REVIEW PAPER

Inulin Fiber Incorporation in Multi-Source Plant-Based Protein Bars: A Review of Texture Improvement, Hardness Reduction, and Functional Benefits

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ABSTRACT
Socioeconomic inequality and its relationship with education are a global challenge affecting most developing nations around the world. Learners from advantaged socioeconomic backgrounds tend to do well academically than those from less advantaged backgrounds, who face weaker outcomes and more challenging pathways through school. Previous reviewed studies emphasise the importance of access to learning materials, parental education, school quality, and neighbourhood conditions in shaping achievement, attainment, and progression. The strength of the relationship is not identical in every setting. It varies by country, school level, the way socioeconomic status is measured, and the academic outcome under consideration. The findings of this systematic review show that inequality works through both direct and indirect channels, and that its effects accumulate over time rather than appearing in isolation. Social reproduction, human capital, ecological systems, and cumulative disadvantage perspectives help explain why educational gaps persist and widen across contexts. The review points to the need for early, coordinated responses that combine policy reform, school support, family engagement, and community-levelInulin is one of the most popular natural functional ingredients in nutrition bars, as it is a naturally occurring fructan and is mainly produced from chicory root and other plant sources, while also having several beneficial physicochemical and health-promoting properties. Inulin is a soluble dietary fibre, and a known prebiotic, which helps to support the composition of gut microbiota, facilitate the production of short-chain fatty acids and decrease the postprandial glycemic response. In nutrition bar formulations, inulin serves multiple technological roles, including acting as a bulking agent, fat replacer, sugar reducer, and texture stabilizer that helps mitigate bar hardening during storage. Its mild sweetness and ability to improve mouthfeel make it particularly valuable in high-protein and reduced-sugar bars. In particular, inulin may find a fantastic application in the fully plant-based protein bars, which are formulated with the chickpea, pea, rice, moong, and jackfruit seed protein concentrates, where hardness, dryness, brittle character, and poor chewability are common quality concerns. However, the digestive tolerance of various individuals varies and when consumed excessively, could cause gastrointestinal discomfort. In total, inulin can enhance the nutritional value, prebiotic and metabolic benefits, moisture retention, hardness during storage, and chewability, and thus can serve as a versatile multifunctional ingredient in the creation of modern plant-based functional bars.

Keywords: *Inulin, prebiotic fiber, plant-based protein bar, chickpea protein, pea protein, rice protein, moong protein, jackfruit seed protein, bar hardness, chewability, texture stability, dietary fiber.*

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Introduction

Nutrition bars such as protein bars, energy bars, and meal-replacement bars represent one of the fastest-growing segments of the functional food market, driven by increasing consumer interest in convenience, health, and performance nutrition (Baker et al., 2022; Sloan, 2019). Consumers are increasingly mindful of the impact of their food choices on their digestive health, glycemic index, weight control, and overall well-being, and are looking for bars that do more than just provide calories. As a result, manufacturers have turned to the use of scientifically proven ingredients with added health and functional benefits. Inulin fiber has been one of these ingredients to step into the spotlight as it has two widely recognized properties, as a prebiotic and as a multifunctional texturizing ingredient (Gibson et al., 2017).

Inulin is one type of naturally-occurring fructan, a chain of fructose molecules linked by β-(2→1) bonds, mainly present in chicory root, Jerusalem artichoke, agave, wheat, onions and other plant tissues (Roberfroid, 2007). Human beings are unable to break down fructans, so it passes through the upper GIT undigested and is fermented by colonic flora, with the production of short-chain fatty acids (SCFAs) including acetate, propionate and butyrate (Roberfroid et al., 2000). Inulin's prebiotic status is based on the fermentative process, and was thought to be a stimulator of beneficial bacteria, particularly *Bifidobacterium* spp., and a promoter of gut ecology and metabolic processes (Slavin, 2013). With rising research interest in gut microbiome's impact on health outcomes, the use of inulin in functional foods has become a growing interest.

Inulin has a variety of physiological properties but also has several technological properties that are useful in the formulation of nutrition bars. It has a moderate water-binding capacity, which helps to retain moisture; its mildly sweet flavor (about 1/3 as sweet as sucrose) adds flavor without adding substantial glycemic load (Niness, 1999). Inulin's creamy or fat-like characteristics in the presence of water has helped it become a successful sugar and fat replacer particularly for those bars seeking to claim the label of "low sugar," "high fiber" or "clean label" (Franck, 2002). These same properties also help to address common formulation challenges of high protein bars such as hardness on storage, poor mouthfeel, and lack of cohesiveness (Diaz et al., 2021). Inulin thus has a sensory effect and an improvement of the nutritional value.

Inulin added to nutrition bars has a number of health benefits. Inulin has been demonstrated to be beneficial for bowel regularity, stool bulk, bifidobacterial population and may have a positive effect on metabolic health parameters such as insulin sensitivity and lipid profile in many clinical trials in humans (Hughes et al., 2022; Guess et al., 2015). For nutrition bars, these attributes mean that they can be a convenient source of meaningful dietary fiber and prebiotic activity, to help consumers aim for digestive and metabolic wellness. Besides, inulin has a low digestible carbohydrate profile and low glycemic index, which are perfect for the diabetic friendly, ketogenic and weight management categories (Alonso-Allende et al., 2024).

Although inulin has benefits, there are a number of formulation challenges when using inulin in bar matrices. Gastrointestinal tolerance is not the same for everyone, though at higher doses, symptoms such as gas or bloating can be seen at certain doses (Slavin & Feirtag, 2011). In addition, the degree of polymerization (DP) of inulin affects its physicochemical properties, which in turn affects its sweetness, solubility, prebiotic property and texture. Additionally, the protein systems, polyols, fruit bases or acidic ingredients may affect the stability of the bar and its sensory characteristics during shelf life (Diaz et al., 2021). The challenges reveal that the strategic formulation approaches vary according to the type of bar and consumer health claims.

The growing interest in functional snacks and the emphasis on a healthy gut and metabolism makes the use of inulin in nutrition bars a very relevant application. This review summarizes the food science, nutrition, microbiological and product development research that underpins the technological, nutritional, sensory and physiological properties of inulin fibre in nutrition bars. The review integrates these observations to provide a thorough overview of the possible applications of inulin in product development, with a potential improvement of the quality of the products and health benefits for consumers.

