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Anti-diabetic potential of selected fruit and vegetable waste – an appraisal of current literature

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Diabetes mellitus is a widespread and rapidly growing health problem throughout the world. Fruit and vegetable waste in the form of peel, seed, skin, pomace, etc. possesses many compounds with potential hypoglycemic effects. Every year large amounts of vital components are lost in the form of discarded fruit and vegetable waste. The current literature reviews the anti-diabetic potential of these waste materials. It also makes an effort to cover the different mechanisms involved in which they exhibit these properties. The key findings indicate that the bioactive components like flavonoids, carotenoids, and polyphenols, and agents like allicin and tannins, not only protect β-cells and insulin sensitivity but also regulate the GLUT4 and PPARγ genes. This brings insight into the fact that these components can act as a potential tool to fight against oxidative stress-related diseases like diabetes. The extracts from mango peel, pomegranate seed, onion peel, and garlic reduced the glucose levels of blood in *in vitro* and *in vivo* studies. This review also finds the gap in the lack of standardization of these procedures and the challenges to commercializing these components More studies are required to get more information about the effective utilization and the commercialization of fruit and vegetable waste-based products. The findings of this research lead to a stepping stone for further research that optimizes the standardization of the extraction procedure to its full harness of using these natural resources in nutraceuticals and therapeutics.

Keywords: Fruit waste; valorization of waste; anti-diabetic potential; nutraceuticals; functional foods

INTRODUCTION

Fruits and vegetables contain various bioactive compounds exhibiting high antioxidant activity and potentially have several health advantages. These compounds are effective against different health and disease conditions, *viz*., obesity, diabetes, infections, and allergies in preclinical and clinical trials [1-3]. These chemicals include compounds like polyphenols, phytosterols, saponins, dietary fibers, and other compounds with high antioxidant activity [4]. Owing to consumer demand and better agricultural practices, fruit output climbed to around 108.34 million tons in the year 2022–23 from 107.51 million tons production in 2021–22, whereas vegetable production jumped to about 212.91 million tons in 2022–2023 from 209.14 million tons in 2021–22 [5]. Since both fruits and vegetables have a short shelf life, it is reported that one-third of the products goes to waste. The major waste generated from fruits and vegetables is in the form of peels, seeds, pulp, overripe or spoiled fruits and vegetables. The peel of most fruits and vegetables is removed before processing, while the extraction of juice from pulp results in the production of pulp residue. Both of these, along with the seeds, constitute a major part of the waste generated from the fruit and vegetable processing industry. For example, apples contain 10.9% of seed, pulp, and peel as by-products. Minimal processing treatments like dicing produce only 53% of the fruit as the final product, and the rest is waste in the form of peel, seed, and unusable pulp. Similarly, pineapple processing produces approximately 50% of waste in the form of peel, core, top, and pulp (14, 9, 15, and 15 percent, respectively). In mangoes as well, only 58% of the fruit is utilized. In the case of apples, these components constitute approximately 11% of the total weight. During dicing operation for minimal processing, only 53% of the total fruit is utilized. Similarly, in pineapple processing, only half of the total fruit weight is edible, and the rest is discarded.

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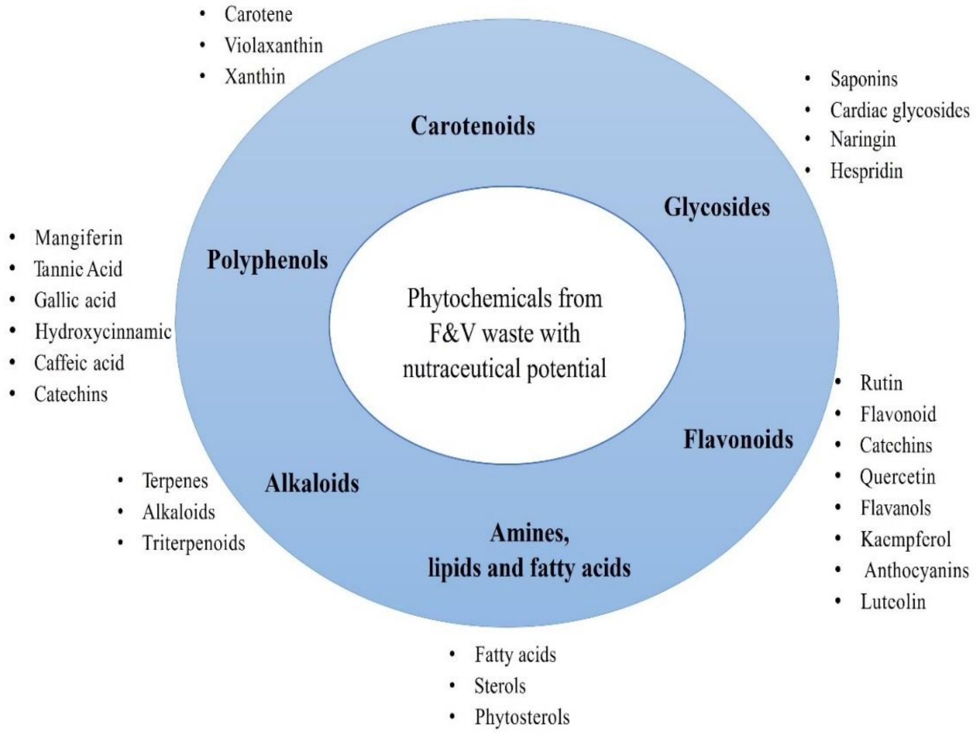

Fig. 1. Major phytochemicals identified from fruit and vegetable waste having anti-diabetic activity.

For mango consumption, only 58% of the fruit is used. Fruit and vegetable waste parts are generally not eaten in their native form and contribute to environmental burden. Management of this huge waste is a challenge and is currently tackled by either incineration or landfill since these are biodegradable in nature. Improper management leads to the production of toxic compounds and gases like methane, which poses not only environmental but also health hazards. Fruit and vegetable waste is rich in useful components that are highly effective against various health conditions (Fig. 1). Extraction, isolation, and purification of phytochemicals from these parts can reduce the issues and help to develop new-age functional foods, sustainable packaging materials, and nutraceuticals [6].

Diabetes is a metabolic condition that involves elevation of blood glucose levels [7]. According to the latest edition of the IDF Diabetes Atlas, 537 million individuals had diabetes in 2021, with a drastic increase predicted to 783 million in 2045. More than half of the cases go untreated in developing and underdeveloped countries. In addition, 541 million people are prone to the risk of type 2 diabetes. About 1.2 million children have type 1 diabetes. Diabetes killed 6.7 million people in 2021 and costed $966 billion in healthcare costs, accounting for 9% of global healthcare spending. High blood glucose levels during pregnancy affect one in every six live births (21 million) [8]. Major management of this disease condition is done using synthetic drugs. There is a great need to use natural remedies to manage and treat this disease spreading like an epidemic. Recent research indicates that these components, like polyphenols, flavonoids, catechins, etc., possess anti-diabetic activity.

