and carbohydrate-based agro-biotechnology (**Figure 4**).

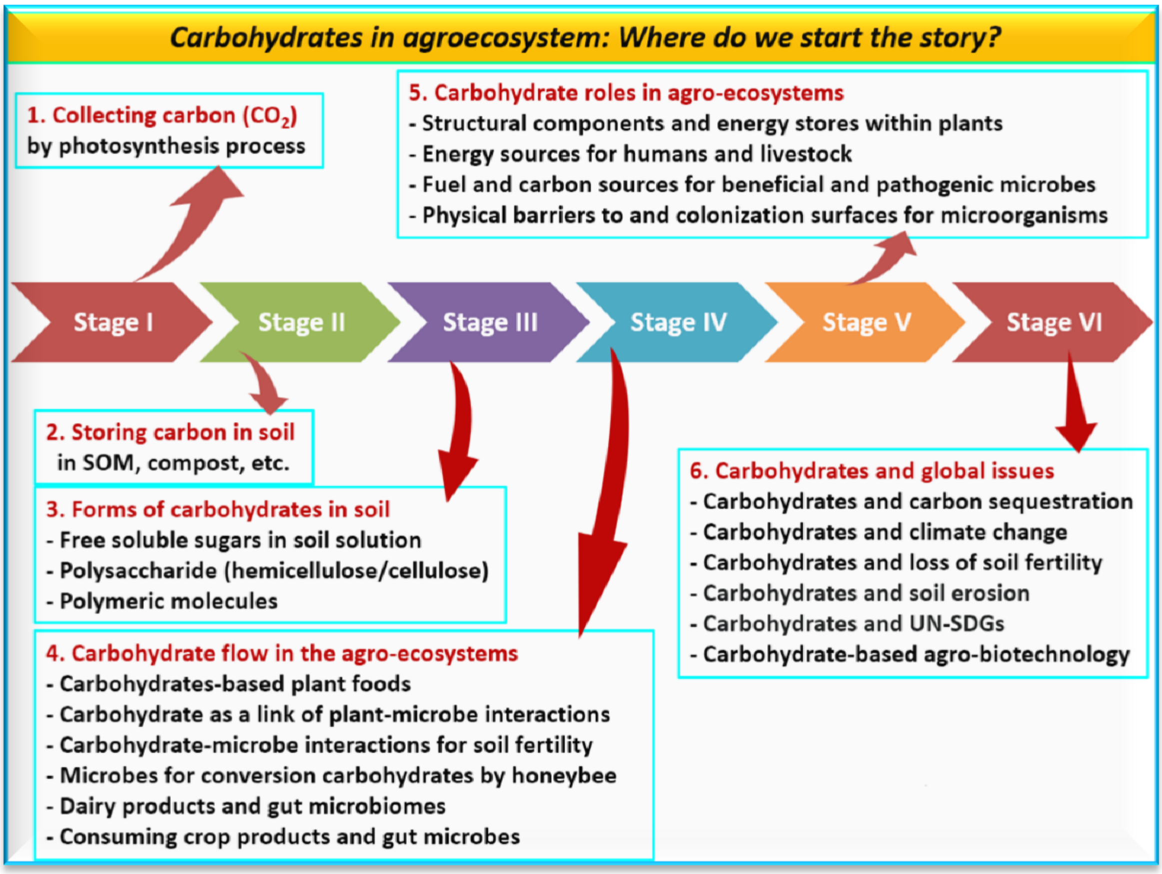

Fig. 4. Carbohydrates have a distinguished journey through their flow in the agro-ecosystem, which may start by collecting CO_2 from the air to build the carbohydrates by the photosynthesis process, then these organic materials might reach humans/animal or soil. This flow islinked with many global issues (adapted from Low et al., 2023). UN-SDGs: United Nations-Sustainable Development Goals.

4.1 Carbohydrates and microbial activities

Carbohydrate flow in the agro-ecosystems has many forms, including different agro-ecosystem compartments (soil, plant, farm animals, microbes, and human). Microbial communities govern these forms as fundamental carbohydrate-microbe interactions (Low et al., 2023). Concerning these interactions, the microbial decomposition of different carbohydrate sources from plants, animals, and dairy products needs to be emphasized (Huang et al., 2022; Low et al., 2023). Plant materials are subjected to decompose by soil microbes under different conditions, which mainly depend on the :diversity of plant and microbe, species and soil properties, and environmental conditions (Guo et al., 2023). Farming under a forest or cropping system is considered a limited factor in microbial activity and carbohydrate decomposition (Li et al., 2022). Under the forest system, it is found that carbohydrate metabolism by bacterial functional groups was negatively correlated with N and P availability in soil. In contrast, pathogenic and saprotrophic fungal groups showed a negative correlation with the dominance of forest tree species (Guo et al., 2023).

Understanding microbial-carbohydrate interactions are important through more focus on the biochemistry of the processes by which carbohydrates were formed, dismantled, elaborated, and consumed by individual and microbe communities (Low et al., 2023). These processes are governed by the active microbial enzymes (CAZyme) during carbohydrate decomposition and their respective substrates of carbohydrates. Based on their catalytic mechanisms, these CAZymes could be classified into the following classes: carbohydrate esterases (Puchart and Biely 2023), glycoside hydrolases (Miyazaki et al., 2023), glycosyl transferases (Sirirungruang et al., 2023), polysaccharide lyases (Pandey et al., 2023), and auxiliary activities (Wardman et al., 2022). The main organic fractions resulting from the decomposition of carbohydrates (compost or indigestible residues) in agro-ecosystems may include sugars, cellulose, hemicellulose, and pectins (Low et al., 2023). Several suggested mechanisms were reported on the decomposition of carbohydrates, which depend on the kind of carbohydrate sources (plants or animals), conditions of the reactions, and type of enzymes, and the purpose of this reaction (Ren et al., 2023). The main general pathway of carbohydrate decomposition involves the metabolism of sucrose and starch, which mainly includes the "*double displacement catalytic mechanism*" in these reactions (Tashkandi and Baz, 2023). For more details on CAZymes, they are assigned into classes (as a level 1) and families (as a level 2) and receive enzyme classification (EC) codes (as a level EC), then deposited in CAZy (https://www.cazy.org/) and CAZypedia (https://www.cazypedia.org/) databases (Tashkandi and Baz 2023).

