Development of Jackfruit *(Artocarpus heterophyllus)* pulp filled Dark Chocolates: A Natural, Dairy-Free Alternative for Lactose Intolerant Diet

Ruchita Shah[1], *Mansi Manoj Kulgod[2], Dr. Lokesh AC[3]

1: - M.Sc student, Department of Food Technology, Faculty of Life and Allied Health Sciences, Ramaiah University of Applied Sciences, Bengaluru, 560054

**2: - Ph.D. Scholar, Department of Food Technology, Faculty of Life and Allied Health Sciences, Ramaiah University of Applied Sciences, Bengaluru, 560054*

(Corresponding author)

3: - Professor, Department of Food Technology, Faculty of Life and Allied Health Sciences, Ramaiah University of Applied Sciences, Bengaluru, 560054

Abstract

Lactose intolerance is defined as a medical condition resulting from a lack of brush-border beta-galactosidase (lactase), which is a prevalent problem among about 68% of the world's adults, thus leading to a marked industrial revolution in the form of producing functional dairy-free confectionery products. Even though regular dark chocolates are intrinsically plant lipids, production of high-quality filled dark chocolates using tropical fruit pulps can be termed an innovation. The mature jackfruit pericarp is rich in nutrients, including high amounts of reducing sugars (fructose and glucose), easily absorbable electrolytes (mainly potassium up to 407 mg/100 g and magnesium from 27 to 37 mg/100 g) and active jackfruit pulp polysaccharides (JFP-Ps). Dark chocolate filled with jackfruit pulp goes beyond being just an alternative to dairy products by acting as a form of therapy for the digestive system. Dark chocolates that are filled with jackfruit pulp act as targeted prebiotics that prevent fast and rapid gas production due to colonic fermentation of hydrogen and methane caused by lactose intolerance. Instead, the fibers are broken down slowly by microbes, leading to increased levels of beneficial bacteria (Lactobacillus and Bifidobacterium) and SCFAs, primarily butyrate. The SCFAs then decrease mucosal inflammation in the gut, increase the expression of ZO-1 and occludin proteins, and lower colonic pH to facilitate calcium and magnesium absorption.

Keywords: Jackfruit pulp, dark chocolate, lactose intolerance, dairy free confectionaries, functional foods

1. Introduction

The world of confectionery is undergoing a two-fold paradigm change – a shift to preventive health care, and a growing appetite for ethical and plant-based options (Swinburn *et al.,* 2019). The prevalence of lactose intolerance is around 68% in global adults, so the global lactose-free market is matured to a great extent as of 2026 (Storhaug *et al.,* 2017). It is a physiological defect that causes a lack of the lactase enzyme, which makes it impossible to break down the lactose into glucose and galactose, and this lack of this enzyme has become a major factor in food innovation. To counter this, the plant-based chocolate market is expected to have a compound annual growth rate (CAGR) of 12.6% and will be valued at US$ 1.3 billion by 2026 until 2033 (Muñoz-Martínez *et al.,* 2025).

Dark chocolate is vegan by itself, but high quality confectionery is frequently filled with "filled" chocolate (usually in the form of pralines or ganaches) that contain dairy fats and milk solids, which are not vegan, to texture and flavor the chocolate. The problem for contemporary food technologists is to substitute other matrices for the milk used in these formulated dark chocolate products, while maintaining the sensory "snap" and "melt in the mouth" characteristics of the dark chocolate shell while increasing the nutrient and fiber content (Ahiduzzaman *et al.,* 2024). Jackfruit (*Artocarpus heterophyllus*) has thus become a strong contender in this respect. Jackfruit is now considered as an “underutilized tropical fruit” due to its high carbohydrate content (16.0–25.4 g/100g) and dietary fibre content (1.0–1.5 g/100g in ripe fruit) which provides natural bulking and sweetening properties (Ranasinghe *et al.,* 2019).

Preliminary comparative research with traditional cocoa has indicated potential synergism between some of the jackfruit components and some of the traditional cocoa components, such as the cocoa aroma-mimetic, roasted jackfruit seed powder, which has been evaluated to be a functional aroma-mimetic for cocoa because of its similarity in development of pyrazine (Gupta *et al.,* 2023). The use of ripe jackfruit pulp as a filler, however, offers a definite benefit: high levels of phytochemicals such as carotenoids, flavonoids and phenolic acids that give the chocolate antioxidant and anti-inflammatory properties (Zahid *et al.,* 2024). Additionally, the natural potassium content of the jackfruit pulp (up to 407mg/100g) and low sodium levels are in sync with today's trend towards ‘clean labels' and provide a natural, tasty and healthy indulgence for cardiovascular health (Swami *et al.,* 2012).