Regardless of these findings, the field is still underexplored, especially in explaining the hypoglycemic mechanism behind each component. Also, the development of value-added products from waste materials can enhance the economic viability of the food industry while addressing public health concerns. However, limited research has explored the large-scale industrial processing and consumer acceptance of these functional products, highlighting the need for further studies to bridge this gap. This review tries to close important gaps in the existing literature by offering bioactive compounds that are obtained from fruit and vegetable waste about diabetes management. Even though there are studies on the role of these bioactive compounds on mechanisms of mRNA expression, β-cell protection, and insulin sensitivity, the source of these compounds and their value-addition opportunities are underexplored. The overview is unique because of the comprehensive evaluation of bioactive connections of waste as sustainable resources for industrial applications and therapeutic active ingredients. This work emphasizes how these natural connections have the potential to transform the diabetes supply by addressing a significant problem of public health and reducing environmental waste.

This review also points out the relationship between the scientific background of these compounds and their potential industrial applications for the utilization of this waste in therapeutic and nutraceutical products like herbal teas, infusions, etc. This study gives a framework for the need for subsequent studies on consumer acceptability and large-scale processing.

MECHANISM OF ANTI-DIABETIC EFFECT

Beta cells which belong to pancreatic islet cells, are responsible for the production and secretion of insulin hormones to maintain blood glucose levels. Glucose enters into the blood after each meal. Then the glucose goes to the beta cell *via* glucose transporter Glut2 and is utilized through glycolysis, raising the intracellular ATP/ADP ratio and closing the ATP-dependent potassium (KATP) channels in the plasma membrane. This leads to membrane depolarization and opening of voltage-gated calcium channels, that allow Ca^{2+} to enter the cell, initiating insulin exocytosis, and releasing insulin into the circulation [9]. Based on the above mechanism, antidiabetic agents generally control glucose metabolism in four major ways: 1) intestine-related, 2) liver-related, 3) pancreas-related, and 4) muscle-related [10].

Polyphenols like catechins, gallates, caffeic acid, etc. from mangoes, pomegranates, potatoes, and red bell peppers inhibit glucose metabolism through the inhibition of carbohydrate-digesting enzymes like α-amylase and α-glucosidase, which reduces the absorption of glucose. This will lead to a reduction of postprandial glucose by the same mechanism as that of the drug acarbose [11]. Alkaloids like d-1,4-dideoxy-1,4-imino-D-ribitol, 6-O-β-D-gluco-pyranosyl-1-deoxynojirimycin from mulberry latex and leaves showed anti-diabetic activity through the same way as that of polyphenols. These compounds reduce alpha-amylase activity by interfering with the catalytic residues of its active site. This leads to the loss of ability of the enzyme to bind with the substrate responsible for glucose digestion [12]. Carotenoids work basically on insulin sensitization through PPARγ expression. The antioxidant property of carotenoids also influences diabetic activity as radical production and oxidative stress influences insulin secretion and resistance to the hormone [13]. AMP-activated protein kinase (AMPK) plays a vital role in the regulation of glucose metabolism. Quercetin and glycosides increase the phosphorylation of AMPK, which significantly elevates the translocation of glucose transporter (GLUT4) that spikes glucose uptake in muscle and adipose tissues [12]. The main mechanism of the hypoglycemic effect of flavonoids is *via* the binding to peroxisome proliferator-activated receptor gamma (PPARγ) and glucose transporter 1 (GLUT1) receptors stimulating lipid metabolism/, glucose uptake, increased insulin action on glucose utilization, and improved glucose tolerance in diabetic animals and humans [14].

NUTRITIONAL, PHYTOCHEMICAL COMPOSITION AND ANTI-DIABETIC POTENTIAL OF VARIOUS FRUIT WASTES

Fruits like jamun, mango, pomegranate, etc. have been shown to have an impact on the management of diabetes. However, recently, it has been concluded in studies that even the waste generated from these fruits has an impact on diabetic regulation. Fruit waste having anti-diabetic properties is discussed in this section.

Mango (Mangifera indica)

Mango, which belongs to the family *Anacardiaceae* and order *Sapindales*, is a tropical stone fruit. With over 1000 varieties, it is grown in over 87 countries and covers over 3.7 million hectares globally [15]. After China, India is the topmost producer of mangoes. During the period 2015-2016, India's mango cultivation covered approximately 2.22 million hectares, resulting in a production of approximately 20 million tons and an average productivity of 8.8 tons per hectare [16]. The three primary parts of a mango are the pulp, skin, and kernel. The pulp contains aromatic compounds, sugars (reducing and non-reducing), amino acids, and other components, including vitamins, minerals, anthocyanins, polyphenols, soluble and insoluble fibers, etc. During mango processing, edible portions are taken, and peels and kernels are often thrown away. These by-products are regarded as bio-wastes with nutraceutical value, indicating their potential use beyond simple disposal [17].

The proximate composition of all byproducts of mango is provided in Table 1. Mango leaves also contain several phytochemicals, like polyphenols, terpenoids, carbohydrates, sterols, carotenoids, vitamins, fatty acids, and amino acids. Phenolic compounds like tannins, terpenoids, phenolic acids, xanthones, benzophenones, and flavonoids are especially prevalent among the peel and kernels [18]. The major phytochemicals in the leaves of mangoes are mangiferin, iriflophenone 3-C-β-glucoside, epicatechin, rhamnetin, catechin, gallic acid (2.98 ppm), chlorogenic acid (3.79 ppm), quercetin (1.08 ppm), m-coumaric acid (0.18 ppm), ferulic acid (2.63), and benzoic acid (1.67 ppm) [19]. In a study, when Egyptian mango seeds were subjected to high-resolution liquid chromatography (HPLC) examination, the presence of various phenolic compounds and acids, like mangiferin, quercetin, gallic acid, and caffeic acid, was observed. Vanillin and tannins were discovered in high quantities, with tannin being the most prevalent at 20.7% [20].