4.2 Carbohydrates and soil carbon sequestration

The journey of carbohydrates in agro-ecosystems is an exciting trip, which might start from collecting of carbon in CO2 form from atmospheric air through photosynthesis (**Figure 4**). Many steps can be noticed during this stage which, including storing carbon in the soil as a crucial process called carbon sequestration. A greater focus on soil organic matter (SOM), from different points of view, such as types, amounts, the decomposition rate, and biological activities in soil, could produce interesting findings that account more for carbon sequestration (Huang et al., 2023). Soil microbial community (SMC) is considered the main driver of the decomposition of organic matter to store C in soils for achieving soil carbon sequestration, which refers to the C-uptake of containing substances from the atmosphere and its storage in soil C pools (Bhattacharyya et al., 2022). Furthermore, the maintenance of soil ecosystem services, regulation of the turnover and delivery of nutrients, and the decomposition rate of SOM are mainly controlled by the structure and activity of SMC (Bhattacharyya et al., 2022). A significant concern on SMC and its interplay with SOM can be noticed in the era of climate change for mitigating the atmospheric greenhouse effect (mainly raising the GHG emissions). This mitigation could be managed by enhancing the inherent soil quality through soil C-sequestration and reducing the accelerated greenhouse effects (e.g., CH_4 from paddy rice cultivation) to counteract the adverse effects of emissions on agroecosystem (Das et al., 2023). What is the relationship between carbohydrates and soil carbon sequestration? This relationship has many features that can be concluded in the following points:

1- The decomposition of carbohydrates (as SOM) should be achieved by the proper soil microbes in the rhizosphere, and these reactions have several benefits to both soil quality and microbial activity (Bao et al., 2021),

2- Plant root exudates consist of carbohydrates and amino acids besides organic acids, which can be exudated into the soil rhizosphere. Carbohydrates from the exudates of plant roots are labile and are quickly consumed by soil bacteria and fungi, enhancing the abundance and diversity of soil microbial populations. These exudates have a remarkable ability to change the soil microbiomes by releasing nutrients and supporting beneficial microbes for promoting plant growth (Vives-Peris et al., 2020).

3- Microbial-derived carbohydrates are considered digestible carbohydrates and are necessary for the degradation of SOM (Gunina and Kuzyakov 2022), and

4- The efficient soil fertility management needs a complete understanding of the interactions between carbohydrates and soil microbes during transforming SOM and its retention across different agricultural practices (Low et al., 2023).

4.3 Carbohydrates and climate change

Carbohydrates, as a kind of organic matter, have different scenarios of decomposition, which may result from some GHGs (CH_4, CO_2, and others) depending on the reaction condition. These gases and their emissions may lead to global warming and climate change. Therefore, the farming type that has different applied agrochemicals (mainly fertilizers, pesticides, and plant growth promoters) has potential impacts on soil microbial activities (Raaijmakers and Kiers, 2022), which might lead to undesirable consequences (Jing et al., 2022). Climate change can cause different stress combinations, from flooding, drought, heat, pathogens, and pollutants, impacting plant farming (Eckardt et al., 2023a, b). These stresses directly and indirectly affect the microbiomes, which in turn may control the availability of carbohydrates in agroecosystems (Rivero et al., 2022). Several studies confirmed the responses of plants to climate change under different abiotic stresses (Chaudhry and Sidhu 2022; Zandalinas et al., 2022; Ali et al., 2023; Khan 2023; Leisner et al., 2023; Verslues et al., 2023).

Why can climate change alter the carbohydrates in the agroecosystem?, soil is a principal pool for carbon sequestration (in the form of carbohydrates). This requires managing soil carbon through more understanding of the role of microbiomes in the assembling processes that impact the fate of carbohydrates in agroecosystems, for emitting as greenhouse gases or storing in soil (Anthony et al., 2020). eduction of greenhouse gas emissions due to animal farming should be adapted through carbohydrate-mediated relationships with microbiomes for a better understanding of climate change (Low et al., 2023). Due to the role of carbohydrate turnover in sequestering carbon in soils through soil microbial activities, carbohydrates need more and more understanding to provide their significant global impacts on climate change. This concept can be emphasized by carrying out the needed research on the digestion of carbohydrates in ruminants and other food animals to reduce greenhouse gases emitted during these processes (Low et al., 2023).

Carbohydrates in soil are subjected to climate changes (mainly raising temperature and the elevated atmospheric CO_2 concentration), besides other stresses (e.g., drought and salinity). These stresses can impact on the biological activity of soil microbes and cultivated plants by generating reactive oxygen species (ROS) with increased climatic variations (Chaudhry and Sidhu, 2022). This global change opened a wide window necessary for exploring the natural phyto-microbiome species which can improve the productivity of stressful plants through secondary metabolite production, nutrient uptake, and resistance against pathogenicity and abiotic stresses with support the beneficial microbes (Khan 2023). The phyto-microbiomes or plant-associated microbes are a group of archaebacteria, bacteria, fungi, and viruses which can mitigate abiotic stress through different mechanisms, including the production of phytohormones, antioxidants, bioactive compounds, detoxification of toxins and harmful chemicals, sequestration of ROS and other free radicals (Singh et al., 2023). Many studies reported on these plant-associated microbes and their role in agrifood tools (Nguyen et al., 2023), crop protection (Asad e al., 2023), integrative plant pathology (Ruiz-Bedoya et al., 2023), genome studies on plant-microbe interactions (Zhang H et al., 2023), microbiomes-mediated signal transduction in plants (Li J et al., 2023), plant endophytes for agro-eco-sustainability (Negi et al., 2023), and medicinal plant-associated rhizobacteria under stress (Vaghela and Gohel, 2023).

5. Applications of carbohydrates

Carbohydrates have several applications in various fields of our life. Carbohydrate-based foods are considered the primary energy source in the human diet (Comerford et al., 2023). Regarding the applications of carbohydrate-based food or other sources of carbohydrates, there are several possible applications, including the nutritional, medicinal, pharmaceutical, and agricultural fields:

1- Carbohydrate-based diet (Jo and Park 2023),

2- Carbohydrate-based drugs and pharmaceutical applications (Tudu and Samanta, 2023; Silant'ev et al., 2023),

3- Carbohydrate-based gelators as drug delivery (Morris et al., 2021; Tyagi et al., 2023),

4- Carbohydrates-based prebiotics (Gouda et al., 2022),

5- Carbohydrate-based hydrogels for the therapy of many human diseases (Zhang Y et al., 2023),

6- Carbohydrate-based therapeutics (Wang et al., 2021),

7- Carbohydrate-based ionic liquids as suitable solvents for converting carbohydrate biomass (Marullo and D'Anna 2022),

8- Synthetic carbohydrate-based vaccine components, as presented in the field of synthetic glycobiology (Hulbert et al., 2023),

9- Carbohydrate-based bioactive molecules for human diseases (Bajad et al., 2021),

10- Carbohydrate-based nanoparticles, as developed for drug delivery for brain tumors (Silant'ev et al., 2023),

11- Carbohydrate-based nano gel formulations, as sensitized for the hypoxic tumors (Diaz-Dussan et al., 2023), and,

12- Carbohydrate-based adjuvants are sustained delivery systems (Garcia-Vello et al., 2020).

The following sub-sections will highlight more focus on the food, pharma, and ecological sectors.