This review aims to systematically assess the incorporation of jackfruit pulp in the dark chocolate system by lactose-intolerant population. It discusses the techno-functional issues including moisture migration and enzymatic browning and the opportunities for jackfruit to become a functional food product of high quality for the confectionery industry (Wani *et al*., 2022)

2. Lactose intolerance: An overview

2.1: Pathophysiology and biochemical mechanism

Lactose intolerance is not a discrete disease entity but rather a clinical state that is associated with a deficiency in the enzyme that breaks the disaccharide lactose ($C_{12}H_{22}O_{11}$) into its absorbable monosaccharides, glucose and galactose (Misselwitz *et al.,* 2019). This usually occurs in the presence of the brush border enzyme beta galactosidase (lactase) in the villi of the small intestine (Jansson-Knodell *et al.,* 2020).

In the absence of lactase activity, lactose stays in the bowel lumen and causes an osmotic gradient that attracts water and electrolytes to the bowel. As the lactose enters the colon, it is broken down by resident microbiota, mainly species of *Bifidobacterium* and *Lactobacillus*, to short-chain fatty acids (SCFAs) and gases, such as hydrogen, carbon dioxide and methane. The characteristic clinical symptoms – abdominal distention, flatulence, osmotic diarrhoea – are caused by these metabolic end products (Toca *et al.,* 2022).

2.2 Classification of lactase deficiency

According to the modern clinical literature, the cause of lactose malabsorption can be divided into four categories:

a. Primary lactase deficiency:

The most frequently seen form is when lactase activity decreases after weaning. It is a genetically programmed and affects ~65-70% of the global population (Swallow, 2003).

b. Secondary lactase deficiency:

A temporary state that is caused by the damage of the mucosa of the small intestines. These can be caused by a variety of illnesses such as Celiac disease, Crohn's disease or acute viral gastroenteritis. Based on research done by Quigley (2025), secondary intolerance is now believed to be associated with Small Intestinal Bacterial Overgrowth (SIBO).

c. Congenital lactase deficiency:

A rare, inherited condition in which babies are born with no enzyme to digest the lactose. New research on the genome has identified which parts of the LCT gene are responsible (Wanes *et al.,* 2019).

d. Developmental lactase deficiency:

Occurs in premature babies (those born before 34 weeks) who don't have an adequate amount of lactase-producing cells in their digestive systems (Heine *et al.,* 2017).

2.3. Diagnostic advancements

The gold standard for diagnosis is the Hydrogen Breath Test (HBT), but other methods have appeared that increase the accuracy of diagnosis:

a. Genetic screening:

Polymorphism testing in the MCM6 gene in order to differentiate between secondary and primary deficiency (Coluccia *et al.,* 2019).

b. Direct-to-customer kits:

The prevalence of home microbiome as well as genetic kits has risen, thus increasing self-diagnosis and fueling expansion of the US $ 14.8 billion lactose-free market (Sawant, 2026)

c. Continuous glucose monitoring (CGM) integration:

CGM is also being investigated in experimental settings as a non-invasive diagnostic tool, looking at the absence of a glucose spike after lactose administration (Di Filippo, 2022).

3. Dairy alternatives: Current status

3.1. Consumer demographics and market evolution

The dairy alternatives market is not just a “dietary niche” anymore and is projected to reach a value of US $ 32.66 billion by 2026, growing at a CAGR of 10.89%, and is expected to reach US$ 91.11 billion by 2035 (Business research insights, 2026).

This increase is largely driven by three factors: rising clinical recognition of lactose intolerance, growing flexitarian eating habits and a growing emphasis on environmental sustainability (Silva *et al.,* 2026).

In Asia-Pacific, high lactase non-persistence rates and a growing middle class with a craving for health-conscious 'clean-label' products made this region the largest in 2025. The North American market is on the other hand, the most innovative and premiumized, particularly with regard to hybridized dairy-plant blends and precision-fermented substitutes (McClements & Kaplan, 2026).

3.2. Plant-based milk alternatives (PBMAs)

a. Legume-based:

Soy milk continues to be the most popular because it has good protein content and calcium levels, best resembling those of bovine milk (Vanga & Raghavan, 2018). Legume milks are known for their high protein content of globular storage proteins, 11S glycinin and 7S beta-conglycinin. Legume milks are complex fractions which naturally provide a dense protein payload of 3.2 – 3.5% which is comparable to the amino acid profiling and structural density of casein micelles (Battisti *et al.,* 2021).

b. Nut-based:

Almond milk is expected to account for 25% of the market in 2026, preferred due to its low calorie and rich Vitamin E (Pointke *et al.,* 2022). Nut milks are oil-in-water emulsions, where the intrinsic amphiphilic proteins, such as amandin, stabilize the emulsion together with the native phospholipids. Almond milk is made up of lipid droplets, tiny oil particles that are suspended in the water, and are packed with monounsaturated oleic acid and polyunsaturated linoleic acid with a thin layer of protective proteins (Devnani *et al.,* 2020).