Table 1. Proximate analysis of common fruit waste

S. No	Fruit	Parts	Carbo-hydrate (%)	Protein (%)	Fat (%)	Fiber (%)	Moisture (%)	Ash (%)	Ref.
1	Mango	Peel	80.70	3.60	2.20	8.40	10.50	3.00	[17]
		Seed	43.31	2.62	2.76	24.75	50.03	1.29	[24]
2	Pomegranate	Peel	64.84	7.80	1.20	19	69.70	5.60	[26]
		Leaves	19.60	11.60	0.96	-	6.50	4.90	[27]
3	Orange	Peel	40.47	16.40%	14.35%	12.47	10.00%	5.51%	[28]
4	Mulberry	Leaves	13.43	9.96	1.51	---	76.68	5.33	[29]
		Pomace	62.8	---	4.90	1.58	14.4	---	[30]
5	Avocado	Seed	48.21	19.94	15.73	4.10	13.27	0.92	[31]
6	Jamun	Seed	21.90	6.40	4.53	16.40	53	1.50	[32]
		Peel	15.35	0.12	0.80	----	79	0.91	[33]
7	Banana	Peel	50.5	5.3	1.60	19.2	6.70	8.8	[34]
8	Watermelon	Peel	32.16	12.42	12.61	26.31	6.44	5.03	[35]
		Seed	32.16	17.75	27.83	43.28	8.50	3.00	[36]
9	Guava	Seed	3.08	11.19	13.93	63.94	6.68	1.18	[37]

Table 2. Major bioactive compounds that exhibit anti-diabetic property in fruits waste

S. No	Fruit	Part	Bioactive compound	Ref.
1	Mango	Leaves	Mangiferin, Iriflophenone 3-C-β-D-glucoside, Quercetin	[38,19, 12]
		Peel	Chlorogenic acid, Mangiferin, Gallic acid, Kaempferol,	17 ,24,39]
		Seed	Gallic acid, Caffeic acid, Chlorogenic acid and Tannic acid	[17,40]
2	Pomegranate	Peel	Catechins, Sterols, Gallic acid, Rutin, Flavanols, Punicalagins,Quercetin, Flavones, and Anthocyanidins	[41-44]
		Leaves	Tannins, Flavones Glycosides like Apigenin and Luteolin	[44,45]
3	Banana	Peel	Phytosterols, Hydroxycinnamic acids, Flavonoids, Lutein, Isolutien, Alpha & Beta carotene, Violaxanthin, Auroxanthin, Neoxanthin, Beta-Cryptoxanthin, Anthocyanins, & Phytochemical.	[46-49]
4	Orange	Peel	Saponin, Flavonoid, Resins, Terpenes, Cardiac glycosides, Hesperidin,Naringin, Neohesperidin, tangeretin, Sinensetin and Narirutin	[50-51]
5	Mulberry	Leaves	1- Deoxynojirimycin, Quercetin, Kaempferol, Glutamine, Lactic acid,Pyruvic acid, Oxalic acid, 5-methoxy tryptamine, Alanine, Gallic acid,Valine, Chlorogenic acid, D-galacturonic acid, Tricetin, Moracin C and α-Glucosidase inhibitors	[52,53]
		Pomace	Cyanidin-3-O-glucoside, Cyanidin-3- rutinoside and Anthocyanin	[54]
6	Avocado	leaves	Tannins, Quercetin-3-Glucoside, Saponins, Triterpenoids	[55]

		Seed	Phenols, Alkaloid, Flavonoids and Saponins, Phytosterols	[56]
7	Jamun	Seed	Gallic acid, Quercetin, Ellagic acid, Flavonoids, Anthocyanin,catechins	[57-58]
		Peel	Gallic acid, Tannins, and Anthocyanin	[59]
8	Watermelon	Seed	Reducing sugar, Flavonoids, Anthraquinones, Alkaloids, Tannins,Terpenoids.	[60]
		Peel	Alkaloids, Saponin, Cardiac glycosides, Flavonoids	[61]
9	Guava	Seed	Phenolic compounds, Carotenoids, Ascorbic acid, and Tocopherol	[62]

Table 3. Overview of the anti-diabetic potential of fruit waste through animal model supplementation studies

S. No	Fruit Part	Compound	Experimental animal	Dosage	Inference	Ref.
1	Mango					
	Peel	Mangiferin	Alloxan induced diabetic rats weighing 100-150 g	Group I: Control Group II: Alloxan+ Extract treatment (200 mg/kg body weight for 21 days) Group III: Alloxan + Mangiferin (20 mg/kg body weight for 21 days orally)	Lower weight gain and more effective reduction in plasma glucose levels in Group II.	[25]
	Seed	Mangiferin, gallic acid, quercetin	Streptozotocin induced diabetic rat	Treatment with mango kernel extract (250 mg, 500mg, and 1000 mg/Kg body weight)	Reduced fasting glucose levels, total cholesterol, and LDL improved β pancreatic function.	[105]
2	Pomegranate					
	Peel	Punicalin, Punicalagin	*In silico* approach	Punicalin, Punicalagin, and ellagic acid were docked against 9 protein targets important for protein metabolism- GFAT, PTP1β, PPAR-γ, TKIR, RBP4, α-amylase, α-glucosidase, GCK, and AQP-2.	All three compounds exhibited significant binding scores.	[106]
	Rind and seed	Punicic acid	Alloxan-induced diabetic rat	Subcutaneous injection of peel and rind ethanolic extract	Reduction in blood glucose levels ($p=0.0295$), cholesterol, and triglycerides.	[107]
3	Banana peel		Oral administration to alloxan-induced diabetic rat	Dosages of 100, 200, and 400 mg/kg/day administered orally for 21 days in different groups	Decreasing plasma glucose by utilization of peripheral glucose and by boosting liver glycogen synthesis	[45]
4	Orange					
	Peel	Saponin, Flavonoid, Terpenes, Cardiac glycosides and terpenes	Male albino Wistar rats	Group I- control Group II-10% peel (w/w) Group III- corn oil (20% w/w, 8 weeks) Group IV- corn oil 20% for 8 weeks; followed by 10% orange peel remedial diet for 4 weeks Group V- 20% Corn oil and	Protective effect of the liver for group IV and V diets	[108]

				10% orange peel remedial diet for 12 weeks followed by histological examination		
5	Mulberry					
	Pomace	Cyanidin, ,4,6-trihydroxybenzaldehyde, and taxifolin	*Caenor habditis elegans* used as model system	-	Reduction in glucose content and ROS. Extract led to activation of DAF-16/FOXO and SKN-1/Nrf2	[109]
6	Jamun					
	Seeds	Gallic acid, quercetin, ellagic acid, flavonoids, anthocyanin, catechins	Hydroethanolic seed extract in a Wistar rat model	100, 200, or 400 mg/kg of ethanolic extract from jamun seeds	Reduction in blood glucose, increase in pancreas weight, improved beta cell function, and reduced insulin resistance	[88]
7	Avocado					
	Leaves	Flavonoids, tannins, quercetin-3-glucoside, saponins	Alloxan monohydrate-induced diabetes mellitus	100-200 mg/kg body weight of aqueous extract	BGL reduction in a dose-dependent manner leads to a 60% reduction in blood glucose after the first dosage	[55]
	Seed	Luteolin, Myricetin	Alloxan-induced diabetes mellitus	36 male rats into 6 groups and treated for 4 days	Significant decrease in blood glucose, and triglyceride. Improved pancreatic function, Activation of P13K/Akt pathway, and inhibition of β cell death	[110]
8	Watermelon					
	Seed	Catechin, Spartein, Lunamarin, Quinine	83 rats with a weight of 125-200 g	Diabetic rats were treated with a dosage of 100-600 mg/Kg of the extract for 21 days.	Reduced anti-diabetic effect	[111]
	Peel	alkaloids, saponin, cardiac glycosides, flavonoids and phenols	Streptozocin-induced diabetic rats	Watermelon rind extract (250-1000 mg/Kg) for 8 days	Blood sugar and triglyceride reduction	[112]
9	Guava					
	Seed	Polyphenols, flavonoids, saponins	Albino rats weighing approx. 190 g	Concentration of 200 and 250 mg/kg/bw fed orally with basal diet	Improvement in blood glucose and lipid profile	[113]