5.1 Carbohydrates in the food sector

Why the are carbohydrates essential in the field of the food industry? What are the main features of carbohydrates as a proper candidate in this field? Carbohydrates' rheological and functional characteristics support their applications in the food sector (**Table 2)**. These desirable properties are helpful in food products, including sweetness, solubility, hygroscopicity, browning capabilities, the ability of preventing the crystallization, coating capabilities and flavor encapsulation (Jokinen et al., 2023). In general, many different types of carbohydrates can be used in food applications, such as starch and their derivatives (Singh et al., 2024), carrageenan (Yahaya et al., 2023), agar (Cebrián-Lloret et al., 2024), polysaccharides or hydrocolloids (Pirsa and Hafezi 2023), alginate (Yan et al., 2024), cellulose (Janik et al., 2024), mannitol (Ma et al., 2023), chitin (Alimi et al., 2023) and chitosan (Qiu et al., 2024). Carbohydrate-based biopolymers, such as bio-based packaging, are well known for their applications in the food sector. These packaging processes offer biocompatibility and biodegradability, which can serve as alternatives for conventional non-biodegradable polymers used as paper coatings (Ramaprabha et al., 2024). The use of carbohydrates as new food packaging materials has many features, including their sustainable nature and their limit destructive impacts on the environment compared with the single use of plastics (Janik et al., 2023). Applying polysaccharides (e.g., chitosan, starch, cellulose, and sodium alginate) as food packaging materials is essential, being their distinguished properties such as eco-friendly, economical, and prospective viable packaging alternatives (Janik et al., 2023). More information on the carbohydrates in the food sector can be found in **Figure (5**).

Table 2. Some published studies on alginate and cellulose in food packaging applications.

Carbohydrates	Applied form	Suggested aim of the applied carbohydrates in brief	Refs.
Alginate	Gelatin-sodium alginate	Producing the active packaging film of gelatin-sodium alginate for enhancing the quality and safety of meat as well as shelf life	[1]
Alginate	Integrated with N-functionalized carbon dots	Using N-functionalized carbon dots for integrated with layered clay and alginate-based films for active food packaging by forming strong H-bonds with alginate and reducing the surface wettability	[2]
Alginate	Sodium alginate mediated with leaf extract	Applying sodium alginate as a biodegradable polymer has eco-friendly qualities and polymer membrane for food packaging application when mediated with Datura metal L leaf extract.	[3]
Alginate	Gelatin-sodium alginate	I was using gelatin-sodium alginate as a matrix biopolymer, cross-linking agent green tea extract as an active multilayer food packaging film was fabricated as an active ingredient.	[4]
Alginate	Sodium alginate-carboxymethyl cellulose/gluten	Producing a film from sodium alginate-carboxymethyl cellulose with gluten blending to increase the mechanical strength and hydrophobicity of this film in food packaging	[5]
Cellulose	Gelatin hydrogel-ethyl cellulose	Producing bilayer film consists of gelatin hydrogel-ethyl cellulose to adjust the humidity for active applied food packaging to prolong the shelf-life up to 7 days under ambient storage conditions.	[6]
Cellulose	Carboxymethyl cellulose and polyvinyl alcohol	Producing active package film from polyvinyl alcohol and carboxymethyl cellulose incorporated with tamarind seed coat waste extracts to extend the shelf-life	[7]
Cellulose	Cellulose nano-composite film	Producing cellulose nanocomposite film from all-green pineapple peel for maintaining the quality of storage cherry tomatoes as a hydrophobic, high-performance and sustainable approach	[8]
Cellulose	Cellulose nanocrystal-metal-organic framework	Using a composite of cellulose nanocrystal-metal-organic framework as an advanced packaging of food	[9]
Cellulose	Cellulose-curcumin composite	Producing cellulose-curcumin composite biodegradable film with high antibacterial activity to preserve the freshness of food products	[10]

Refs. [1] Elhadef et al. (2024) [2] Mao et al., 2023 [3] Chinnaiah et al., 2023 [4] Shan et al., 2023 [5] Thivya et al., 2022 [6] Shan et al. (2024), [7] Kuchaiyaphum et al., 2024, [8] Zhu et al., 2024, [9] Rui et al., 2024, [10] Wang et al. (2024).

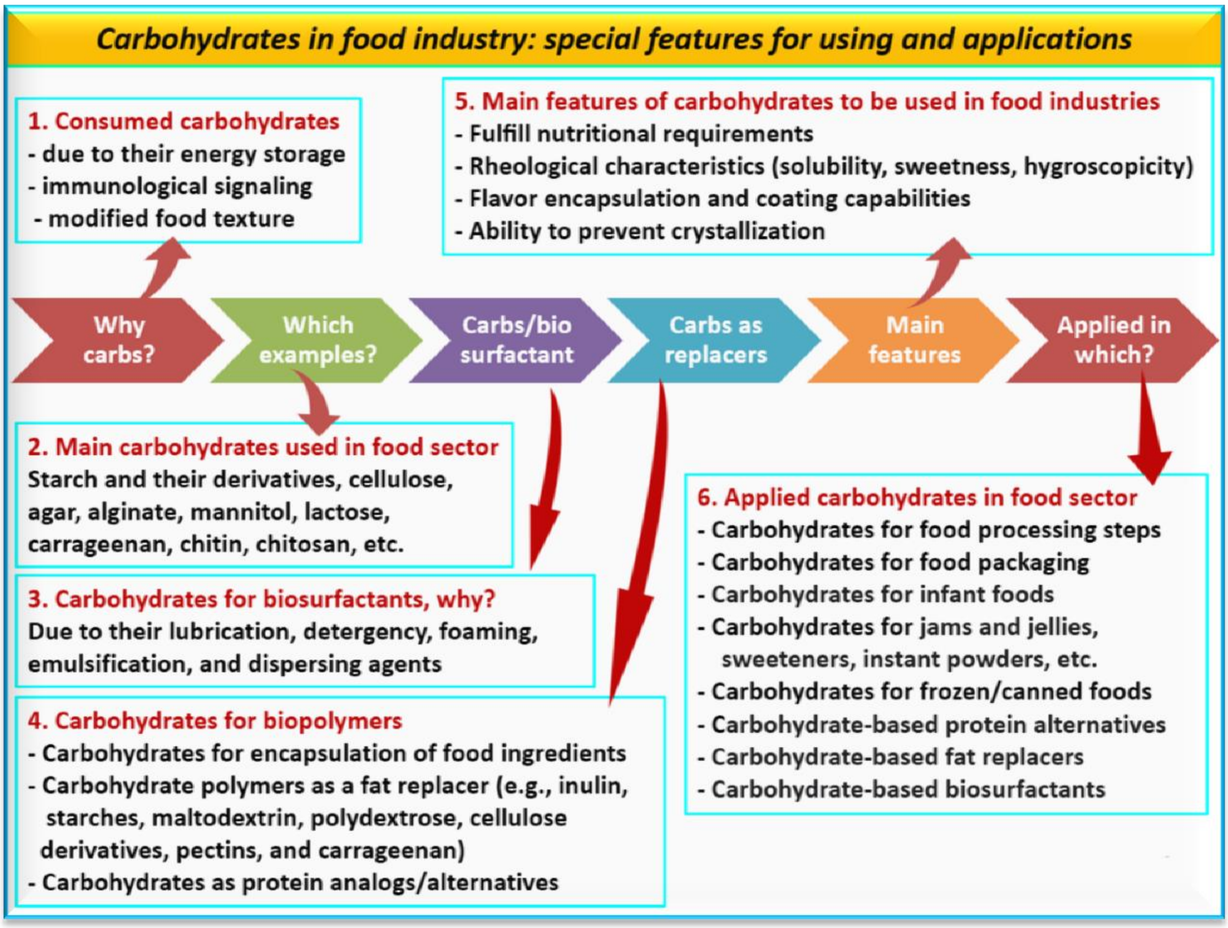

Fig. 5. Carbohydrates in the food sector: their unique features and different applications (adapted from Low et al., 2023, and Ramaprabha et al., 2024).