c. Cereal-based:

The most rapid adoption has been for oat milk, which is known for its excellent creaminess and 'frothing' properties in specialty coffee applications, since 2020 (Zakidou *et al.,* 2024). The secret of cereal milks is the intentional and controlled breakdown of the complex carbohydrates. Food-grade enzymes – alpha and beta-amylase enzymes are used in processors to convert the tough raw starches present in the oat into shorter chains of maltose, giving a tender, pure sweetness without the taste of table sugars added (Babolanimogadam *et al.,* 2022).

d. Seed-based:

New alternatives consist of hemp, flaxseed and sesame, which contain high levels of omega-3 fatty acids (Wroniak *et al.,* 2021). Seed milks are an excellent source of nutrients, they're naturally rich in polyunsaturated fatty acids (PUFAs) namely alpha-linolenic acid (Omega-3) and linoleic acid (Omega-6). The protein fractions (e.g., edestin in hemp) are very digestible and are very uncommon causes of food allergies (Beriziky *et al.,* 2023).

e. Pseudo-cereal based:

In its quest to provide nourishment for a gluten-free diet, quinoa milk and buckwheat milk are emerging (Zhang *et al.,* 2025). Pseudo-cereals are totally gluten-free and have an extremely well-rounded nutritional profile. They are rich in proteins possessing essential amino acids, such as lysine and sulfur containing amino acids, often lacking in traditional grains, such as wheat or rice (Vajdovich *et al.,* 2025).

4. Jackfruit: Nutritional and functional properties

Artocarpus heterophyllus products have become a sophisticated international trade with a presence in the global market beyond the subsistence level. At the end of the 2025 base year, the global jackfruit market is estimated to be worth USD 362.51 million (Nansereko & Muyonga, 2021). Overall, the category is expected to swell to USD 493.21 million by 2034, growing at a steady Compound Annual

Growth Rate (CAGR) of 3.48% to 5.22%, driven by the structural shift in the flexitarian consumer population as well as a significant decline in consumer sentiment towards over-engineered, ultra-processed plant isolates (Aschemann-Witzel *et al.,* 2020).

4.1. Proximate composition and energy density

The ripe pulp of jackfruit (*Artocarpus heterophyllus*) is a complex matrix, with the major component being water (70–80%), but its energy content is still quite high relative to other tropical fruits (Waghmare *et al.,* 2019).

This high moisture content does not result in any significant decrease in the energy density of the fruit, which is about 84–95 kcal/100 gm. It is significantly higher than several other tropical fruits, including pineapple or watermelon and is due mainly to the high amount of carbohydrates it contains, from 16.0% to 25.4% for the ripe fruit (Srivastava & Singh, 2020).

The latest proximate analyses of the edible tissues show that:

a. Carbohydrates:

The growth process of jackfruit from young to mature is a physiological change. Structural fibre and protopectins are the predominant carbohydrates of tender (unripe) jackfruit. These starches are rapidly converted into free sugars by the intrinsic enzymes (such as acid and neutral invertases) during their ripening (Durán-Soria *et al.,* 2020).

The sugar content per 100 gm usually ranges from 16 gm to 25.4 gm, mostly sucrose, glucose and fructose when it comes to ripe fruit pulp (Lin *et al.,* 2022). According to Nwafor *et al.* (2017), a mature ripe pulp has a carbohydrate content of 6.90 gm per 100gm.

b. Dietary fibre:

Contains 1.0g–1.5g per 100g of crude fibre. The large proportion of soluble to insoluble fibre is an important functional property for chocolate filling as it results in the "jam-like" viscosity without the necessity of high levels of supplemental pectins (Brahma & Ray, 2023). This was in line with studies done by Rinshana (2025) who reported the equivalent values of the mature ripe jackfruit pulp. This confirms that enzymes in the fruit will soften as the fruit itself becomes mature. This lower level of structural fibre is extremely advantageous for the chocolate production process because the pulp can be easily ground to a silky texture, without the need for vigorous mechanical grinding.

c. Proteins:

Comprises of 1.2 gm to 1.9 gm per 100 gm, which is significantly higher than most of the commercial fruit fillers (Jagtap *et al.,* 2010). Studies done by Sarangi *et al.* (2023) highlighted the protein percentage in the non-edible parts to be around 6% to 10.6% along with heavy crude fibre arrays. Advanced internal hydrolysis in soft varieties breaks down proteins and complex pectins into simple soluble monomers, which makes them more fluid but less resistant to structural stresses during manufacture of products.

d. Potassium (K):

Highest recorded levels are as high as 2880 mg/100g in certain cultivars. This is because of the high potassium content that can decrease the sodium that is present in processed confectionery, which can help regulate blood pressure (Amadi *et al.,* 2026).

c. <u>Vitamin C and B-complex</u>:

It is a major source of ascorbic acid (7–14 mg/100g) and is one of the few fruits with a high content of pyridoxine (B6), niacin and riboflavin. These vitamins play important metabolic co-enzyme roles in lactose intolerant people, where food may be limited in variety (Goswami & Chakrabarti, 2016).