Nutrition bars are an excellent opportunity to increase the nutritional fiber content of these products, improve digestive function and improve the nutritional and taste value without compromising the nutritional goals. However, the formulation issues associated with these benefits are still present such as gastrointestinal tolerance, the potential for interaction between other components of the bar and the formulation, and the functional performance of the inulin depending on its type and degree of polymerization. This review examines the technological, nutritional, sensory, and physiological roles of inulin in nutrition bars, with particular emphasis on its potential application in fully plant-based multi-source protein bars for reducing hardness, improving chewability, and enhancing product stability during storage.

When used in bars, inulin can serve multiple roles:

1. Functional fiber (enhances dietary fiber content; supports gut microbiota)
2. Sugar replacer (provides slight sweetness without spiking blood glucose)
3. Fat replacer (provides creaminess or bulk)
4. Texturizer (binds moisture; improves chewiness)
5. Prebiotic ingredient (supports bifidogenic effects)

This review synthesizes current evidence on inulin's impact on nutrition bar quality and its health-related implications.

The innovative feature of this review is that it is recommended to include inulin in the entirely in-plant based, multi-source protein bars to make them tender and edible during their storage. A realistic bar consists of of chickpea, pea, rice, moong and jackfruit seed protein extracts, and combined with almonds, flax, cashews, cardamom, jaggery, salt and water or jaggery syrup. Inulin can be used as an ingredient of such formulations in prebiotic form as a dietary fiber, and as a texture-modifying agent, which can be used to maintain moisture, proteinfiber interactions, cohesiveness in the matrix, and enhance sensory acceptability.

2. Review Methodology

The present review was composed after reviewing the literature published in the field of inulin, inulin-type fructans, prebiotic dietary fibers, nutrition bars, protein bars, plant protein formulations, texture stability, glycemic response, satiety, and digestive tolerance. Keywords related to these topics were used to search the scientific databases, including Google Scholar, PubMed, Scopus, and Web of Science, which were inulin, oligofructose, prebiotic fiber, nutrition bar, protein bar, plant-based protein bar, bar hardening, texture stability, glycemic response, and digestive tolerance. The studies were selected in case they talked about the physicochemical, nutritional, physiological, sensory, or technological characteristics of inulin and its use in food systems. Special emphasis was placed on the researches that were pertinent to high-protein and plant-based bar matrices. Articles that were not directly related to inulin, dietary fiber functionality, food texture, and bar formulation were eliminated.

3. Physicochemical and Functional Properties of Inulin Relevant to Nutrition Bars

3.1 Solubility and Water-Binding Capacity

Inulin has a number of important physicochemical properties that are relevant to its use in nutrition bars, such as its solubility and water-binding capacity, which can impact on the texture, moisture-holding capacity, shelf-life and processing characteristics of the product. The degree of polymerization (DP), molecular structure, temperature and processing conditions have a significant influence on the solubility of inulin. Short-chain inulin (also known as oligofructose) is highly soluble in water at room temperature, whereas long-chain inulin is less water-soluble and needs to be heated to become fully hydrated (Niness, 1999; Franck, 2002). This DP-dependent solubility is relevant in the formulation of bars: low DP inulin provides sweetness and bulk, while high DP inulin builds more coherent and gel-like matrices, which creates a better texture.

Solubility is greatly affected by temperature. The solubility of long-chain inulin is low at low temperature, but increases at high temperature because of the disruption of the intra- and intermolecular hydrogen bonding (Roberfroid, 2007). Partially dissolved long-chain inulin can recrystallize on cooling to form microcrystalline domains that are responsible for gelation and increased textural stability (Glibowski & Bukowska, 2011). The solubility dynamics affect bar processing: warm mixing aids dispersion, cooling during setting aids to network formation, which allows for stabilization of soft textures.

In addition, inulin has a high-water binding capacity because of the presence of a large number of hydroxyl groups which are able to form hydrogen bonds with water molecules (Fernandes et al., 2011). This moisture holding capacity is beneficial in nutrition bars, helping to keep them soft, prevent staling and control the water flow between ingredients. Inulin can be used to prevent textural degradation in high protein bars because protein carbohydrate interactions can cause the bar to harden during storage. Another benefit of water binding is that it aids in cohesive structure, which is useful for composite bar systems that contain nuts, seeds, or dried fruits.

In addition, the water binding properties of inulin help to lower water activity (a_w) in the final product, which helps to stabilize the microorganisms and improve shelf life. In particular, the long-chain inulin creates structured hydrates which bind water into a gel network, resulting in a soft, elastic matrix which is suitable for bar applications. In the high moisture formulations, however, excessive water-binding could lead to stickiness, so a balance between water content, DP and mixing conditions is required.

To sum up, the inulin's solubility and hydration properties are ideal for the formulation of nutrition bars, which leads to improved texture, softness, sensory properties and formulation stability.

The hydration-related features are particularly important when using plant-based protein bars when the protein concentrates of chickpea, pea, rice, moong and jackfruit seed may compete with water to lead to dense or brittle texture development during storage. The water holding capacity of inulin in multi-source plant protein bar products could prevent moisture migration, hardness formation, and maintain chewability of the products.

3.2 Mild Sweetness and Sugar Replacement

Another nutritional benefit of inulin is its mild sweetness and bulk, which means it can be used as a substitute for sucrose or other caloric sweeteners in the nutrition bar formulation without affecting the flavor or texture of the bar. The sweetness of inulin-type fructans is highly dependent on degree of polymerization. Short-chain oligofructose is sweet and long-chain inulin is not very sweet but is used primarily as a bulking, texturizing and fat-mimetic ingredient (Niness, 1999; Franck, 2002). This low-intensity, clean sweetness is ideal for reduced sugar bars formulated for diabetic, low-glycemic or weight-management use, where a high level of sweetness might not be required, and a natural flavour profile is desired.

The lowest molecular weight inulin fractions (DP < 10) are the most sweet, they are more soluble and have a sweetness profile similar to the traditional sugars (Roberfroid, 2007). Long-chain inulin (DP ≥ 23), on the other hand, has little sweetness value but is very important for bulking, allowing the replacement of sugar without loss of product volume and textural properties. Commercial formulations of bar products often involve blends of long-chain and short-chain inulin, to ensure optimum sweetness perception and structural properties.