The field of food packaging has received much more progress in recent years due to the great outstanding achievements in nano- and technology in this industry. This is obvious in several studies which reported on the modified polysaccharides (Janik et al., 2023), with a focus on the anti-microbial activity (Duda-Chodak et al., 2023), the sustainable approach of polysaccharide bio-based hydrogel (Sudheer et al., 2023), and the nano-biodegradable polymer materials (Liao et al., 2023). Thus, producing food biopolymer films is essential in the food packaging industry, to ensure the food system's success, quality, and safety of food products (Sudheer et al., 2023). Many recent published studies confirmed the importance of applying nano-biopolymer materials in the food packaging industry, such as nano-chitin (Liao et al., 2023), cellulose/ chitosan/nano-ZnO composite film (Cen et al., 2023), and nano-cellulose (Cataño et al., 2023). Valorization of agro-wastes (e.g., straw of rice and wheat) has been applied in food packaging such as cellulose (Bangar et al., 2023a, b), besides food wastes of fruit and vegetable (Karimi Sani et al., 2023).

5.2 Carbohydrates in therapeutics and pharma

Carbohydrates are essential macro-molecules for human health with many therapeutic and pharmacological applications (**Figure 6**). Carbohydrates play several direct/indirect roles in various crucial biological processes including cell communication, organogenesis, fertilization, cell regulation, tissue healing, and pathogenesis (Xiang et al., 2021). Carbohydrates have unlimited benefits in the biological and therapeutical relevance due to their previous biological functions (Cao et al., 2022). Carbohydrate-based therapies are frequently employed hematological and cardiovascular conditions, such as inflammatory disorders, anti-thrombotic therapy, and wound healing (Hossain and

Andreana 2019). Carbohydrate-based therapeutics may include carbohydrate-based antiviral drugs, anti-cancer drugs, antibacterial drugs, anti-diabetics, and carbohydrate-based cardiovascular drugs (Cao et al., 2022; Wang et al., 2022; Ramaprabha et al., 2024). Carbohydrate polymers are promising drug delivery candidates, attracting researchers and pharmaceutical companies due to their taste masking, targeted drug delivery, fast integration, controlled drug release, and extended drug release (Ramaprabha et al., 2024). The commonly used carbohydrates (polysaccharides) in drug delivery may include gum of guar, xanthan, dextran, gellan, alginate, mannan, pullalan, hyaluronan, chitosan, chitin, and chitosan oligo-polysaccharides (Banerjee et al., 2023; Kumar et al., 2023; Manna et al., 2023; Galasso et al .2023).

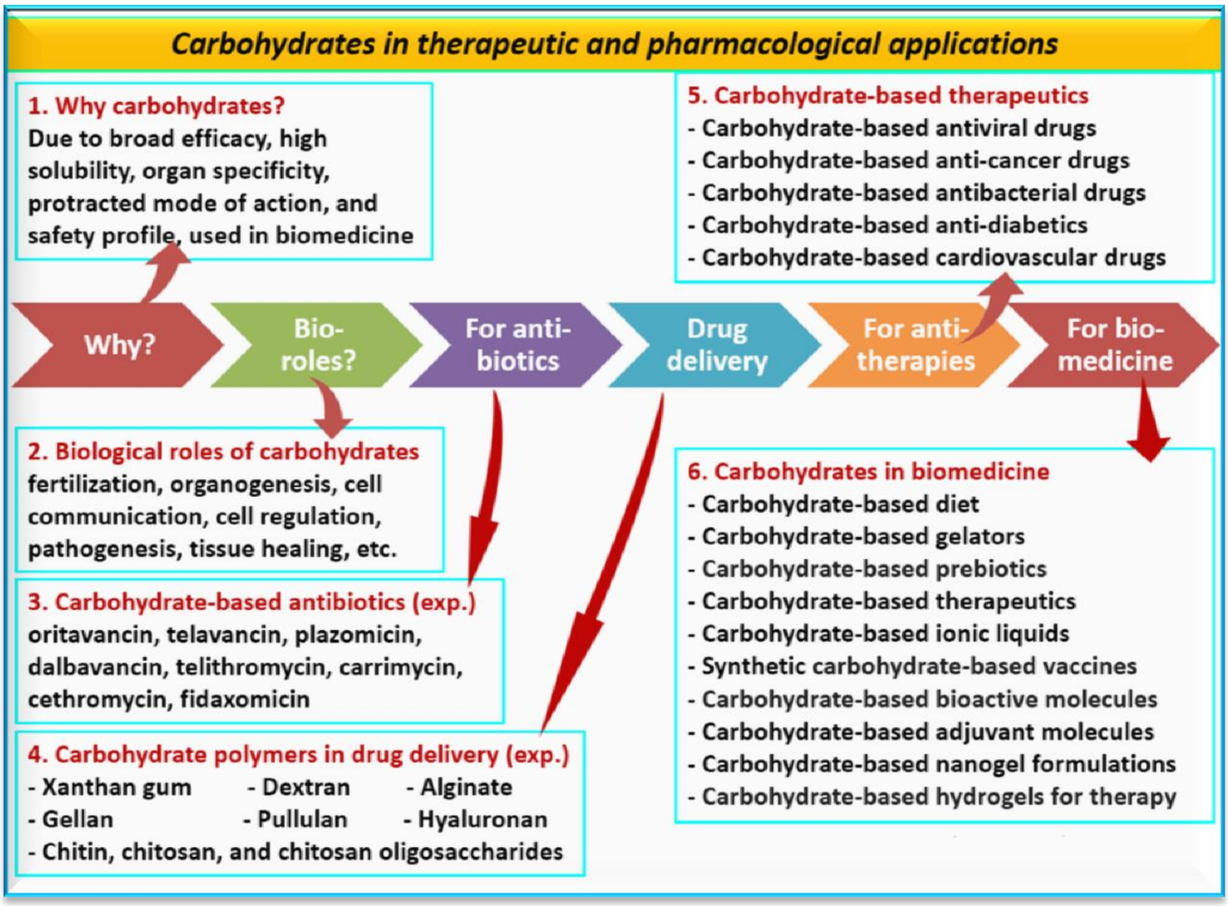

Fig. 6. Suggested therapeutic and pharmacological applications of carbohydrates (sources: Xiang et al., 2021; Cao et al., 2022; Low et al., 2023; Ramaprabha et al., 2024).