4.2. Phytochemicals and antioxidant capacity

Ripe jackfruit is rich in a wide range of phenolic compounds which have high radical scavenging activity (FRAP and DPPH assays).

a. <u>Flavonoids and carotenoids</u>:

The composition of flavonoids in mature jackfruit pulp is dominated by certain flavan-3-ols and flavonols, including catechin, epicatechin, rutin, and quercetin (Lalruatdiki *et al.,* 2026). On a health level, these molecules are a huge asset to the consumer who has to deal with food intolerances or metabolic sensitivities. Quercetin and rutin are natural inhibitors of alpha-glucosidase and alpha-amylase enzymes in the small intestine. These flavonoids help to moderate the quick rise and fall of blood glucose after eating, which makes them useful to even out blood sugar levels. It makes the filling made of jackfruit a great low-glycemic substitute for regular chocolate cream or fondants, which are rich in corn syrup (Patil *et al.,* 2023).

The unique yellow-orange colour of pulp is due to the presence of beta carotene, lutein and zeaxanthin. These pigments are absorbed by the lipids and are therefore very soluble in cocoa butter, the fat of dark chocolate (Gamage & Ratnayake, 2026). The carotenoids are very hydrophobic and so possess very different properties to the water soluble phenolics. The molecules naturally get aligned in the interface between the jackfruit core and the dark chocolate shell, smoothly fitting within the continuous cocoa butter fat phase (Ostolska & Zbikowska, 2024).

b. <u>Phenolic acids</u>:

Gallic acid, ferulic acid and tannic acid are some major acids found. The compounds' research from 2024 noted inhibition of alpha-glucosidase, which may help to delay or moderate the glycemic response of the chocolate treat (Zahid *et al.,* 2024).

The primary low molecular weight phenolic anchor in the pulp is gallic acid (3,4,5-trihydroxybenzoic acid). It also has an excellent solubility in water, which enables it to blend uniformly with the concentrated fruit juices (Ansari *et al.,* 2024).

Part of the ferulic acid is attached to the cellulose fibres of the cell walls. Homogenization or ball milling the pulp, these bound structures are mechanically "unlocked" and the overall level of protective and active plant compounds present in the finished chocolate filling is elevated (Kim *et al.,* 2026).

c. <u>Antioxidant assay</u>

DPPH (2,2-diphenyl-1-picrylhydrazyl): The DPPH assay is used to assess the hydrogen donating ability of the antioxidants in the pulp and their ability to convert the violet-colored DPPH radical to a stable yellow diamagnetic molecule. The DPPH scavenging efficiency of ripe jackfruit pulp is always high, and its half-maximal inhibitory concentration (IC_{50}) varies from 1.2 to mg/mL as a function of the solvent used for extraction. This high reactivity will help the filling to neutralize the free radical chain reactions at a very early stage (Ma *et al.,* 2022).

FRAP (Ferric Reducing Antioxidant Power): The electron donating capacity of the pulp under acidic conditions is measured by the FRAP assay. The antioxidants in the jackfruit convert a colourless ferric form into intense blue ferrous form. The high FRAP values obtained for mature pulp indicate that the phenolics in it have high ability to break down ROS by single electron transfer reaction (Kotha *et al.,* 2022).

4.3. Functional properties for chocolate manufacturing

a. Water holding capacity:

The pulp has a high WHC, essential to avoid "syneresis" (leakage) within the dark chocolate's shell (Mani, 2018). This high ability is because of the many types of structural polysaccharides present in the walls of this fruit, cellulose and hemicellulose. The chains of these polysaccharides have numerous hydrophilic –OH group sites that form hydrogen bonds with the water molecules around them. The process allows for the movement of water from a free state to a bound state (Jiang *et al.,* 2024).

b. Pectin and gelling behaviour:

Natural pectin (approx. 0.8–1.2%) is present in jackfruit. This can be used during the formulation of the chocolate filling to produce a "shelf stable" filling that doesn't allow the chocolate to migrate moisture from the filling to the chocolate shell (Jacqueline *et al.,* 2024). The self-gelling phenomenon is responsible for providing the ideal thixotropic qualities during the mechanized production process. In its resting state inside the industrial hopper, the pectin complex forms a firm gel matrix with high yield stress. This ensures that no premature oozing of the filling takes place. Upon the introduction of pressure from the pumps of the mechanized system, there is a temporary breakdown of the relatively weaker calcium–pectin bond. This causes the fluidity of the material to increase instantly, facilitating easy passage of the material through the narrow nozzles and depositing it inside the already formed chocolate molds without any obstruction (Gholamipour-Shirazi *et al.,* 2020).