All these phytochemicals have pharmacological properties like anti-inflammatory, anticarcinogenic, antimicrobial, antioxidant, antidiabetic, etc. Several researchers have investigated the hypoglycemic properties of *Mangifera indica* (mango) leaves and seed kernel extracts. In diabetic rats and mice, the extracts drastically helped in lowering the fasting blood glucose and serum cholesterol. Long-term dosages of these extracts stabilized the glucose levels in diabetic rats; however, single oral doses had strong hypoglycemic effects in type 2 diabetic rats. The extracts also show antihyperglycemic properties in several diabetes model animals [21]. Mangiferin is found to regulate a key enzyme in gluconeogenesis, i.e., fructose-1,6-bisphosphatase. This regulation leads to a decline in glucose synthesis in the liver and thereby helps in controlling blood glucose [2].

From a study, the levels of yeast α-glucosidase were inhibited by mango leaf extract in a dose-dependent manner, wherein IC50 values were found to be 0.0503 and 0.5813 mg/ml, respectively [22].

During the *in vitro* diabetic property analysis of mango peel extract, significant antidiabetic properties were found effectively by inhibiting pancreatic enzymes. Strong potential in maintaining the levels of blood glucose was shown for the dose-dependent inhibition, with IC50 values of 4 μg/ml for α-amylase and 3.5 μg/ml for α-glucosidase. Most importantly, IC50 values of peel exhibited higher efficiency against glucosidase compared to α-amylase and were notably lower than those reported for other plant extracts [23].

In another study conducted by Lasasno *et al*. on mango peels and seed kernels, kernels exhibited a high inhibitory effect against α-amylase and α-glucosidase. Compounds like mangiferin, naringenin, and isovitexin in the peel, as well as beta-glucogallin, theogallin, and 2-hydroxy-3,4-dimethoxybenzoic acid in the seed kernel, were detected in LC-MS analysis. Both portions of the fruit are strong in minerals, vitamins, and fiber, indicating their potential as functional additives in the food sector due to their significant anti-diabetic qualities. Mango peels are also a rich source of crude fiber (8.4%) and carotenoids, both of which have been reported to improve insulin function and metabolic profile and regulate blood glucose [24].

In Table 3, we have displayed the three groups of alloxan-induced diabetic rats (weighing 100-150 g) that were taken for a study: Group I (Control), Group II (alloxan + extract therapy at 200 mg/kg body weight for 21 days), and Group III (alloxan + mangiferin at 20 mg/kg body weight for 21 days orally). A weight gain of 8.81% in Group I and 3.3% in Group II was observed. There was a drastic decrease in plasma glucose from 310.5 to 88.5 mg/dL in Group II and from 310.5 to 91.16 mg/dL in Group III. The LD50 of mango peel extract was greater than 2000 mg/kg body weight, whereas the LD50 of mangiferin was 300 mg/kg when ingested orally. Additionally, lipid profile improvements were observed [25].

Pomegranate (Punica granatum)

Punica granatum, commonly called pomegranate, belongs to the family *Punicaceae* and is mostly found in Iran, which is thought to be its major source of origin [63]. The production of pomegranate juice creates large byproducts, such as peels and seeds, which provide disposal issues and contribute to waste management issues. Pomegranate peels account for around 24% of the total fruit weight [64]. The proximate composition of dried pomegranate peel is presented in Table 1. Pomegranate peel is also rich in phytochemicals and contains catechins, sterols, gallic acid, rutin, flavonols, quercetin, fatty acids, punicalagin, quercetin, flavones, and anthocyanidins (Table 2). The anti-diabetic effect of the fruit extract that includes bioactive compounds like ellagic acid deoxy hexoside, cyanidin-3-O-glucose, and vanillic acid derivatives was investigated using the albino mouse of type 2 diabetes induced by streptozotocin (STZ). The anti-diabetic activity of the extract was shown by STZ injection significantly increasing serum glucose levels, consistent with previous findings, which can be attributed to its high phenolic content. The extract's efficacy is associated with compounds such as valoneic acid dilactone (VAD) and flavonoids, which play a key role in diabetes management [65].

The peel extract of pomegranate also shows superior inhibition of α-glucosidase, an enzyme responsible for digesting dietary carbohydrates due to the presence of saponins, known for their impact on diabetic complications and hypoglycemic effects through mechanisms such as insulin response restoration and α-glucosidase activity inhibition. Additionally, phenols and flavonoids present in the extracts contribute to their significant α-glucosidase inhibition, highlighting the therapeutic potential of pomegranate peels for managing diabetes [66].

Orange (Citrus sinensis)

Orange is from the family *Rutaceae* and is majorly cultivated in tropical and subtropical climates, with a global production of 120 million tons. According to statistics for 2021, citrus fruits are the second major fruit cultivated globally, totaling 161.8 million tons and covering an area of more than 10.2 million hectares. Oranges, a predominant citrus variety, accounted for the majority, with a production of 75.57 million tons, representing 46.7% of the total citrus fruit produced, from an area of 9.93 million hectares [67].

The orange waste consists mainly of three different portions: flavedo or exterior peel, albedo or interior peel, internal tissue, and seeds, in which peels contribute to the largest portion of the waste, which is 40-45%. However, the portion of the peel is abundant in polysaccharides such as cellulose, hemicellulose, and pectin [68]. The proximate composition of orange peel is presented in Table 1. Compounds identified from the orange peel that possess anti-diabetic potential include neohesperidin, hesperidin, narirutin, naringin, sinensetin, tangeretin, and other flavonoids and phenolics [69] (Table 2). The flavonoids, like hesperidin and naringin, decrease the activities of glucose-6-phosphate and phosphoenol pyruvate.

One of the mechanisms involved in anti-diabetic properties is the inhibition of peroxidation that reduces the activity of the α-amylase enzyme. This enzyme is responsible for converting complex carbohydrates to glucose, increasing hepatic glycogen content, stimulating insulin secretion, and repairing secretory defects in pancreatic β-cells [70]. In the study conducted by Ahmed *et al.* (2017), anti-hyperglycemic, anti-hyperlipidemic, and antioxidant effects of orange peels were observed. Rats were induced to have type 2 diabetes by nicotinamide/streptozotocin (STZ). They were then treated orally with peel extracts and flavonoids for antioxidant treatment, effectively improving various diabetic markers in the diseased rats. The treatments improved insulin production, restored liver glycogen content, normalized liver enzyme activities, improved lipid profiles, and enhanced antioxidant defense mechanisms. It was also observed that administration of the extract increased mRNA expression of insulin receptor β-subunit, GLUT4, and adiponectin in adipose tissue. Overall, the extract and flavonoids exhibited potent antidiabetic effects by enhancing insulin action and improving insulin signaling pathways in adipose tissue [71] (Table 3).