5.3 Carbohydrates and nano- agro-management

What is the expected role of carbohydrates in nano-management in the agriculture sector? Which agricultural fields are subjected to carbohydrate-based nano-management? related to nano-management using carbohydrates, especially biopolymeric nanoparticles generated from plants and microbes (Verma et al., 2020). These fields may involve plant nano-protection (Korbecka-Glinka et al., 2022; Kongala and Kondreddy 2023), nano-agrochemicals using nano fertilizers, nano pesticides, and nano-gene delivery (Saberi Riseh et al., 2023; Sharma et al., 2023), nano-biosensors (Chopade et al., 2023), nano-management of pollution (Rizwan et al., 2022; Rub et al., 2023; Zhao et al., 2023), and nano-valorization of agro-wastes (Bala et al., 2023). Almost all agricultural activities can be achieved using carbohydrate-based nanomaterials, including seed sowing/seedling cultivation (Rostamabadi et al., 2023), during growing stages or pre-harvest (Mawale and Giridhar 2024), and postharvest (Jahani et al., 2023). The most common carbohydrate-forms used in these agro-practices may include nanofibers or nano-biopolymers-based polysaccharides, which originated from microbes, plants, and animals (**Figure 7;** Bahrami et al., 2019; Kou et al., 2024). These polysaccharide nano-biopolymers should have specific characteristics, including excellent biocompatible, antibacterial, low immunogenic and biodegradable properties (Ramaprabha et al., 2024). There are several applications of carbohydrate-based nano-biopolymers in agriculture (**Table 3),** such as applying bioactive agents to alleviate biotic stress on plants (Saberi Riseh et al., 2022), controlling the slow-release of pesticides by nano-formulation (Maan et al., 2024), applying biocides through encapsulation of trace elements onto biopolymers for crop protection (Enwemiwe et al., 2024), and cellulose-based fertilizers for increasing crop production and soil quality (Skrzypczak et al., 2023).

Table 3. Some published studies on chitosan and cellulose-based composites in agriculture.

Carbohydrates	Applied form	Suggested benefit of the application	Refs.
Chitosan	chitosan nano-biopolymer	Apply grapefruit peel essential oil by encapsulation to enhance cherry tomato's shelf-life and postharvest quality.	[1]
Chitosan	Chitosan zinc nanocomposite	As slow-release nano-Zn fertilizer through the alternative method as a nanocarrier used in agronomic biofortification of nutrients	[2]
Chitosan	Chitosan–guar gum biopolymer	Controlled release of the pesticide of chlorpyrifos through encapsulation into the bio-polymer-based nano-formulation	[3]
Chitosan	Chitosan nano-composites	Chitosan-based nanocomposites are promising candidates for wastewater treatment as adsorbents.	[6]
Chitosan	Chitosan encapsulated NiO nanocomposites	Enhanced wheat production through promoting the uptake of nutrients and photosynthesis as an eco-, long-term manner and a viable strategy for sustainable farming	[7]
Chitosan	Chitosan-putrescine NPs	Applied nano-composite alleviated Cd-toxicity in grapevine by enhancing photosynthetic status & antioxidant enzymatic activity.	[8]
Chitosan	Chitosan fabricated biogenic Ag-NPs	Applied nano-form reduced bacterial leaf spot disease by increasing water use efficiency and net photosynthetic rate and decreasing stomatal conductance and transpiration rate compared to the infected plant.	[9]
Cellulose	Nano-cellulose based materials	For remediation, the agricultural resources of the chemical pollutants as the sorbents	[4]
Cellulose	Cellulose-based nanobiocomposite	Purification of water/wastewater via adsorption, photocatalytic, and antibacterial approach using cellulose nano-bio-composites	[5]
Cellulose	Cellulose-based fertilizers	Increased nutrient accessibility, crop productivity, and soil health by promoting soil quality parameters, including microbial activity, organic content, and soil water retention	[10]

Refs. [1] Jahani et al. (2023) [2] Cyriac et al., 2023 [3] Maan et al., 2024 [4] Hassanisaadi et al., 2023 [5] Zhang Z et al., 2023 [6] Bhatt et al. (2023), [7] Sharma K et al., 2023, [8] Panahirad et al., 2023, [9] Giri et al. 2023, [10] Skrzypczak et al. (2023)