Beyond its sweetness, the sugar replacement potential of inulin is also its ability to provide bulk and mouthfeel when reducing the amount of sugar in a product, which could otherwise be thin or dry. Inulin being polysaccharide gives body and smoothness without a significant increase in calorie content and has a calorie content of about 1.5kcal/g while sucrose has a calorie content of 4kcal/g. Inulin is therefore a very interesting ingredient for the formulation of products positioned for low calorie, low sugar, or high fibre. It also has the ability to bulk and keep composite bar matrices with protein isolates, nuts or seeds together.

In addition, inulin in its mild sweetness is able to mask bitterness or off-notes from other ingredients used in nutrition bars, such as whey protein isolates, plant proteins, cocoa polyphenols or some vitamins and minerals. Oligofructose has been found to enhance the flavor perception, overall palatability and flavor balance in reduced sugar formulations (Franck, 2002). This flavor-modulating aspect is especially important in high protein bars that could have chalky or bitter flavors.

Besides being caloric and flavoured, inulin's sugar-replacement effect helps to reduce postprandial glycemic response, as it is not digested and absorbed in the small intestine and therefore has no effect on blood glucose or insulin levels (Holloway et al., 2007). Inulin-based bars can thus be developed as a replacement for conventional sugar-based bars, which may help support glycemic control and fit within various dietary guidelines, including low-glycemic, ketogenic, and diabetic diets.

It should be noted, however, that the amount of sugar that can be reduced in the food depends on the intensity of sweetness desired, as inulin cannot be used to completely replace the sweetness of sucrose without the addition of other sweeteners. Thus, inulin is often combined with high potency sweeteners (such as stevia, monk fruit) or polyols (such as erythritol, maltitol) to produce a sweetness balance and an ideal bar texture and stability.

Overall, inulin's unique properties, such as its low sweetness, its use as a sugar bulk, its ability to enhance flavor balance, and its low caloric and glycemic impact, make it a valuable addition to contemporary nutrition bar formulations that cater to health-conscious consumers.

3.3 Bulking and Fat-Replacement Properties

One of the most useful technological applications of inulin in the formulation of a nutrition bar is as a bulking agent and fat replacer. These properties are based on its molecular structure, hydration properties, gel-forming ability and sensory properties, which allow inulin to behave like sugar or fat, but with much less caloric content.

3.3.1. Bulking Properties in Reduced-Sugar Formulations

Inulin can be used in formulations where sucrose or other caloric sweeteners have been reduced or eliminated for providing structural bulk. Inulin has a caloric contribution of 1.5 kcal/g, which provides significantly less calories than sucrose (4 kcal/g) or standard carbohydrates, enabling product developers to achieve texture and volume without the additional calories. This is especially important in nutrition bars where you need to provide a high amount of mass without a high amount of sweetness, such as for low sugar nutrition bars, diabetic friendly nutrition bars, or weight-management nutrition bars.

The polysaccharide nature and water binding properties of inulin are thought to be responsible for the bulking effect, and to allow inulin to occupy space in the bar matrix like sugar solids (Franck, 2002). Low-DP inulin and oligofructose offer improved dissolution and dispersed phase consistency, and long-chain inulin offers particulate and textural body. These properties make reduced-sugar bars easier to pull from the mold, without becoming dense, brittle or rubbery, which is a typical problem with removal of crystalline sucrose.

3.3.2. Fat-Replacement Functionality

Long-chain inulin is known to be an effective fat replacer, especially in low fat foods that are usually fat rich to impart a desired mouthfeel. Long-chain inulin at proper concentrations forms a microcrystalline gel network, which acts like fat droplets in dispersions, giving a creamy, lubricating mouthfeel (Niness, 1999; Glibowski & Bukowska, 2011). This fat-mimetic behavior is the result of small, uniform inulin molecules crystallizing in water and creating a lubricating, semi-solid structure.

These properties are crucial for fat reduction without affecting sensory acceptance and texture. Inulin is also used for fat replacement, which is also in line with consumer demands for lower calorie, lower fat and clean label products.

3.3.3. Rheological and Textural Impacts

The fat replacement effect of inulin has been measurable and results in a change in the rheological and textural properties. Inulin gels have been found to be viscoelastic, with the storage modulus (G′) being dominant, which means that they have gel-like functionality (Glibowski & Bukowska, 2011). This behaviour can be exploited in stabilising semi-solid and solid matrices, such as bars, in which inulin can be employed as a structural stabiliser.

3.3.4. Caloric and Nutritional Advantages

In addition to technological benefits, inulin provides notable nutritional advantages when used as a fat replacer:

- Lower caloric density
- Added dietary fiber
- Prebiotic functionality
- Minimal glycemic impact

This combination allows manufacturers to improve the overall nutritional profile of bars without compromising the sensory experience.

3.3.5. Synergy with Other Ingredients

Inulin is often combined with other fat mimetics (such as soluble fibers and gums) and/or sweeteners (such as stevia, polyols) to complement sweetness and texture. Inulin can be used with polyols (maltitol, erythritol) or glycerin for increased hydration, reduced stickiness and shelf flexibility and stability.

In plant-based protein bars, inulin might be used in combination with nut ingredients, seed components and jaggery syrup to enhance binding, mouthfeel and structural stability. In a bar formulation with almonds, flaxseed and cashews, cardamom, jaggery, salt and water or jaggery syrup, inulin can help to create a structure that is cohesive and has good chewability.

4. Nutritional and Physiological Effects in Nutrition Bars

The majority of the physiological benefits of inulin have been shown in inulin-type fructans as food supplements or as components of a general food system. Thus, these benefits are only considered to be formulation-relevant potential benefits when discussed in the context of nutrition bars, and only when backed by studies with real products of the nutrition bars. Depending on the dose of inulin, its degree of polymerization, the composition of the barium, the diet of the animals and their gut microbiota, the physiological reaction can differ.

4.1.1 Prebiotic Activity

One of the most widely studied dietary fibers for prebiotics, which are selectively promoting beneficial gut microorganisms that provide health benefits to the host. Inulin has a β-(2→1)-linked fructose structure that makes it indigestible by human digestive enzymes, allowing inulin to reach the colon undigested where it is fermented by certain populations of microbes. This selective fermentability is key to its prebiotic properties and is crucial to many of the physiological benefits claimed for foods that contain inulin like nutrition bars.

The use of inulin in fully plant-based protein bars can offer an added functional benefit, delivering plant protein enrichment and prebiotic dietary fiber delivery (Sharma et al., 2025). Hence, a protein supplement using bar matrix of chickpea, pea, rice, moong and jackfruit seed protein concentrate can be used as a convenient source for protein and for gut health.