Mulberry (Morus Alba L).

Mulberry comes from the family *Moraceae*, which is commonly found in Asia. They are not only used for culinary purposes but also have great recognition for their medicinal properties. These contain different nutrients and bioactive compounds such as anthocyanins, rutin, quercetin, and chlorogenic acid, which have proven bioactive properties. The fruits are sorosis. The color of the immature fruits is generally green, and as the fruit matures, it turns to violet and black [72].

Mulberry leaves are used for the treatment of hypertension and diabetic individuals who are obese [73]. The moisture content of fresh leaves ranged from 71.1 to 77% approximately, crude protein ranged from 4.7 to 10%, and crude fat was found in the range of 0.6 to 1.5%. Ash content was observed to be in the range of 4.2 to 5.3%, and carbohydrates ranged from 8.0 to 13% [30, 74] (Table 1). Mulberry pomace is the remaining mass left after juice extraction, and it corresponds to approximately forty percent of the whole weight of the fruit. Mulberry fruit has an essential amino acid score of 100 or higher, making it an excellent nutritional product and a significant source of minerals and vitamins, according to the World Health Organization (WHO) [75]. Fresh mulberry fruit contains a larger amount of protein than raspberries and strawberries and is almost equivalent to blackberries. Furthermore, its anthocyanin concentration exceeds that of blackberry, blueberry, blackcurrant, and redcurrant. Furthermore, *M. alba* fruit includes both necessary and non-essential amino acids [76].

Mulberry pomace is obtained by pressing mulberry biomass. It contains trace amounts of minerals like sodium, potassium, nickel, etc., which act as a substrate for citric acid production [77]. Mulberry leaves are found to have iminosugar alkaloids, especially 1-deoxynojirimycin (DNJ), which inhibits mammalian glucosidase enzymes. The concentration of DNJ varies amongst mulberry types. Chemical analysis reveals a variety of antioxidative substances, including phenolic acids (e.g., caffeic, gallic) and flavonol compounds (e.g., rutin, isoquercitrin). Mulberry leaves have high quantities of total phenolics and flavonoids, according to quantitative analysis [78].

A study investigated the hypoglycemic effects of mulberry leaf extract and mulberry leaf polysaccharides against an alkaloid called Ramulus Mori in mice having type 2 diabetes (Table 3). Morusin, kuwanon C, and morus Yunnan in mulberry leaf extracts act as potential agents accountable for hypoglycemic activity. The study showed that both the leaf extract and polysaccharide helped treat diabetes in mice [79]. The flavonoid quercetin and the alkaloid 1-deoxywildixamycin (DNJ) are also found to have a major role in the anti-diabetic properties of mulberry leaves [80], Table 2.

Mulberry marc extract (MMA) was administered to diabetic rats that had been induced with streptozotocin for a period of 4 weeks. And it's been shown that the treatment significantly reduced the blood glucose level. Decreased oxidative stress led to a lowering of insulin resistance (Fig. 2) [81]. Another observation made from the study is that the content of anthocyanin in mulberry marc is much higher than in the juice, which can be the probable reason for its high anti-diabetic potential [81].

Avocado (Persea Americana)

Avocado is a member of the *Lauraceae* family of plants and is found in tropical regions including Nigeria. Avocados are generally green to yellow in color and have a single large seed. The edible portion of the fruit comprises 50-80% of the total fruit weight [82]. Avocados are rich sources of mono- and polyunsaturated fatty acids, vitamins and minerals [83]. Proximate analysis of seeds showed moisture content ranging from 8.6% to 34.28%, fat content ranging from 0.33% to 16.54%, fiber content ranging from 2.87% to 26.33%, ash content varying between 2.40% and 3.82%, with some samples showing higher mineral content.

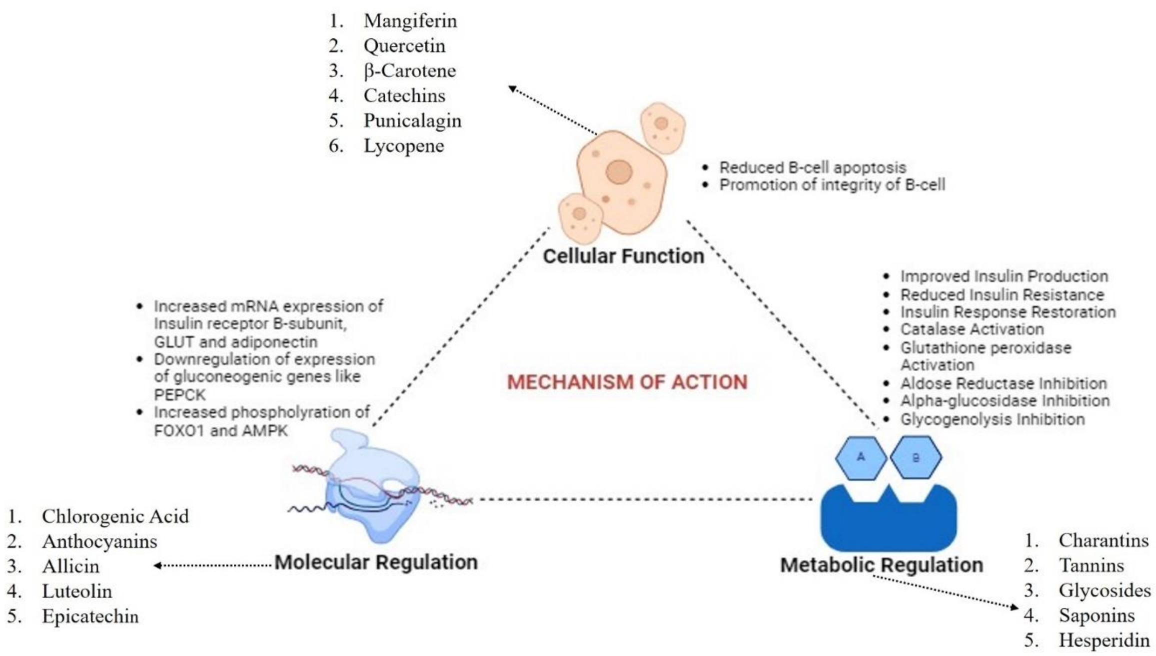

Fig. 2. Mechanism of action for blood glucose regulation exhibited by various phytochemicals extracted from fruit and vegetable waste.