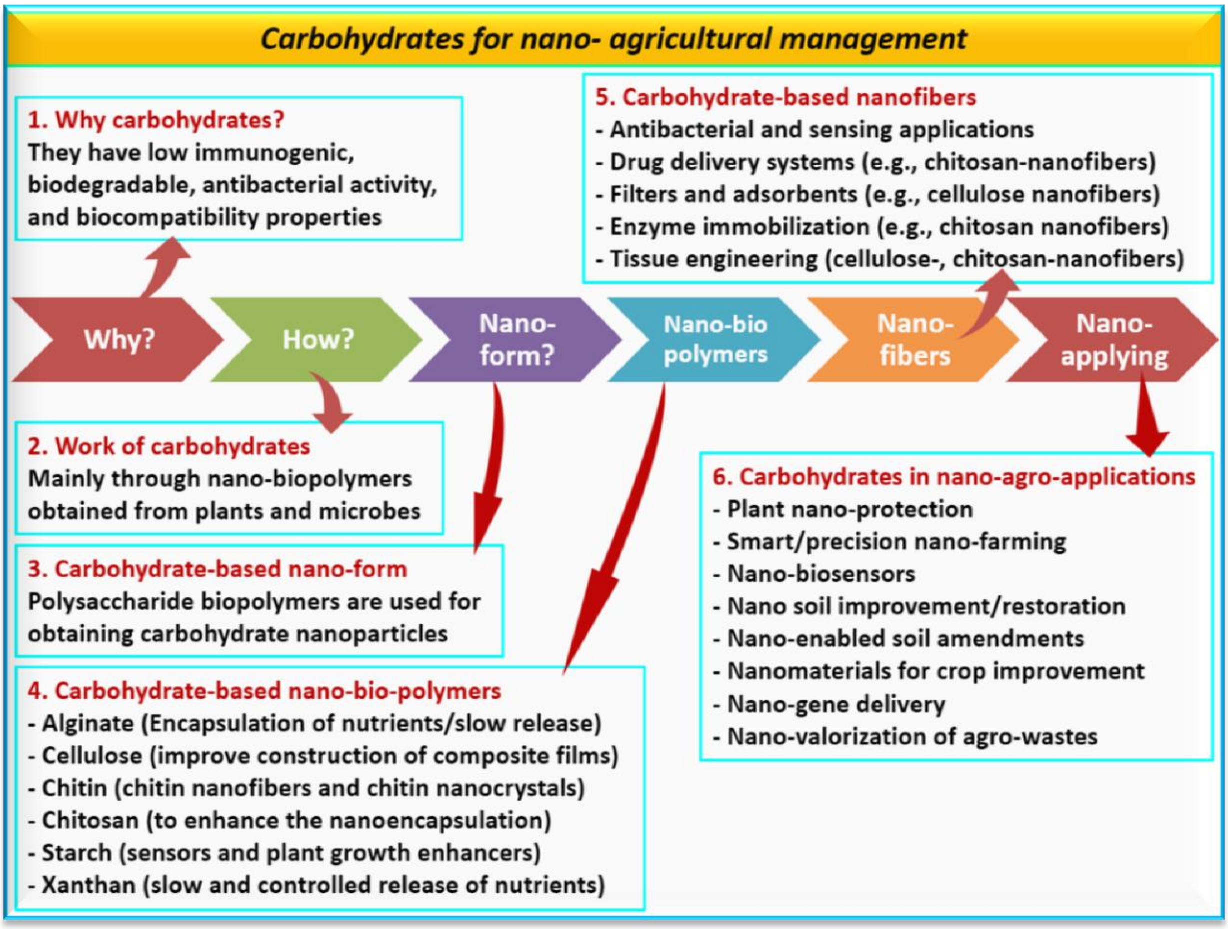

Fig. 7. Applying carbohydrates in the nano-management of different activities in agriculture (sources: Bahrami et al., 2019; Verma et al., 2020; Ramaprabha et al., 2024).

6. Carbohydrate-based foods and human health

Why are carbohydrates important for human health? Which quality criteria control this importance? Firstly, carbohydrate-based foods are essential for improving human health, depending on the carbohydrate quality indices (source of food, percent of added sugar, and fiber content). In contrast, the negative impacts on health are linked to high intakes of added sugar and high glycemic index (Schulz and Slavin 2021). Three necessary suggested quality indices of carbohydrates were proposed including environmental sustainability, degree of processing, and carbohydrate-containing foods as a source of protein (Schulz and Slavin 2021). In general, carbohydrates have diverse compounds including starches, sugars, and dietary fiber, which are found naturally in dairy products and fruits (sugars). In contrast, starches are found in cereals, bread, and starchy vegetables (Figure 8). The digestion of carbohydrates begins in the mouth through converting starch (polysaccharides) by salivary amylase, and the end-product will be monosaccharides (glucose), after more action of oligo-saccharides in the small intestine.

There are enormous themes related to carbohydrates and human health reported by several researchers with a focus mainly on the role of carbohydrates in human diets (Papadopoulou and Nikolaidis, 2023; Dyńka et al., 2023), carbohydrate-based diets and human diseases (Sievenpiper 2020; Varaee et al., 2023), and the functional carbohydrate-based hydrogels for therapy (Zhang Y et al., 2023). Carbohydrate content in a diet is crucial and should be consumed enough to avoid causing many human diseases (Jung and Choi 2017; Wachsmuth et al., 2022). Several human diseases were reported to be linked to high or low intake of carbohydrates, such as diabetes (Zhang Y et al., 2023), epilepsy (Kossoff 2023), depression and anxiety (Varaee et al., 2023), cardiovascular diseases (Jo and Park 2023), obesity (Ludwig 2023), and the mortality (Qin et al., 2023; Zhao Y et al., 2023). The most critical question in this context is when the intake of carbohydrates will be the reason for a disease or treatment. The answer might be associated with the dietary carbohydrate quality and quantity, on one hand, and human characteristics, on the other hand. It is found that increased dietary carbohydrate intake and consumption are linked to the increased risk of cardiovascular diseases and stroke, along with all-cause mortality (Qin et al., 2023).

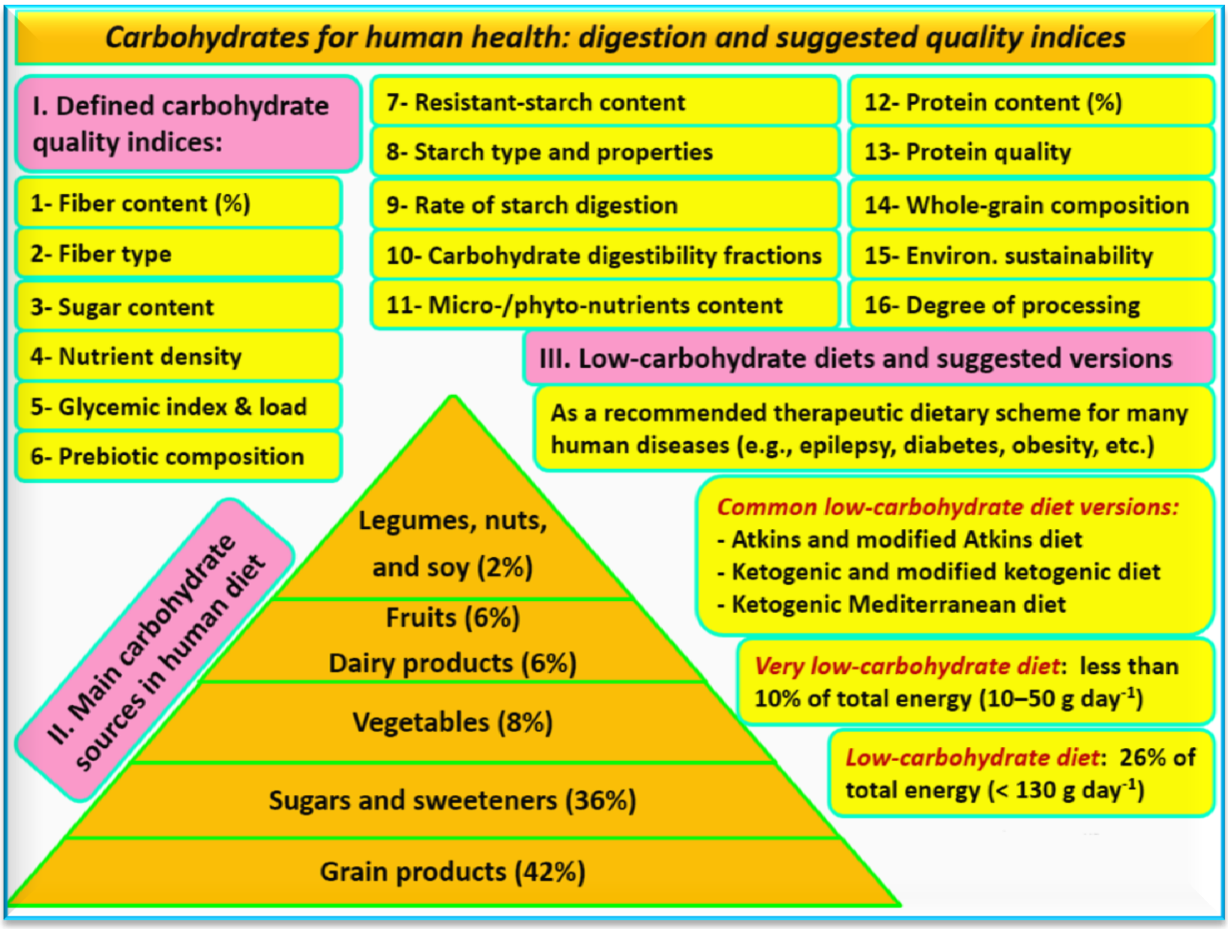

Fig. 8. Carbohydrates for human health including many defined quality indices (part I), the primary sources of carbohydrates (part II), and low -carbohydrate diet systems (part III) (Source: Schulz and Slavin 2021; Wachsmuth et al., 2022; Papadopoulou and Nikolaidis 2023).