4.1.2. Selective Stimulation of Beneficial Gut Microbiota

Inulin selectively stimulates the growth of Bifidobacterium spp. and Lactobacillus spp., two groups of bacteria that are linked to gut homeostasis, barrier function and immune modulation (Roberfroid, 2007). Many human and animal studies show that inulin can effectively increase the number of bifidobacteria in feces, sometimes within 1-2 weeks (Gibson et al., 2017). The specificity of this stimulation is what makes inulin different from other non-prebiotic fibers and shows its functional specificity.

4.1.3. SCFA Production and Colonic Health

Fermentation of inulin generates SCFAs (acetate, propionate, butyrate) that are important for colonic and systemic health. Butyrate is especially significant as the main energy source for colonocytes, and as a regulator of inflammation and epithelial proliferation (Flint et al., 2012). Acetate and propionate also have metabolic advantages, such as effects on satiety regulation, lipid metabolism and glucose homeostasis.

Increased SCFA production derived from inulin fermentation has been linked to:

- Enhanced gut barrier function
- Reduced local inflammation
- Improved stool frequency and consistency
- Protective effects against colorectal carcinogenesis (Roberfroid, 2010)

These mechanistic links provide strong support for the inclusion of inulin in functional foods aiming to improve digestive health.

4.1.4. Impact on Bowel Function and Digestive Comfort

Inulin has proven to be effective in improving bowel function through the increase in stool bulk and frequency in clinical trials, and is therefore beneficial for people with functional constipation (Slavin, 2013). This effect is primarily because of the production of biomass and proliferation of microbes in the colon due to fermentation.

In sensitive people, however, short-chain inulin can lead to gas and bloating, whereas long-chain inulin is fermented more slowly and is better tolerated by the gastrointestinal system (Alles et al., 1996). This DP dependent difference is used to guide formulation of products, particularly in food products where tolerance is a consumer concern, like nutrition bars.

4.1.5. Immunomodulatory Benefits

Recent studies have indicated that inulin may have an indirect effect on immune function via gut immune interactions. Butyrate, a type of SCFA, affects immune cells in the following ways:

- Improving the function of regulatory T cells (Tregs)
- Decreasing the release of pro-inflammatory cytokines
- Supporting mucosal immunity (Koh et al., 2016)

The immunomodulatory pathways highlight the possible beneficial effects in metabolic and inflammatory diseases, but further studies are required to define dose response relationships in functional foods.

4.1.6. Relevance for Nutrition Bar Applications

It is also a very effective way to provide prebiotic benefits in convenient and shelf-stable products, such as nutrition bars, through the addition of inulin. The bifidogenic effects and stimulation of SCFA are meaningful in bars containing ≥3 g of inulin per serving, contributing to:

- Enhanced digestive wellness
- Support of the gut microbiome
- Improved glycemic management
- Increased satiety through SCFA-mediated pathways

These properties align with consumer interest in digestive health and microbiome-supporting functional foods.

Inulin is a well-established prebiotic. Consumption through bars can:

- Increase *Bifidobacterium* and certain butyrate-producing taxa
- Promote SCFA formation (acetate, propionate, butyrate)
- Improve colonic transit
- Support gut barrier function

Bars with 3–8 g of inulin per serving can typically deliver meaningful prebiotic benefits without excessive GI discomfort.

4.2 Glycemic Response

Inulin has a well-established role in modulating postprandial glycemic responses due to its biochemical resistance to digestion and absorption in the small intestine. Because inulin is composed of β-(2→1)-linked fructose units that humans lack the enzymes to hydrolyze, it passes through the upper gastrointestinal tract intact and therefore does not contribute to blood glucose or insulin secretion (Roberfroid, 2005). This makes inulin fundamentally different from digestible carbohydrates such as glucose, sucrose, or starch, and an ideal ingredient for formulating low-glycemic nutrition bars.

The quantity of jaggery used, the overall amount of carbohydrates, the overall amount of protein, the overall amount of fat (nuts and seeds), and the overall amount of fiber (inulin and flaxseed) will determine the net effect of the glycemic response of recipes containing jaggery or jaggery syrup (Rao and Singh, 2022). Therefore, the inulin may be used to reduce glycemic impacts of the bar but the inulin is not sufficient to make a jaggery-based bar a low glycemic one until the overall formulation is optimized and tested.

4.2.1. Low Glycemic Index and Absence of Postprandial Glucose Spikes

As inulin cannot be digested and absorbed in the small intestine like glucose, it does not contribute any meaningful amount of available carbohydrate and has a minimal direct effect on the postprandial blood glucose. Substituting sugars or rapid absorbable carbohydrates in foods with inulin would help a long way in lowering the total glycemic impact of the food (Niness, 1999). The replacement of digestible carbohydrates with inulin or oligofructose has been proven to inhibit the postprandial glucose and insulin response, and it is due to this fact that it can be used in diabetic-friendly preparations (Holloway et al., 2007).

Nutrition bars partially replacing sugars with inulin can therefore improve blood glucose control, especially when paired with proteins or fats that further slow glucose absorption.

4.2.2. Effects on Insulin Sensitivity and Glycemic Regulation

Inulin also has an insignificant direct effect on glucose metabolism, but may have a beneficial effect on insulin sensitivity due to its fermentation effect in the gut. Inulin can be fermented by the microbiota of the colon, producing short-chain fatty acids (SCFAs), especially propionate and butyrate, which have been associated with improved glucose homeostasis (Koh et al., 2016). Propionate could also regulate gluconeogenesis in the liver and butyrate could act as a barrier to gut integrity and decrease systemic inflammation, which could have indirect effects on insulin signaling.

Inulin supplementation has been found to decrease the levels of fasting glucose, fasting insulin and HOMA-IR in overweight or insulin resistant individuals in clinical trials (Guess et al., 2015). These effects seem to be dose-, duration-, and inulin-type dependent, with the long-chain inulin having greater metabolic effects than the short-chain oligofructose.

4.2.3. Modulation of Appetite and Postprandial Hormones

Inulin may also have an indirect effect on glycemic control by altering satiety hormones. The SCFAs activate the release of glucagon-like peptide-1 (GLP-1) and peptide YY (PYY) that increases insulin secretion, slows down gastric emptying and decreases appetite (Delzenne et al., 2011). Chronic inulin consumption has been shown to increase GLP-1 response, which may be beneficial for hunger, weight and postprandial glucose control.