c. Thermal stability:

Chocolate enrobing adds a very small amount of heat to the product, which is not enough to destroy the antioxidant activity of the jackfruit pulp (JFP) due to its relative thermo-stability (Owori *et al* 2022). Such thermal stability is a major strength from a technological perspective. In comparison to dairy-filled cream, which has a high propensity for deterioration or flavor changes due to exposure to the heat of processing, the phenolic compounds found in the jack fruit maintain their heat stability. Once they are incorporated into the praline formulation, they act as an ongoing antioxidant shield that inhibits oxidation of the surrounding cocoa butter by oxygen radicals (Lombardi, 2025)

4.4. Prebiotic effect

a. Stimulation of beneficial genera: The jackfruit pulp polysaccharides are used as selective substrates for *Lactobacillus* and *Bifidobacterium*. The jackfruit fibres undergo fermentation by these bacteria, resulting in a marked enhancement of their abundance (Hu *et al.,* 2026).

b. Pathogen inhibition: In contrast, polysaccharides of this kind have been reported to down-regulate pro-inflammatory microbial groups including *Akkermansia* and *Desulfovibrio,* which are frequently higher in gut dysbiosis (Zhu *et al.,* 2022).

c. <u>Metabolic cross-feeding</u>: Acetate, along with lactic acid, is produced as a result of the first stage breakdown of JFP-Ps by B*ifidobacteria*, in large amounts. It does not build up inside the colon; instead, it is immediately taken up by another group of good bacteria that produces butyrate, such as *Faecalibacterium prausnitzii* and *Eubacterium rectale*. These bacteria use the acetate along with their own metabolic waste through an enzymatic reaction known as butyryl-CoA: acetate CoA-transferase, thus resulting in increased butyrate production (Zhao *et al.,* 2024).

d. <u>Probiotic proliferation</u>: There is an evident rise in the number of *Lactobacillaceae*. These bacteria utilize soluble polysaccharides to produce organic acids which ultimately help lower the pH value of the colon resulting in conditions which inhibit the growth of acid-intolerant harmful pathogens such as *E.coli* and *Salmonella enterica* (Gao *et al.,* 2025).

4.5 Enhancement of short-chain fatty acids and intestinal barrier repair

The fermentation of jackfruit pulp by gut microbiota produces important metabolites called short-chain fatty acids such as propionate, acetate and butyrate (Wu *et al.,* 2025).

a. <u>pH modulation</u>:

SCFAs which are produced, lower the luminal pH of the colon. The acidic atmosphere prevents the development of pH reactive pathogens and also helps in the digestion of minerals such as calcium and magnesium, which are often deficient in lactose-intolerant individuals who avoid dairy products (Azad *et al*., 2020).

b. <u>Tight junction proteins</u>:

The polysaccharides from jackfruit have been reported to upregulate the expression of occludin and zonula occludens-1 (ZO-1), the "glue" that keeps cells in the intestine together (Zeng *et al.,* 2024).

c. <u>Mitigation of oxidative stress damages</u>:

Although SCFAs enhance protein synthesis, the phytochemicals in jackfruits concentrate within the enterocyte membrane, wherein they counteract the ROS generated locally due to inflammation. This, in turn, prevents oxidative damage to the microvillar membrane, which could otherwise cause damage to the existing tight junctions (Villarreal-Silva *et al.,* 2021).

d. <u>Mucosal layer integrity</u>:

Polysaccharides of jackfruit pulp increase the thickness of mucus layer. This gives a biological "shield" against further inflammation for a lactose-intolerant person, whose gut may be chronically inflamed by accidental ingestion of lactose (He *et al.,* 2026).

5. Applications in dairy-free products

5.1. Rheological studies

Mouth feel depends on the yield stress and plastic viscosity of both the shell and the core.

a. <u>Yield stress</u>:

Minimum stress required to make the substance start flowing. High yield stress design will ensure that the center of the jackfruit does not move inside the chocolate casing while shipping (Chen *et al.,* 2026).

b. <u>Viscosity reduction</u>:

Due to shear stresses created during chewing, the pulp's viscosity drastically reduces. This makes it easier for the tongue to be covered by the taste molecules, resulting in an experience of "melting" similar to that of dairy fats (Liu *et al.,* 2026).

c. Thixotropic behavior:

Jackfruit pulp exhibits pseudoplastic (shear thinning) behavior. After the consumer chews the chocolate, the force exerted helps in flowing smoothly, mimicking the meltability of a dairy ganache (Medina-Torres *et al.,* 2020).

d. Fibre-lipid interaction:

Insoluble fibers found in the jackfruit serve as a matrix for its structure. In their combination with dark chocolate, these insoluble fibers are capable of interfering with the fat crystal structure of cocoa butter. According to recent findings of research carried out in 2026, it is necessary to use emulsifiers such as lecithin at 0.5% and PGPR (Marappan *et al.,* 2025).

e. Starch-lipid complexes:

As the chocolate filler is developed, the starch granules are able to interact with cocoa butter to form complexes. This results in a scaffold structure that enables the stabilization of the emulsion without any artificial emulsifiers (Naseer *et al.,* 2025).