7. In vitro digestion models of carbohydrates

What does the digestive model mean? Why did researchers aim to design *in vitro* models of digestion? Because human digestion's process is costly, complicated, differs from one person to another and is restricted by ethical limitations (Directive 2001/20/EU, 2001). Also, using animals as alternative models for humans should be avoided as much as possible (Directive, 2010/63/EU 2010). Therefore, these considerations have led researchers to design and use *in vitro* models to simulate the human digestive system for research purposes (Sensoy 2021). The human digestive system consists of the digestive tract and the accessory organs controlled by nerve networks and hormones (Saladin, 2017). The digestive tract can be described as an open-ended tube of 8–9 m in length starting from mouth to anus, consisting of the pharynx, oesophagus, stomach, small and large intestines. Accessory digestive structures are the teeth, tongue, salivary glands, liver, gall bladder, and pancreas (Ogobuiro et al., 2023).

In vitro, digestion models have been developed since the 1990s for food digestion studies. Moreover, digestion models are tools that could be applied to innovative and develop novel food products (functional foods) for human health. These models could be helpful to for the conscious designing of functional food products by estimating the in vivo behavior of nutrients or food components in the gastrointestinal tract after meals (Xin et al., 2023). Knowing the result of the intake of food components in the human digestive system is attracted the researcher's attention because its relation to nutrition and health, where foods contain components that could have either positive or negative effects on human health (Sensoy, 2021). So, the foods' structure and composition significantly affect their functional and nutritional potentials during digestion (Dupont et al., 2018).

In many countries all over the world, part of the population has malnutrition diseases or is overweight. The relation between dietary foods with health and disease has been strengthened. These links increased the consumer's awareness of the functional properties of the foods, the consequence of the food industry was promoted (Bornhorst et al., 2016). Studying food digestion in vivo (in human or animal) or in vitro methods (by simulation) is possible. Both methods have their advantages and disadvantages. Even though *in vivo* studies can give direct results, the ethical requirements and variation of the digestive system from one to another made the *in vitro* models preferred to use. These *in vitro* methods could be employed in food, nutrition, and medical research because of their speed, low cost, and reproducibility due to standardized and controlled conditions compared to *in vivo* studies (Egger et al., 2019). Many *in vitro* simulation methods have been designed to transcribe the complex human digestive system. They attempt to repeat the physiological conditions of the human digestive system as soon as possible. The models have been improved extensively over the years, and some have been used widely in the food, nutrition, and medical industries (Sensoy 2021).

In vitro digestion models are widely applied to investigate the structural changes, digestion, and release of food components under simulated gastrointestinal conditions. Compared to the *in vivo* digestion tests, the *in vitro* ones reflect the digestion and utilization of food after ingestion and have the advantages of being cheaper, timesaving, repeatable and without moral and ethical restrictions Guo et al. 2021a). The *in vitro* studies carried out on simulated digestion models of polysaccharide carbohydrates have been reviewed (Guo et al. 2021a); these studies provided an essential information for further examinations on the changes happen in the content, structure, and active ingredients of polysaccharides before and after digestion. Polysaccharides are biological macronutrients, consisting of monosaccharides units connected by glycoside bonds to make polymers. Polysaccharides could be classified based on different ways (Guo et al., 2021b) according to their composition (homo- and heteropolysaccharides), their physiological function (structural and storage polysaccharides), their origin (animal, plant and microbial origin polysaccharides) and digestibility (digestible and indigestible polysaccharides). Polysaccharides exhibited several biological activities: antibacterial (Yang et al., 2021), anti-tumour (Zhang et al., 2021), antiviral (Guo et al., 2021), antioxidant potential (Fang et al., 2021), immunomodulation (Huang et al., 2021) and hyperglycaemic (Pan et al., 2020).

Recently, *in vitro* simulated digestion models for edible and medicinal plant polysaccharides have been developed (Mao et al., 2019; Wu et al., 2020; Zhang et al., 2020). In this concern, the effects of simulated saliva-gastrointestinal on the *in vitro* digestibility of polysaccharides, physicochemical properties and bioactive components of *Siraitia grosvenorii*; a perennial plant from Cucurbitaceae family, were studied (**Table 4;** Guo et al. 2022). The antioxidant potential and phytochemical bio-accessibility from eight fruit juices as a response to *in vitro* simulated gastrointestinal digestion (Mihaylova et al. 2021) have been investigated. The catabolic property of mushrooms (*Dictyophora indusiata*) polysaccharide during *in vitro* digestion and its effect on Gut microbial and human health was examined (Zhao et al., 2023). Moreover, the impact of balsamic vinegar of Modena (BVM) dressing on digestibility and accessibility/availability of food components (bioactive molecules) that are released from the starch-rich meal (boiled potatoes) using an *in vitro* digestion method has been studied (Urbinati et al., 2021). Vinegar has been reported to possess antioxidant, antimicrobial, and antitumor activity, and it can regulate blood pressure; its effects are mainly related to its content of carotenoids, phytosterols, phenolic compounds, and vitamins C, and E. Vinegar could improve digestive system function, appetite stimulation, and reduce hyperglycemia, hyperlipidemia, and obesity (Budak et al. 2014; Ho et al. 2017). To achieve food security, improve nutrition, conserve marine resources and maintain the aquaculture industry, an *in-vitro* engineered digestion protocol for fish has been established lately and purposed to be improved and developed (Wang et al., 2021). This method will prove a faster and cheaper way to assess nutrient digestibility. To obtain healthier food products, gastrointestinal *in vitro* digestion and fermentation studies/methods of carbohydrate-rich foods have increased (León et al., 2023) and become most popular in food nutrition or pharmaceutical sectors.

INFOGEST digestion models are the most used methods to study the gastrointestinal digestion of different foods (fruit, vegetable, cereal, dairy, egg, meat, and fish). Moreover, they are increasingly used to understanding the behaviour of plant-based foods in the human gastrointestinal tract. This model can also be used to monitor the bioavailability of proteins, lipids, carbohydrates, vitamins, and minerals in food matrices. This knowledge can help us to design foods with improved nutritional and health effects for humans (Zhou et al .2023).