The hormonal effects of inulin make it a great choice for nutrition bars targeting weight management or blood sugar support.

4.2.4. Implications for Nutrition Bar Development

The incorporation of inulin into nutrition bars supports the development of low-glycemic, high-fiber, and metabolic-health-oriented products. Replacing sugars or high-GI carbohydrates with inulin:

- Reduces postprandial glucose and insulin spikes
- Lowers the glycemic index (GI) of the final product
- Helps stabilize energy release
- Supports insulin sensitivity over time
- Enhances satiety through SCFA-mediated pathways

- Contributes fewer calories (1.5 kcal/g) than digestible carbohydrates

These properties align with consumer demand for foods that help regulate blood sugar, particularly among individuals with diabetes, prediabetes, or metabolic syndrome.

4.3 Impact on Satiety and Energy Intake

Inulin has been extensively studied with regard to its effects on satiety and total energy intake due to its fermentability, gastrointestinal hormone effects, and effects on gastric emptying. A functional ingredient with these properties that may be of interest for use in nutrition bars for weight loss, appetite control and metabolic health is inulin.

4.3.1. Enhanced Satiety via Gastrointestinal Hormones

A key way in which inulin contributes to satiety is by regulating gut-derived hormones that control appetite. Inulin is fermented in the colon to produce short-chain fatty acids (SCFAs) that activate enteroendocrine L-cells to release:

- Glucagon-like peptide-1 (GLP-1)
- Peptide YY (PYY)
- Oxyntomodulin

The combined effects of these hormones are to reduce gastric emptying, improve insulin secretion and increase the sensations of satiety (Delzenne et al., 2011). In human studies, chronic inulin-type fructan consumption produces a significant increase in postprandial GLP-1 and PYY levels, with resulting measurable appetite suppression. (Cani et al., 2007).

4.3.2. Reduction in Energy Intake

In fact several controlled clinical studies have shown that inulin or oligofructose, taken regularly, can result in a reduction in spontaneous energy intake. Cani et al. (2006) found a significant decrease in total daily caloric intake of 5–10% after 16 g/day of oligofructose for 2 weeks and increased satiety ratings. In another randomized trial, those who consumed 21 g/day of inulin-type fructans had lower hunger scores and decreased energy intake at the next meal (Liber & Szajewska, 2013).

These effects are due to:

- Higher levels of satiety signalling hormones
- Delayed gastric emptying
- Increased production of SCFAs which affect appetite pathways
- Modulation of appetite-related neural circuits via the gut–brain axis

4.3.3. Influence on Gastric Emptying and Digestion

Inulin is not broken down in the upper gastrointestinal tract, but it can affect gastric motility. Soluble fibre and the hormones induced by SCFA increase the viscosity of the stomach, thereby slowing down the rate of gastric emptying and thus prolonging the feeling of fullness after eating (Slavin & Green, 2007). This longer gastric residence time could contribute to weight management effects observed in intervention trials and decrease appetite.

4.3.4. Effects on Body Weight and Adiposity

Long-term consumption of inulin has been demonstrated to cause slight weight loss and a loss of adiposity, especially of visceral fat. When inulin was taken by overweight adults for 18 weeks, at 18 g/day, it caused a significant reduction in body weight, BMI and body fat percentage compared to the placebo group (Guess et al., 2015). These metabolic changes are paralleled by increased satiety and calorie intake, suggesting a role for inulin in weight-control programs.

4.3.5. Implications for Nutrition Bars

In the case of nutrition bars, inulin acts as a prebiotic that helps to promote feelings of fullness and control appetite in a few ways:

- Increases volume and fibre, which leads to increased gastric distention
- Increases release of postprandial GLP-1 and PYY
- Provides a balanced release of energy
- Helps prevent the "rebound hunger" that leads to increased food consumption and weight gain.
- Slows down stomach emptying, giving greater fullness

The fiber content, deceleration of the digestion process and the mechanisms of fermentation related to inulin may have a potential role in satiety; however, the extent to which this will occur will depend on the product-specific human study. This makes inulin an attractive addition to bars marketed for weight management, meal replacement, or appetite control.

Inulin, especially long-chain types, slows gastric emptying and increases satiety hormones (GLP-1, PYY). Nutrition bars enriched with inulin may:

- Reduce appetite
- Support weight management
- Enhance fullness compared to conventional bars

4.4 Digestive Tolerance

Inulin is a fermentable and osmotic component that may result in gastrointestinal (GI) side effects in sensitive individuals and, therefore, digestive tolerance is an important consideration when developing nutrition bars with inulin. The degree of polymerization (DP), dosage, and individual gut microbiota composition are major determinants of tolerance. It is important to know these factors to maximize consumer acceptance and to optimize the desired prebiotic and health effects.

Due to FODMAP sensitivity, consumers with IBS or FODMAP sensitivity may experience bloating, gas or abdominal discomfort with lower dosages of inulin, so it may be necessary to adapt to the product slowly or provide consumers with guidance.

4.4.1. Mechanisms of Gastrointestinal Symptoms

Inulin is indigestible in the small intestine but is quickly fermented in the colon to release hydrogen, methane and carbon dioxide. This can cause gastrointestinal problems such as bloating, flatulence, abdominal discomfort, and occasionally diarrhea (Roberfroid, 2007). The effects are common of fermentable fibers and are a physiological interaction with the gut microbiome.

Short-chain inulin (oligofructose) is more easily fermented than long-chain inulin, and is likely to be responsible for more acute gas production, while long-chain inulin is more slowly fermented and is generally better tolerated in the digestive system (Alles et al., 1996).

4.4.2. Dose-Dependent Tolerance

Inulin is digestively tolerated in a dose-dependent manner. In clinical trials, it has been consistently shown that doses of 5-10 g/day are well tolerated by most people, and symptoms are more likely at doses of 20 g/day or more. Gradual increases in intake allow adaptive changes in the microbiota and fermentation patterns, increasing tolerance.

Human trials demonstrate:

- ≤10 g/day: Generally well-tolerated
- 20–30 g/day: May experience mild GI symptoms
- ≥20 g/day: Increasing incidence of bloating, flatulence, and discomfort (Kolida & Gibson, 2007)

These thresholds are used to guide practical thresholds for nutrition bars, which are usually set at 3-8 g of inulin per serving.