5.2. Texturizer and whole-food filler in confectionery

The incorporation of ripe jackfruit pulp into the dairy-free confectionery matrices, such as the replacement of dairy fats, fluid cream ganache and fondants, is a current topic of interest in food modification (Lončarević *et al.,* 2022). The primary technical challenge in developing dairy-free alternatives to pralines and filled dark chocolates is the elimination of milk creams, which are often used as plasticizers, rheology modifiers and flavor carriers and are derived from bovine sources (Subramaniam, 2016).

Ripe jackfruit pulp is rich in a high concentration of soluble sugar matrix, which are naturally existing in the fruit as a mixture of sucrose, glucose and fructose along with intrinsic heteropolysaccharides (pectin and hemicelluloses). The research also shows that vacuum-evaporated jackfruit concentrate (between 65 –72 Brix) can effectively be used as a pseudo-plastic structural network without the need of a second chemical bodying agent in dark chocolate shells (Tiwari *et al.,* 2016).

The vacuum processed gel is a stable hydrogel formed by the natural pectins in the pulp (0.8–1.2% by weight). This hydrogel is very good at absorbing free water molecules which lowers the inside vapour pressure of the core. An important parameter to reduce interfacial syneresis and to prevent degradation of adjacent crystals of triacylglycerols (TGs) in cocoa butter (Kaur *et al.,* 2023). Additionally, the natural tartaric, malic and citric organic acids present in the pulp lower the micro-pH to approximately 4.8 – 5.3, which creates an unfavorable electrochemical environment for the survival of common confectionery spoilage organisms, while at the same time delivering a clean rounding out of the rich, bitter flavor of dark cacao (Pinkaew *et al.,* 2024).

5.3. Jackfruit seed powder as a hydrophobic emulsifier and cocoa powder mimic

The engineering properties of jackfruit seed flour (JSF) are very high functional density filling properties. Processed jackfruit seed flour is made up of 60-65% starch and 3.5-4.5% proteins which has a uniquely balanced amino acid profile (Spada *et al.,* 2017). Roasted jackfruit seed powder forms high levels of volatile pyrazines, strecker aldehydes and sulfur-containing esters when subjected to solid-state fermentation under aerobic and anaerobic conditions, similar to those used for cocoa beans during traditional processing. Such compounds faithfully replicate the sensory "top-notes" and aromas of true processed cacao (Teo *et al.,* 2024).

Roasted jackfruit seed flour has been used in a dairy-free chocolate formulation to replace 10-30% of raw cocoa powder without compromising of the proximate composition, hardness, and plastic viscosity measure of the chocolate product matrix (Molu *et al.,* 2021).

Importantly, the protein isolates obtained from jackfruit seeds have excellent interfacial surface activity and amphiphilic properties, which is vital for the production of lactose-free and vegan confectionery. They are capable of stabilising plant-fat droplets in continuous aqueous streams, without the need for animal-derived sodium caseinate or chemically modified soy lecithins, just as they act as natural clean label emulsifiers (Ma & Chen, 2023).

5.4. Unripe jackfruit as a macromolecular scaffold in structural meat analogues and hybrid milk

Unripe jackfruit has a very tight, hard, and insoluble matrix made of cellulose and cross-linked protopectins. This material produces a cohesive, very fibrous, meat-like consistency when cooked (Yi *et al.,* 2024).

In recent times, there has been a shift towards the development of structural hybrids of highly concentrated globular plant protein isolates like pea protein isolate (PPI) and soy protein concentrates with texturized young jackfruit (Bee Chi, 2025). The percentage of young jackfruit fiber in vegetable protein matrix is around 35% and forms an interactive web at microstructural level. This combination aligns under high shear to provide correct prediction of tensile properties, elastic chew and juice retention of animal tissue (da Silva *et al.,* 2024).

In addition, these cell-wall polysaccharides are also good low-calorie fat mimetics and stabilizers due to their high water-holding capacities (WHC) and oil-holding capacities (OHC). This assists in controlling the structure of a thick, spoonable cream, cultured yogurt and non-dairy cheese analogues (Benvenutti *et al.,* 2025).

6. Relevance to lactose intolerance

6.1. Elimination of hidden lactose and epithelial cross-contamination risk

The most important clinical action to take in the treatment of secondary hypolactasia and primary lactase non-persistence is strict avoidance of lactose. In confectionery production, dark chocolate is often touted as a readily available dairy-free food. But the industrial processing lines have a big risk of "hidden lactose" and cross contact (Cheengolova *et al.,* 2024).