Protein content ranged from 1.33% to 17.94%, and carbohydrate content from 7.75% to 44.70% demonstrating considerable variability in proximate composition among the different seed samples [84]. Avocado leaves, apart from being anti-diabetic in nature, are also well known for their antimicrobial, and anti-inflammatory properties. These consist of approximately 5% moisture, and 4% fat. They are rich in protein and fiber (25.54±2.52% and 38.40±5.12 %, respectively) (Table 1) [31]

Kouame *et al.* (2019) studied the effect of glucose regulation properties of avocado leaves extracted with methanol in type 2 diabetes rats. The study was conducted for a period of approximately 30 days and showed a reduction in intestinal glucose levels. The components that reduce the levels are saponins, polyphenols, notably flavonoids, etc. The mechanism of anti-diabetic action is either by reducing the rate of absorbing the glucose present in the intestine or by inhibiting the glycogenolysis mechanism. Another method mentioned is by promoting the integrity of beta-cells and enhancing the release of insulin [85].

Jamun/ Indian blackberry (Syzygium cumini)

Syzygium cumini belongs to the family *Myrtaceae* and is generally cultivated in the tropical and subtropical regions. Major countries producing jamun are Bangladesh, Pakistan, Nepal, Sri Lanka, Indonesia, Malaysia, India, South America, and Eastern Africa [86]. Jamun is a tree with silky smooth leaves, with shoots that may reach a height of 8 to 15 m. Its glossy, leathery leaves are opposite, obovate to oval or elliptical in shape. The dark purple fruit and seeds have precise measurements: the fruit is 31 mm long, 28.7 mm wide, and weighs 18.32 g; the seed is 18.20 mm long, 11.05 mm wide, and weighs 1.62 g [87]. Jamun seeds contain an abundance of nutrients such as dietary fibers, anthocyanins, chlorophyll, phytosterols, amino acids, vitamin C, and B-complex vitamins. They also include minerals (calcium, iron, salt, magnesium, zinc, phosphorus, chromium, vanadium, potassium), essential oils, albumin, and lipids. The fatty acid profile indicates the existence of several fatty acids, with β-sitosterol being the main phytosterol [88].

The proximate composition of jamun seeds varies as follows: moisture content ranges from 9.34% to 16.34%, carbohydrates constitute 31.62% to 41.4%, total dietary fibers range from 2.3% to 16.9%, crude fat content varies from 0.83% to 1.18%, and ash content is approximately 2.18%. The acidity level falls between 0.02 and 0.06 gm/L while the pH ranges from 3.79 to 4.83. The energy value is estimated at 335.64 Kcal, and total soluble solids (TSS) measure at 3.7 °Brix and crude protein content varies from 1.97% to 8.5% [89]. The proximate composition of jamun seed and peel is given in Table 1. The whole jamun fruit possesses significant quantities of antioxidants like flavonoids, phenolic acids, and anthocyanins. The seeds are rich in protein, fat, glycosides, alkaloids, ellagic acid, gallic acid, and minerals like zinc and chromium.

In a clinical trial, an aqueous ethanolic extract of jamun dried and powdered seeds was administered to Sprague-Dawley rats. The extract effectively halted hyperglycemia and reduced serum triglyceride and total cholesterol levels. This antidiabetic effect is attributed to the seed's ability to lower free radicals, enhance pancreatic beta-cell function, and activate enzymes like catalase and glutathione peroxidase [88]. Terpenoids, glycosides, saponins, flavonoids, phenols, etc., are some of the key constituents responsible for inhibiting glucose in jamun seeds. Extracts from jamun seeds, including gallic acid, valoneic acid dilactone, rubuphenol, and ellagic acid, inhibited aldose reductase (AR) with IC50 values of 0.77, 0.075, 0.165, and 0.12 µg/mL, respectively [88].

Banana (Musa acuminata)

Banana is the world's most productive fruit crop, producing 127.3 million tons. It is also the fourth most valuable agricultural product, worth USD 63.6 billion, after rice, wheat, and milk [90]. Banana is a member of the *Musaceae* family and is said to have evolved in the tropical areas of Southern Asia. These are grown as a food source and possess a high nutritional value [91]. Peel is one of the prominent wastes produced in large amounts from banana fruit and accounts for approximately 40% of the total fruit weight. Peels from ripened bananas have been analyzed to contain crude protein, soluble sugars, and total phenolic compounds (8%, 13.8%, and 4.8%, respectively). Major functional components extracted from banana peel include cellulose, hemicellulose, and pectin along with other low-molecular-weight compounds [92].

Banana peels are a major source of garbage in households, and they cause a foul odor because of the gases emitted by digestion in the absence of air. The peels are highly susceptible to microbial contamination and mechanical damage. The proximate composition of banana peel is given in Table 1. The peels contain high moisture and low lipid content [33]. The prevalence of phenolic substances like gallocatechin and anthocyanins like peonidin and malvidin in banana peel is also reported [93].

In a study it was found that the groups treated with banana peels had serum blood glucose levels ranging from 11.12 to 12.57 mmol/dl. The insulin treatment group showed similar results (11.25 ± 10.2 mMol/dl), supporting *Musa paradisiaca* peels' hypoglycemic effects [94]. In a similar study, different concentrations of dried banana peel (5%,10%, and 15%) and a control group with a basic diet were supplemented to diabetic Sprague-Dawley strain albino rats. It was found that diabetic rats (positive control) had significantly higher mean VLDL-C levels (41.33±3.51 mg/dl) compared to the negative control group (29.33±1.15 mg/dl). Adding dried banana peels at levels 1, 2, or 3 significantly decreased VLDL-C levels ($P<0.05$) in comparison to the positive control group. Interestingly, the group at level 5 had the lowest decrease, with a mean value of 33.66±5.68 mg/dl [95].

Watermelon (Citrullus lanatus)

Watermelon is a creeping herbaceous plant that originated in South Africa and belongs to the *Cucurbitaceae* family. The propagation of watermelon is done using seeds, and the growth is favorable towards warm temperatures (25°C). Only half of the fruit is eaten; the rest is in the form of seeds and rind. The seeds and peels of watermelon are the major waste generated. This section gives an account of the antidiabetic potential of watermelon waste [96].

Protein, vitamin B, many essential minerals like magnesium, potassium, phosphorus, and fat, as well as phytochemicals, are all abundant in watermelon seeds. Seeds are rich in protein, carbohydrates, fats, fiber, and ash (17.75%, 15.3%, 27.83%, 43.3%, and 3%, respectively) [35]. The interior regions of fruit peels, which are usually pale green or white, are edible and high in nutrients. The rind has been found to include alkaloids, saponins, cardiac glycosides, flavonoids, phenol, moisture, protein, fiber, and carbs. This emphasizes the nutritional benefits and various chemicals found in the inner peel layers [97]. Watermelon peels are high in protein, fat, ash, fiber, salt, potassium, calcium, copper, iron, magnesium, zinc, and phosphorus. Furthermore, the peels have considerable antioxidant characteristics, including free radical scavenging activity (IC50 of 147.30 mg/kg) and a high total phenolic content of 2.47 g/100 g. This shows that watermelon peels might be an excellent source of natural polyphenols, antioxidants, and minerals [98].