4.4.3. Influence of Degree of Polymerization (DP)

The DP of inulin strongly influences tolerance.

- Short-chain inulin/oligofructose (DP < 10): Rapid fermentation → higher gas production → lower tolerance
- Long-chain inulin (DP ≥ 23): Slower fermentation → reduced gas accumulation → improved tolerance (Kruse et al., 1999)

Long-chain inulin is therefore preferable for high-fiber or prebiotic nutrition bars where minimizing gastrointestinal side effects is a priority.

4.4.4. Adaptation of the Gut Microbiota

Microbial adaptation is the basis for the development of tolerance to repeated ingestion. Inulin has been tested in humans, and it has been shown that chronic consumption of inulin for 1-2 weeks decreases gas production and discomfort, due to adaptation of the colonic bacteria to the increased substrate supply (Bouhnik et al, 2007). This adaptation is associated with higher levels of Bifidobacterium, which have more efficient inulin fermentation pathways with fewer gas-producing pathways than other taxa.

4.4.5. Interaction with other ingredients

Tolerance can be influenced by bar composition. The fermentation kinetics of inulin can be altered by co-ingestion with proteins, lipids or polyols. Polyols (sorbitol and xylitol) commonly found in low-sugar bars can also independently cause GI upset and may worsen symptoms when added to fermentable fibres (Grabitske & Slavin, 2009). Cumulative GI load is thus a factor to consider in formulating.

4.4.6. Practical Considerations for Nutrition Bar Formulation

To optimize tolerance, nutrition bar developers commonly:

- Use long-chain inulin for slow fermentation
- Limit inulin content to 3–8 g per bar
- Combine inulin with less fermentable fibers (e.g., soluble corn fiber)
- Avoid high levels of poorly tolerated polyols
- Provide intake guidance for consumers new to prebiotic fibers

These approaches allow bars to deliver prebiotic benefits while minimizing potential digestive discomfort.

Excessive inulin can cause GI symptoms:

- bloating
- flatulence
- abdominal discomfort

Inclusion levels of approximately 3–8 g per bar may be practical for balancing prebiotic benefit and digestive tolerance, but total daily intake from all fiber-containing foods should be considered, especially for individuals sensitive to fermentable carbohydrates.

5. Effects on Texture and Sensory Quality in Nutrition Bars

5.1 Texture Enhancement and Hardness Reduction in Plant-Based Protein Bars

Inulin contributes significantly to the textural quality of nutrition bars due to its unique physicochemical properties, which include its ability to form gels, bind water, and create fat-like mouthfeel. These characteristics make inulin a versatile functional ingredient used to improve product structure, stability, and sensory appeal without increasing caloric density.

One significant problem of plant-based protein bars is that concentrates of plant protein will tend to hydrate and form thick matrices, and produce dry, chalky or brittle textures (Table 1). The problem may be more intense with multi-source protein bars with chickpea, pea, rice, moong, and jackfruit seed protein concentrates because each of the protein sources has disparate hydration capacities, particle dynamics and interplay with syrup binding substances.

Table 1. Functional relevance of inulin in plant-based protein bar formulation

Functional aspect	Role of inulin	Relevance to plant-based protein bars	Expected formulation benefit	Citation
Moisture retention	Inulin binds water through hydroxyl groups and helps regulate water mobility in food matrices.	Plant protein concentrates can absorb water and contribute to dry or hard textures during storage.	Helps maintain softness and reduces storage-related hardness.	Mensink et al. (2015)
Texture and chewability	Inulin contributes bulking, gel formation, and fat-mimetic mouthfeel.	Useful in chickpea, pea, rice, moong, and jackfruit seed protein bars where dense texture may reduce acceptability.	Improves chewability, cohesiveness, and mouthfeel.	Franck (2002)
Protein–fiber interaction	Inulin can modify functional and textural properties of protein-based food systems.	Multi-source plant proteins may show complex hydration and binding behavior.	Supports a more cohesive matrix and may reduce brittleness.	Drakos et al. (2021)
Hardness control during storage	Protein bars commonly harden because of moisture migration, protein interactions, and formulation imbalance.	Plant-based bars may face similar or greater hardening due to protein concentrate behavior.	Provides a rationale for using inulin to reduce hardness and improve shelf-life texture.	Diaz et al., (2021)
Digestive tolerance	Inulin provides prebiotic benefits, but excessive intake may cause gas, bloating, or discomfort.	Inulin dosage must be optimized in high-protein, high-fiber bars.	Supports practical dosage selection while maintaining consumer tolerance.	Slavin & Feirtag (2011)

5.1.1. Gel-Forming Ability and Structural Support

Long-chain inulin has shown a strong tendency to gel in the form of microcrystalline networks when mixed with water and sheared. The gelation property can increase the firmness and cohesiveness of nutrition bars, which is important for the structure of the bars (Franck, 2002). Inulin gels are like fat because they produce small crystals that are dispersed in the gel and hold water in place, giving the gel a smooth and creamy consistency.

In nutrition bars, this property:

- Improves bar hardness and shape retention
- Prevents crumbling during processing and storage
- Enhances chewiness and bite consistency

The gel network also supports the incorporation of other functional ingredients such as proteins, nuts, and grains.

5.1.2. Fat-Mimetic Properties

The fat-replacement property of inulin has been well known, as inulin can form a creamy and lubricating mouthfeel which is comparable to lipids (Niness, 1999). Inulin can be used to replace part of the fat phase in bar formulations without compromising the desirable textural properties, even when using 5-10% inulin. Inulin has fat-mimetic effects such as:

- Improved smoothness and creaminess
- Enhanced palatability without added fat calories
- Better distribution of flavors and sweeteners

These properties support the development of reduced-calorie or low-fat bars without compromising sensory experience.

5.1.3. Water Binding and Moisture Retention

Inulin's high water-binding capacity enhances moisture retention, resulting in softer textures and improved shelf-life stability (Mensink et al., 2015). This is especially valuable in high-protein bars, which can harden over time due to protein–moisture interactions.

Inulin helps:

- Maintain softness over storage
- Reduce bar drying or hardening
- Improve chewability in low-moisture bars
- Stabilize texture across temperature fluctuations

This property makes inulin a preferred ingredient for extending the freshness of nutrition bars.