The incorporation of the structured 100% plant-based filling with the ripe pulp of jackfruit totally obviates any need for regular dairy lipids (anhydrous milk fat, butter oil, condensed milk) in making chocolate ganaches and soft pralines. The design of an exclusively structured vegetable lipids and polysaccharides matrix ensures that the final candy product is a pure biochemical matrix with no contamination. This, in turn, gives permission for a clean-label approach that can clearly state "Zero Lactose" or "Certified Dairy-Free" to shield any extremely sensitive individuals from allergens and subsequent mucosal irritation (Dominici *et al.,* 2022).

6.2. Controlling diarrhea and balancing gut microbiota fermentation

As the lactose deficient person eats food products containing lactose, there will be no enzymatic action on lactose at all, and thus the disaccharide sugar will enter into the cecum and colon intact. The presence of this amount of sugar changes the osmotic pressure within the intestines drastically. Due to the resulting osmotic difference, large amounts of fluid are drawn into the intestines (Goosenberg, 2025).

At the same time, the microflora of the colon quickly ferments this additional source of carbohydrates, thus producing volatile gases like hydrogen, carbon dioxide, and methane, as well as acid intermediates (Misselwitz *et al.,* 2019)).

The inclusion of the jackfruit pulp as the source of the chocolate filling leads to a completely new profile of carbohydrates that includes simple carbohydrates (monosaccharides like fructose and glucose) as well as difficult-to-digest polymers of carbohydrates (pectins, cellulose, and hemicelluloses) (Alruwali & Alshdayed, 2023). These free monosaccharides are rapidly absorbed through the active process of absorption (SGLT1) and diffusion (GLUT5) in the upper part of the jejunum, without the participation of the enzyme lactase (Koepsell, 2020).

At the same time, the jackfruit pulp polysaccharides (JFP-Ps), being high-molecular weight polysaccharides, are metabolized throughout the large intestine. In contrast to the unpredictable and volatile fermentation of free lactose, JFP-Ps are digested under the control of specific metabolic regulation. This controlled process produces desirable Short Chain Fatty Acids (SCFAs), including acetate, propionate, and butyrate, without producing any explosive gas production (Gao *et al.,* 2024).

6.3. Microbiome restoration and epithelial homeostasis

Continuous consumption of lactose by malabsorption patients will lead to constant subclinical mucosal inflammation, localized gut dysbiosis, and increased permeability of the intestines ("leaky gut syndrome"). Modern research conducted on the relationship between gut microbes mapping has shown that polysaccharides from the pulp of jackfruits are excellent prebiotics that are used for remodelling a damaged microbiome (Keely & Barrett, 2022).

Jackfruit pulp polysachharides serve as a fuel source that promotes the growth and colonization of *Lactobacilli* and *Bifidobacteria* species in the human colon. Such acid-producing bacteria play a very important role in establishing digestive balance and in restoring gut microbiota following any dietary stress (Petsong *et al.,* 2023).

However, it is evident that there is an increase in levels of colonic butyrate when there is microbial breakdown of jackfruit fibers. Butyrate is the main source of energy used by colonocytes. Therefore, intake of jackfruit contributes to healing of the damaged cells lining the intestines (Zheng *et al.,* 2024).

7. Challenges and limitations

7.1. Melanin polymerization

The enzymes present in fresh jackfruit pulp are copper containing, mainly polyphenol oxidase (PPO) and peroxidase (POD). These enzymes would instantly turn internal mono- and o-diphenols to highly reactive quinones when cells were ruptured during pulping. These quinones then polymerise to form dark brown or greyish pigments called melanins (Shah *et al.,* 2024).

7.2. Volatile escape

Steam blanching or pasteurization at temperatures above 85-90 °C are the traditional methods used to completely inactivate PPO and POD. Ripe jackfruit, however, is the jackfruit signature "bubblegum" fruitiness, which is caused by the highly volatile low molecular weight esters, mainly isopentyl acetate, ethyl isovalerate and butyl acetate (Nisar et al., 2021). These scents are completely evaporated when the pulp is thermal concentrated in the open air and yields a flat brownish jam-like paste devoid of any varietal aroma (Maia *et al.,* 2004).

7.3. Hydroxymethylfurfral synthesis

Rapid non-enzymatic browning (Maillard reaction and caramelization) pathways will begin when the core of a fruit with high reducing sugar content (fructose and glucose) is extended heated (El Hosry, 2026). This creates off flavors and high concentrations of the compound 5-hydroxymethylfurfural (HMF), which is carefully monitored by international food safety agencies for its long-term potential toxicity to the cell (Kayisoglu, 2026).