Clinical studies evaluated the anti-diabetic potential of watermelon seeds. A study was carried out on alloxan-induced diabetic rats to evaluate the hypoglycemic activity of watermelon seeds. The components in the seeds were extracted by using methanol. The results demonstrate that different concentrations of the seed extract lowered blood glucose levels by 57.9 mg, 66.4 mg, and 93 mg, respectively [99], Table 3. The methanolic extract of the peel was dissolved in dimethyl sulfoxide of various concentrations in an *in vitro* investigation of watermelon peel. In a Tris-HCl buffer (2 units/ml), porcine pancreatic-amylase was also added to the solution. This *in vitro* study suggested that watermelon peel extract imparts its anti-diabetic activity by inhibiting alpha-amylase activity, a carbohydrate-digesting enzyme [100].

Guava (Psidium guajava L.)

Guava is a member of the *Myrtaceae* family and belongs to the genus *Psidium*. It is a fruit that is largely grown in different regions of the world. After India and China, Brazil is the world's third-largest producer [101]. Guava is well known for its medicinal properties, especially related to the gastrointestinal tract. Recently it was found to have anti-inflammatory, anti-microbial, antispasmodic, and anti-viral properties in addition to antidiabetic properties [102]. The major byproducts obtained from the guava processing industry are seeds. Twelve percent of the total fruit weight is comprised of seeds [103]. Guava seeds contain nutraceuticals that have medicinal importance, like polyphenols, flavonoids, tannins, and saponins. Guava seed oil has a considerable amount of polyunsaturated fatty acids (especially linoleic acid), an adequate amount of monounsaturated fatty acids (mostly oleic acid), and a modest quantity of saturated fatty acids. Physicochemical parameters of oil imply stability, with low acid and peroxide levels. The oil is high in tocopherols and carotenoids, which contribute to its significant antioxidant activity of 58.90% [104] (Table 2).

NUTRITIONAL, PHYTOCHEMICAL COMPOSITION AND ANTIDIABETIC POTENTIAL OF VEGETABLE WASTE

Vegetable waste is rich in phytochemicals, carotenoids, and other components that contain antioxidant and anti-diabetic properties. This section deals with the anti-diabetic potential of vegetable waste. Also, other parameters like nutritional composition are discussed.

Lemon (Citrus limon)

Lemon (*Citrus limon*) is a member of the *Rutaceae* family. Citrus fruits have many phytochemicals and bioactive components like α-/β-pinene, sabinene, β-myrcene, d-limonene, linalool, α-humulene, and α-terpineol [114]. Lemon peel is a rich source of protein (9.42%). Apart from protein, it has a moderate amount of fat (4.98%), a high amount of ash (6.26%), and fiber (15.18) (Table 4). It is rich in macro and micronutrients like sodium (755.5 mg/100 g), potassium (8600 mg/100 g), calcium (8452.50 mg/100 g), iron (147.65 mg/100 g), magnesium (1429.50 mg/100 g), and phosphorus (6656.25 mg/100 g) [115]. In research on β-cell-specific toxin-induced diabetic rats, a methanolic extract of lemon peel was administered fortnightly, resulting in a substantial reduction in the glucose level of blood as compared to control groups. The study concluded that the presence of flavonoids like naringin and hesperidin is related to their antidiabetic properties [116].

Another study which contains groups that received low-dose and high-dose lemon peel extract (500 mg/kg BW), showed a reduction in glucose levels as compared to the control groups (Table 6.).

Table 4. Proximate analysis of vegetable waste

S. No	Vegetables	Parts	Carbohydrates %	Protein %	Fat %	Fiber %	Moisture %	Ash %	Ref.
1	Lemon	Peel	----	9.42	4.98	15.18	81.23	6.26	[118]
2	Potato	Peel	4.97	10.76	4.98	68.73	8.01	10.56	[119]
3	Drumstick	Seed	48.26	36	39	2.87	9.56	8.24	[120]
		Leaves	8.1	25.4	6.00	33.2	7.5	9.2	[121]
4	Red bell Pepper	Seed	3.35	14.1	6.66	32.4	88	2.06	[122]
5	Bottle gourd	Seed	8.30	35	39	59.05	17.5	5.08	[123]
6	Bitter gourd	Seed	51.29	14.30	11.50	20.5	8.50	2.9	[124]
7	Pumpkin	Seed	26.46	5.63	38	49.83	9.00	2.50	[125]
8	Coriander	Stem	---	12.58	9.12	37.0	6.2	8.53	[126]
9	Onion	Peel	80.60	3.90	3.20	26.84	91.05	11.46	[127]

Table 5. Major bio-active compounds that exhibit anti-diabetic property in vegetable waste

S. No	Vegetable Name	Part	Bioactive compounds	Ref.
1	Lemon	Peel	Hesperidin and naringin & flavonoids	[117]
2	Drumsticks	Seed	Glucomoringin, flavonoids, catechin Chlorogenic acid, quercetin, kaempferol, gallic acid, ellagic acid and ferulic acid	[128-130]
		Leaves	Polyphenols, flavonoids, quercetin, chlorogenic acid and isothiocyanates	[131-133]
3	Red bell pepper	Seed	Sterols (Campesterol, Stigmasterol, β-Sitosterol), triterpenes (betulinic acid), tocopherols, luteolin, quercetin and capsaicin	[134,135]
4	Bottle gourd	Seed	Flavonoids, terpenoids	[123]
5	Bitter gourd	Seed	Hydroxycinnamic, quercetin	[136]
6	Coriander	Stem	Gallic acid	[137]
7	Pumpkin	Seed	Flavonoids, tannins, phenolic and saponins.	[138]
8	Potato	Peel	Polyphenols (caffeic acid and gallic acid), flavonoids (chlorogenic acid, quercetin)	[139]
9	Onion	Peel	Phenolic and flavonoids	[127]

Table 6. Overview of the anti-diabetic potential of animal waste through animal model supplementation studies