The reason for this is that inulin can be used to soften these vegetarian bar systems of hardness in 3 different ways: moisture retention, protein-fiber interaction and improved cohesiveness. It possesses hydroxyl network that allows it to hold water and reduce water flow and interaction with protein particles and syrup binders could give a more flexible and integrated structure. The effects can cause the storage to be less brittle and chewable.

5.1.4. Prevention of Sugar Crystallization

Inulin can interfere with sucrose crystallization due to its ability to bind water and alter the viscosity of the sugar matrix. This prevents gritty or grainy textures and contributes to a smoother mouthfeel in bars using syrups or reduced sugar systems (Richardson, 2019).

This is particularly relevant in:

- Reduced-sugar bars
- High-fiber bars
- Bars using polyols or alternative sweeteners

By preventing crystallization, inulin helps ensure homogenous texture and consistent bite quality.

5.1.5. Synergistic Interaction with Proteins and Polysaccharides

Inulin interacts synergistically with milk proteins, plant proteins, and other hydrocolloids, affecting texture and structural formation. Studies report that inulin enhances the rheological properties of protein matrices, increasing viscosity and improving deformation resistance.

In nutrition bars, this synergy:

- Enhances protein bar cohesiveness
- Reduces brittleness in high-protein formulations
- Supports gel formation and texture retention during storage

This makes inulin an especially valuable tool for formulating high-protein bars, which often struggle with undesirable hardness over time.

5.1.6. Implications for Nutrition Bar Development

Overall, inulin enhances texture in nutrition bars by:

- Acting as a fat mimetic
- Providing structural support via gelation
- Retaining moisture
- Reducing hardness over storage
- Improving creaminess and mouthfeel
- Preventing sugar crystallization
- Supporting cohesiveness in high-protein matrices

The properties allow product developers to make soft, stable and palatable bars with low sugar and fat content according to the consumer preference of healthier snacking products.Inulin improves texture through:

- Softening effect in high-protein bars
- Prevention of hardening during storage
- Increased cohesiveness and binding of particulates (nuts, seeds)

The degree of polymerization of inulin (long chain) is more likely to enhance chewiness and decrease brittleness. To this end, the incorporation of inulin into the vegetarian protein bars cannot be regarded as a typical fiber fortification approach but the process of the textural stability in question as well. Chickpea, pea, rice, moong and jackfruit seed protein concentrates can be incorporated in formulations to provide softness, improved bite quality and consumer acceptance in formulations compared to shelf life.

5.2 Flavor Modulation

Flavor modulation is required especially in the case of plant-based protein bars because pea, chickpea, moong, rice and jackfruit seed proteins may have a beany, earthy, bitter, or chalky taste. Inulin may also be employed to increase the release of sense of flavor and mouthfeel, other ingredients such as cardamom, jaggery, almonds, cashews and flax seeds may be employed to increase the sensory acceptability by balancing the sweetness, aroma, nuttiness and aftertaste.

Inulin contributes mild sweetness and flavor masking:

- Minimizes bitterness of plant proteins
- Reduces astringency in cocoa-based formulations
- Enhances creaminess and smooth flavor release

5.3 Shelf-Life Stability

Over time, many bars harden or dry. Inulin helps maintain shelf-life by:

- Retaining moisture
- Reducing crystallization in sugar-alcohol and protein blends
- Helping reduce storage-related hardening by improving moisture retention and limiting undesirable textural changes in protein–carbohydrate matrices.

Instrumental hardness, chewiness, water activity, moisture distribution, and sensory acceptability must be assessed with regard to shelf-life stability of jaggery syrup-and-protein bar in combination with various protein concentrates during storage (Ayatti, 2021). Inulin can also help to achieve a more successful stability but it will only be checked in the context of specific packaging, temperature and storage conditions.

6. Formulation Considerations for Plant-Based Protein Bar Manufacturers

6.1 Proposed Plant-Based Protein Bar Matrix

The realistic plant-based protein bar matrix may utilize the following sources of protein: chickpea, pea, rice, and moong, jackfruit seed protein concentrate. They may be combined with almonds, flaxseeds, cashews, cardamom, jaggery, salt, and water or jaggery syrup to improve binding, sweetness, flavor, addition of lipids and quality. In this matrix prebiotic fiber and texture modifying ingredient can be incorporated with inulin to improve the retention of moisture, improve the formation of hardness and improve the chewability.

6.2 Ideal Dosage

- For plant-based protein bars, an initial inulin range of approximately 3–8 g per serving may be more practical for balancing fiber enrichment, texture improvement, hardness reduction, and digestive tolerance.

6.3 Selecting Inulin Type

Small portions of inulin as short chains, or oligofructose may be useful when a light sweetness and solubility is needed, but may ferment more quickly and cause greater gastrointestinal distress in sensitive persons. Plant-based protein bars are more suited to long-chain inulin, in which case it is preferable to decrease hardness, enhance chewability, and perform as a fat-mimetic ingredient and preserve moisture. Sweetness, texture, prebiotic benefit, and digestive tolerance Blends of long and short-chain inulin might provide a trade-off between sweetness and texture and prebiotic effect and digestive tolerance.

6.4 Compatibility with Protein Ingredients

Protein–fiber interactions affect bar hardness. Inulin can mitigate hardening in bars containing:

- chickpea protein concentrate
- pea protein concentrate
- rice protein concentrate
- moong protein concentrate
- jackfruit seed protein concentrate
- It stabilizes protein matrices and reduces brittleness over time.

Hydration and textural behaviour Multi-source plant protein systems may exhibit complicated hydration and textural behaviour because of the variations between water absorption, particle size, solubility, and interaction with binders among every protein concentrate. Inulin may also help to improve the properties of such systems, including the capacity to withhold moisture, decrease brittle character, and improve the adhesion of protein particles, nuts, seeds and jaggery syrup.

6.5 Ingredient Interactions

The ingredients that can be used in the proposed plant-based bar matrix include almonds and cashews which can serve as sources of fat, flavor, and mouthfeel, flaxseed as they can serve as sources of fiber, lipids, binding support, cardamom as it may help to impart aroma and mask plant-protein off-notes, jaggery or jaggery syrup as it may be a source of sweetness.