7.4. Nozzle clogging and fibrous jamming

In the continuous mixers used in the industry, the fibre bundles of cellulose and hemicellulose found in the perianth of jackfruit are long and insoluble which does not shear smoothly. These micro-fibres collect in the fine-gauge injection nozzles when being deposited automatically in pre-formed dark chocolate shells. This structural build-up causes variations in fluid velocity, which could result in uneven fill volumes, punctured shells or a blockage of the nozzle (Rinshana, 2025).

7.5. Varietal disparities

The internal structural morphology of cultivars is very diverse. There are two main classes of processing varieties: *var. crispum* (hard, firm carpel) and *var. flaccidum* (soft, fibrous, highly gelatinous carpel). The different insoluble cellulose to free sugar ratio of these varieties interferes with the normal operation of standard automated pumping, injection and enrobing line equipment (Sampath, 2020).

7.6. Microbial spoilage and perishability

The perianths of ripe jackfruit have high initial water activity ($a_w \approx$ 0.95-0.98) and a neutral pH (5.2–5.8) in their interior. This results in the fresh pulp being very conducive to the growth of post-harvest fungal pathogens such as *Rhizopus artocarpi* (jackfruit soft rot) and *Aspergillus niger* (Sandoval Contreras, 2022).

8. Future perspectives

The confectionery industry is seeking an alternative to the traditional thermal concentration method due to the high number of volatile aroma compounds lost and their degradation during thermal processing, with High-Pressure Processing (HPP) being considered the promising option for cold-pasteurization. Research has shown that the typical and common spoilage yeast and moulds can be reduced by more than 5 log upon hyperbaric pressure treatment of ripe jackfruit pulp in the range of 400 to 600 MPa at room temperature (25°C) (Saranya *et al*., 2025).

8.1. Aroma preservation

The customer's receptiveness to the premium fruit-flavored candies is based on maintaining the true aromatic signature of the fruit mass. The ripened pulp of jackfruits has a unique aromatic signature due to its higher content of low-molecular esters, alcohols, and aldehydes (Xu *et al.,* 2025). The low molecular weight esters (isopentyl acetate for example) which impart the tropical fruitiness to jackfruit are not affected by HPP, and do not impart cooked off flavor as with traditional pasteurization (Chalumput, 2026).

8.2. Enzymatic control

Ohmic heating is a significant improvement in large-scale manufacturing, where whole enzyme inactivation is necessary. The electric current is passed directly through the conductive jackfruit pulp which results in the instant volumetric heating (Abedelmaksoud *et al.,* 2022). Works in seconds, this quick method inactivates polyphenol oxidase (PPO) enzyme in a second step to stop the enzymatic browning process without burning the sugars and without creating any harmful hydroxymethylfurfural (HMF) components (Coelho *et al.,* 2023).

8.3. Geometric moisture barriers

The 3D printing technique helps to create an internal geometry of honeycombs rather than a cavity being just filled. The structure will encapsulate the wet phase of jackfruit inside chocolate cubes and will therefore minimize the gradient of vapor pressure as well as prevent capillary flow (Forschungsgemeinschaft, 2022).

8.4. Cyclodextrin complexes

The capture of volatile flavoring elements of jackfruit in the hydrophobic pockets of beta-cyclodextrins results in the formation of an effective powder that can be used in the formulation of dark chocolate without being confined to the role of a separate centre fill. Thus, a shelf-stable chocolate bar containing jackfruit flavoring can be made (Indiarto *et al.,* 2024).

9. Conclusion

With the advancement of structure and nutrition in the plant-based confectionery industry, food scientists have found natural whole-food ingredients that could replace dairy matrices while retaining high sensory value

Being filled with jackfruit, this dark chocolate is free from lactose and hence helps protect around 68% of the adult world population, who suffer from lactase non-persistence, from accidental consumption of lactose leading to inflammation in the intestines. What is more important is that the presence of undigestible jackfruit pulp polysaccharides (JFP-Ps) makes this matrix an excellent prebiotic carrier. They undergo fermentation slowly and gradually in the colon, preventing any fast production of gases like in the case of lactose intolerance. Instead, they promote the growth of beneficial gut bacteria (*Lactobacillus* and *Bifidobacterium*) and produce beneficial short-chain fatty acids (SCFAs), especially butyrate.

SCFAs produced locally help in reducing inflammation in the intestines, promote the synthesis of tight-junction proteins (ZO-1 and occludin) for repairing the integrity of the intestines, and acidify the colon to promote the dissolution of minerals like calcium and magnesium.

With the use of non-thermal food manufacturing approaches such as HPP technology used in cold pasteurization, dual-extrusion technology employed in 3D food printing to ensure accurate moisture content, and zero-waste cascade process in biorefineries, the food industry is able to transform jackfruit pulp into an exquisite, healthy, and easily digestible sweet treat.

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