Starch is the primary source of carbohydrates in the human diet. Various factors affect their digestibility (Toutounji et al., 2019). In vitro, starch digestion to describe oligosaccharide or glucose release was reviewed early by Dona et al. (2010). Slow starch digestibility is an essential trait in food since high postprandial glucose levels have been associated with different non-communicable diseases such as type 2 diabetes, obesity, hyperglycemia, and cardiovascular diseases (Pautong et al. 2022). Non- or slowly digestible carbohydrates (resist digestion) may have beneficial physiological effects, such as low-calorie (to prevent obesity), low-glycemic index (to control cardiovascular and diabetes disease), and low-digestible (to reduce the intestinal transit time and modulate the gut microbiota composition and activity) (Hernandez-Hernandez et al., 2019). Argyri et al. (2016) have proposed an *in vitro* digestion protocol that could be applied to predict glycemic response, which is highly linked with chronic diseases such as obesity and type 2 diabetes, in foods or meals. In the same context, glycemic indexes of some Turkish bread were evaluated using *in vitro* enzymatic carbohydrate digestion (*Yusufoğlu* et al 2021).

On the other hand, digestible carbohydrates may have different impacts on human health as acting as dietary fiber and prebiotics (Rastall et al. 2019). Evaluating the quality of carbohydrates (which means 40–80% of daily intake), ng the quality of carbohydrates (40–80%) is an essential intervention for glycemic control. More than half of the population worldwide, mainly in Asia, derives more than 50% of daily calories from rice as a staple carbohydrate source. So, in rice-based diets, reducing a variety's glycemic index (GI) through postharvest, genetics, and cooking, are critical issue (Jukanti et al., 2020). Finally, it is recommended to use multiscale food digestion that aims to provide a quantitative analysis of food digestion processes by combining *in vitro* and *in vivo* studies. This multiscale approach will optimize functional food properties to facilitate food product development (Bornhorst et al., 2016).

Table 4. Studies on enzymatic degradation of carbohydrates in some plant species

Plant species (family)	Type of carbohydrates/ biological activities	Enzymatically degraded products	Biological activity after degradation	Ref.
Cicer arietinum L. (Fabaceae)	Pectins (galacturonic acid-rich pectic polysaccharides), that give rigidity to the cells	Monosaccharide (galactose)	Loss of cell wall rigidity that accompanies growth and ripening	[1]
Cicer arietinum L. (Fabaceae)	Antioxidant, anti-inflammatory, and amylase inhibitor	Mannose, glucose, and galactose	Abolish cell death-inducing endoplasmic reticulum stress	[2]
Fagopyrum esculentum Pseudocereals (Polygonaceae)	Dietary fiber poly-saccharides with large quantity of pectins	Ferulic acid oligosaccharides	Buckwheat polysaccharide fractions have probiotic properties	[3]
Fagopyrum tataricum Pseudocereals (Polygonaceae)	In functional foods for treatment of health, malnutrition, wheat allergy and celiac patients	Arabinan and galactan oligosaccharides	Maintain gut microbiota	[4]
Amaranthus caudatus pseudocereal grains (Amaranthaceae)	Dietary fiber polysaccharides	Fiber polysaccharide fractions	Improving the fermentative and rheological properties of wheat dough, the elasticity of the breads	[5]
Oat: *Avena sativa* (Poaceae)	Dietary soluble fiber (β-glucan) polysaccharide of glucose molecules linked by β-glycosidic bonds	Glucose	Enzymatic hydrolysis preserved the nutritional quality of oat bran	[6]
Rye: *Secale cereale* L. (Poaceae)	Dietary fiber carbohydrates (arabinoxylans, fructans and glucans)	Endogenous enzymes of starch degradation to amylase	Total content of arabinoxylans in the sourdough breads was increased, and solubility	[7]
Proso Millet: *Panicum miliaceum* L. (Poaceae)	Starch with high amylose content, high-resistant starch digestible starch, dietary fiber	Digestible starch was hydrolyzed to D-glucose	Glucose through aerobic or anaerobic respiration and fermentation	[8]
Proso Millet: *Panicum miliaceum* L. (Poaceae)	Proso millet can be incorporated into wheat-based breads and pasta	D-glucose content was measured with GODOP reagent	It stored as starch in plants and glycogen in animals to be used the metabolic processes	[9]
Psilium husk: *Plantago ovata* (Plantaginaceae)	Polysaccharides fiber and polysaccharides hydrocolloids (mucilage)	Polysaccharides hydrolyzed to xylose, arabinose, galacturonic acid	Insulin resistance and fasting blood glucose	[10]
Psilium husk: *Plantago ovata* (Plantaginaceae)	Improve lipid profile and the cardiovascular health In gluten-free bread production	Maltose could be detected in the baking dough samples	Reducing the acrylamide content	[11]
Chia: *Salvia hispanica* L. mint family (Lamiaceae)	D-glucose, D-mannose, D-galactose, D-galacturonic acid, D-xylose and D-glucuronic acid	Chia seeds polysaccharides (CSP-A) were extracted and purified	Hypoglycemic, immune-boosting, antibacterial, antioxidant, anti-tumor and anti-radiation	[12]
Linseed (flaxseed): *Linum usitatissimum* L. (Linaceae)	Soluble/insoluble dietary fiber, mucilage poly-saccharides (L-arabinose)	Enzymes of lignan hydrolysis from its complex	Biological impacts of lignans as antioxidants, antiviral, and anticancer	[13]

Refs. [1] Minzanova et al. (2018), [2] Zhu et al. (2022), [3] Sofi et al. (2022), [4] Xiang et al. (2023), [5] Zhu (2020), [6] Tan et al. (2023), [7] Koj and Pejcz (2023), [8] Balli et al. (2023), [9] Narciso and Nyström (2023), [10] Bacha et al. (2022), [11] Bartkiene et al. (2023), [12] Xiao et al. (2023), [13] Sangiorgio et al. (2023).

8. Conclusions

Carbohydrates are important sources of plant and animal food for human nutrition. Carbohydrate-based plant foods include grains, vegetables, fruits, legumes, and animal sources like dairy products. These macromolecules have several biological benefits for human health, nutritional, pharmaceutical, and biomedical benefits. Surprisingly, the story of carbohydrates starts in soil, where cultivated plants collect, store, and sequester carbon through the photosynthesis process. The transformation of CO_2 by plants is the starting point to form carbohydrates, which may decompose microbially in soil again. Carbohydrate-based foods contain essential nutrients such as sugars, dietary fiber, and necessary elements (K, Ca).

On the other hand, the higher intake of high-carbohydrate-based food may cause many human diseases such as obesity, diabetes, cardiovascular diseases, epilepsy, depression, and anxiety. The complete story of carbohydrates in agroecosystems starts from soil and in soil through many global issues, including soil carbon sequestration, loss of soil fertility, soil erosion, and climate change. Applied carbohydrates in the food sector involve food processing, packaging, carbohydrate-based protein alternatives, carbohydrate-based fat replacers, and biosurfactants. Concerning the therapeutic and pharmacological applications of carbohydrates, they include carbohydrate-based prebiotics, therapeutics, and carbohydrate-based hydrogels for therapy. Carbohydrates have distinguished applications for nano-management in agriculture as referring in nano-biosensors, nano-soil improvement, nano-enabled soil amendments, nanomaterials for crop improvement, nano-gene delivery, and nano-valorization of agro-wastes. A crucial need is requested for the digestive model of carbohydrates to understand this macromolecule and its potential for human health.

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