Inulin performs well with:

- polyols (erythritol, maltitol)
- glycerin
- nut butters
- chocolate/compound coatings

It may interact unfavorably with:

- high-moisture fruit purees (may increase stickiness)
- high-acid ingredients (partial hydrolysis may occur)

7. Consumer and Regulatory Considerations

7.1 Fiber and Prebiotic Claims

In many regions (EU, US), inulin qualifies as dietary fiber and permits labeling claims such as:

Depending on the local laws and the quantity of supporting evidence, inulin-based bars may become the subject of dietary fiber-related claims. However, prebiotic and digestive-health claims should be restricted to such instances, where it is permitted by local labeling authorities and with the required scientific support.

7.2 Clean Label and Plant-Based Marketing

A bar formulated with chickpea, pea, rice, moong, and jackfruit seed protein concentrates, along with almonds, flaxseed, cashews, cardamom, jaggery, salt, and inulin, may support plant-based and clean-label positioning. However, claims such as “high protein,” “high fiber,” “prebiotic,” “low glycemic,” or “digestive health supporting” should be made only after confirming nutrient composition, inulin dose, glycemic impact, and applicable regulatory requirements.

Inulin is plant-derived and aligns with trends toward:

- natural ingredients
- plant-based bars
- reduced-sugar products
- high-fiber wellness snacks

7.3 Sensory Acceptance

Consumer studies show positive reactions to inulin-enriched bars due to:

- improved texture
- mild sweetness
- perception of health benefits

Excessive inulin, however, may lead to negative feedback if digestive discomfort occurs.

8. Limitations and Challenges

8.1. Gastrointestinal (GI) Tolerance Issues

One of the most significant limitations:

- Symptoms are dose-dependent; intolerance often appears above 5–10 g/day in sensitive individuals.
- People with IBS (Irritable Bowel Syndrome) may experience stronger reactions because inulin is a FODMAP (fermentable carbohydrate).

8.2. Limited Heat and Processing Stability

- Inulin can break down at high temperatures (typically above 135–150°C), affecting sweetness and functional behavior.
- High shear processing can degrade long-chain inulin into shorter fructo-oligosaccharides (FOS), reducing:
    - fiber content
    - bulking ability
    - fat-mimicking texture

8.3. Off-Flavor & Masking Challenges

While inulin is mildly sweet, large quantities may create:

- a slightly chalky mouthfeel
- beany or nutty aftertastes, especially in plant-based products
- possible flavor interactions with proteins (e.g., pea, whey)

Formulators often need additional flavor maskers.

8.4. Solubility Limits

- Cold-water solubility is moderate; high concentrations can cause:
    - grittiness
    - poor dispersion
    - sedimentation
- Short-chain inulin is more soluble but produces more GI issues.

8.5. Hygroscopicity & Stability in Storage

- Inulin absorbs moisture easily, which can lead to:
    - clumping
    - reduced flowability
    - textural changes in finished products (e.g., bars getting softer over time)

Proper packaging and moisture control are required.

8.6. Compatibility Issues in High-Protein Formulations

Inulin interacts with certain proteins, which can lead to:

- Hardening of protein bars over shelf life (water migration)
- Unwanted increases in viscosity in shakes
- Reduced stability in dairy alternatives

8.7. Variable Sweetness and Functionality

- Inulin-type fructans are less sweet than sucrose, with sweetness varying according to degree of polymerization. Short-chain fractions contribute more sweetness, while long-chain inulin contributes little sweetness and mainly supports bulk and texture.
- Replacing sugar completely often leads to:
    - poor taste
    - weaker structure
    - reduced browning
- Requires combination with other sweeteners (stevia, allulose, etc.).

8.8. Cost and Supply Chain Sensitivity

- Price depends on crops like chicory root, Jerusalem artichoke, and agave.
- Weather conditions and regional supply disruptions can increase cost.
- Organic inulin is more expensive and less widely available.

8.9. Regulatory Limits in Some Markets

- Some countries restrict how inulin can be labeled as fiber or a prebiotic.
- Health claims vary by region (EU vs. US vs. Asia), complicating product development.

8.10 Plant-Based Protein Bar-Specific Challenges

There may be some formulation challenges with the inulin-based multi-source plant-based protein bars. Chickpea, pea, rice, moong, jackfruit seed protein concentrates may differ in their hydration behavior, flavor profile, particle size and their response with jaggery syrup. Large amounts of inulin may make it stickier or can be digestively uncomfortable and low amounts may not aid in making food harder or easier to chew. Therefore, there should be an optimization of formulation to balance the texture, taste, degree of protein, degree of fiber, shelf life stability and consumer tolerance.

9. Future Research Directions

The method of improving the shape and dosage of inulin to incorporate in multi-source plant protein bar to ensure it is not firm during storage without affecting chewability, sensory and digestive tolerance needs further research. Special attention should be paid to recipes with chickpea, pea, rice, moong and jackfruit seed protein concentrates as these vegetable proteins may be different regarding their ability to absorb water, protein fiber interaction as well as their contribution to end bar texture.

Further research needs to evaluate the interaction of inulin with practical formulation ingredients (almonds, flax, cashews, cardamom, jaggery, salt and water or jaggery syrup). Instrumental analyses such as hardness, chewiness, cohesiveness, water activity, moisture retention and shelf-life stability should be used to determine consumer acceptability to accompany sensory evaluation.

Human trials are also needed to assess the digestive tolerance, satiety, glycemic response, and effects of microbiomes in association with inulin-enriched plant-based protein bars. Such a study would help to identify the most appropriate incorporation levels of inulin that would be both functional and would not cause any gastrointestinal discomfort.

10. Conclusion

Inulin as a multifunctional ingredient in nutrition bars has a great potential because of its dietary fiber provision, prebiotic properties, sweet mildness, ability to retain moisture, increased cohesiveness and textual stability. Its application could become especially helpful in entirely vegetarian protein bars that are produced with the help of chickpea, pea, rice, moong, and jackfruit seed protein concentrates, and hardness, dryness, brittle properties, and low chewability may be some limitations to the acceptance of the product by the users. Such matrices may be used in which a reduction in hardening caused by storage of water or interaction of proteins and fibres or increased cohesion of the matrix can occur with the use of inulin. Practical formulation should consider the nature and quantity of inulin, overall fiber content, the digestive tolerance, sweetness requirements, the interactions found between the inulin and other ingredients (almonds, flax, cashews, cardamom, jaggery, salt, water or jaggery syrup). An appropriate point of departure may be an inclusion range of 3-8 g/serving but they should be tested on products. Future research should aim to optimize inulin content of multi-source plant protein bars to reduce hardness during storage without reducing chewability, sensory acceptability and digestive tolerance.

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