S. No	Vegetable part	Bioactive Compound	Experimental design	Dosage	Inference	Ref.
1	Potato peel	Polyphenols	Male Wistar rats were given streptozotocin to develop diabetes. Potato peel was shown in two different concentrations 5% and 10%	Six rat groups: control, 5% and 10% potato peel, STZ-treated, and STZ with 5% or 10% potato peel. Pellet diets with or without potato peel were given for 4 weeks.	Potato peel powder lowered blood glucose and reduced liver and kidney hypertrophy in diabetic rats.	[45, 173] [174]
2	Lemon peel	Polyphenols	Rats weighing 240–280 g were chosen for the study.	Animals were divided into four groups: control (normal and diabetic), low-dose, and high-dose lemon peel extract (500 mg/kg BW).	Low blood glucose observed for high lemon peel extract dosage	[117, 175]
3	Drumsticks					
	Seed	Glucomoringin, along with flavonoids	Adult albino rats having streptozotocin-induced diabetes	Animals were divided into 4 groups- Control (Both diabetic and normal), and treated with moringa seed powder (50 and 100 mg/Kg body weight)	A dose-dependent relationship was observed between seed powder and glucose level.	[129, 176]
	Leaves	Polyphenols and flavonoids	Male Sprague-Dawley rats having streptozotocin-induced diabetes	Animals were divided into 5 groups- Control (Both diabetic and normal), and treated (glibenclamide- 2.5 mg/Kg body weight and moringa leaf extract 300 mg/day)	Notable drop in glucose levels for extract-treated animals	[147, 177]

4	Red bell pepper seed	Carotenoids, tocopherols, luteolin, quercetin and capsaicin	Male mice were divided into 4 groups each containing 4 mice.	Animals were divided into 4 groups- Control (Both diabetic and normal), and treated (Red bell pepper seed extract- 200 mg/Kg body weight and metformin 150 mg/day)	Extract administration improved the glycaemic control biomarkers.	[151]
5	Bitter gourd seed	Triterpenoids, saponins, flavonoids, alkaloids	Alloxan-induced male Albino Wistar rats (120 mg/kg BW)	Animals were divided into 4 groups- Control (Both diabetic and normal), and treated (glibenclamide- 0.07 mg/Kg body weight and bitter gourd seed extract 150 mg/day body weight) for 30 days.	The high anti-diabetic potential was observed for extract-treated animals.	[158]
6	Bottle gourd					
	Seed	Ascorbic acid, Carotenoids, Vitamin B-complex, Cucurbitacins, Flavone C-glycosides, Saponins	Six adult albino female rats having diabetes induced with alloxan (100 mg/kg BW) were chosen for the study.	Diabetic groups were treated with bottle gourd pulp extract (250mg/kg BW) and seed extract (250 mg/kg BW)	The study revealed that blood glucose went down to 112 mg/dl from 210 mg/dl after the treatment with bottle gourd seed extract.	[155]
7	Pumpkin seed	Hypoglycemic proteins and seed oils	Streptozotocin-induced adult male mice (55 mg/kg BW)	In total, five groups were made including Control (Normal and diabetic) and treated (Metformin - 65 mg/kg; Ethanolic pumpkin flesh extract -150 mg/kg and seed extract - 150 mg/kg)	The blood glucose levels reduced from 304.67 mg/dl to 74.33 mg/dl on the 14th day.	[162, 178]
8	Coriander stem	Antioxidants and Phenols	Alloxan-induced (150mg/kg BW) male and female Wistar Albino rats weighing 150–180 g were used.	Groups: Control (Normal, Diabetic), Treated (Glibenclamide 5 mg/kg/day, Coriander Leaf 150 mg/kg, Coriander Stem 200 mg/kg)	Group 4 showed hypoglycemic effects with a blood glucose level of 124.40 ± 1.66 mg/dL, while the positive control (Group 2) had 256.47 ± 1.61 mg/dL.	[166]
9	Onion					
	Peel	Quercetin and other total phenolic compounds	Overnight fasted Alloxan-induced Sprague Dawley rats (120mg/kg BW).	Groups: Control (Normal, Diabetic), Treated (1%, 3%, 5%, 7% OPE)	Reduction in blood glucose level for 3% OPE treated group	[172, 179]

The study examined four groups: normal and diabetic controls, along with treatment groups. Group 1 exhibited a noticeably elevated FBG level of 283 mg/dl. Continuing from thirty-five days of LP extract treatment markedly lowered blood glucose levels of rats with diabetes from 280 mg/dl to 180 mg/dl with a low dosage of lemon peel extract and from 277 mg/dl to 155 mg/dl with a high dosage of lemon peel extract [117].

Potato (Solanum tuberosum)

Potato is a member of the family *Solanaceae*, and it has been marked as the fourth in the world's most utilized food crop after rice, wheat, and maize [140]. The major producers of potatoes in the world are China, followed by India and Russia, with an annual production of 88, 45, and 30 million tons, respectively. During processing, 15 to 40% of waste is generated as potato peel, which can be beneficial in many ways [141].

Potato peels contain much more protein, fiber, ash, and minerals (except magnesium) than the flesh of the tuber. Amongst microminerals, potassium is the most abundant element in both portions of the potato tuber, followed by P, Mg, Ca, Fe, Zn, B, Mn, and Cu [142]. The proximate composition of potato peel is given in Table 4. Some of the phenolic acids present in potato peel are caffeic acid, protocatechuic, gallic acid, chlorogenic acid, vanillic acid, ferulic, and salicylic acid. Major flavonoids isolated from potato peel include quercetin, catechin, epicatechin, and naringenin. Among these, chlorogenic acid, quercetin, gallic, and caffeic acid have potential antidiabetic properties [143] (Table 5).

An *in vitro* study suggests that the potato peel possesses potent antioxidant properties, making it suitable for use in functional or healthy foods to mitigate oxidative stress, which has been identified as a major contributor to the pathophysiology of diabetes mellitus. In β-cell-specific toxin-induced diabetic rats, potato peel has been shown to impact both antioxidant status and glycemic index. A four-week diet supplemented with potato peel powder lowered the levels of the blood of infected rats. The aqueous extract of potato peel contained 3.93 mg/g of polyphenolics on a dry weight basis [144].

Another study, which contained 6 groups of male Wistar rats that were induced with diabetes using streptozotocin (STZ), showed a significant reduction in blood glucose levels. It had a control group, two groups receiving 5% or 10% potato peel, an STZ-treated group, and two groups treated with STZ along with either 5% or 10% potato peel. The treatment was administered through pellet diets over four weeks. It showed a significant reduction in blood glucose levels in rats that were fed with potato peel powder. Additionally, the treatment helped reduce liver and kidney hypertrophy in diabetic rats, indicating its potential protective effects. [145] (Table 6).

Drumstick (Moringa oleifera)

Drumstick is a member of the family *Moringaceae;* it has white, sweet, scented flowers, and it's very commonly found all over India. Moringa trees have remarkable nutritional value and medicinal properties [146]. Many phenolic compounds like lignans, flavonoids, and phenolic acids are present in the moringa plant. Medioresinol, quercetin, and caffeoylquinic acid derivatives are also present in moringa plant. Research has shown that moringa leaves can cure Type 1 and Type II diabetes [133].

The proximate analysis of *Moringa oleifera* leaves showed high protein content and low levels of fat, fiber, and ash. They also contained significant amounts of vitamin C, calcium, phosphorus, and potassium. Functional properties like water absorption capacity and foam stability were observed [121]. A study conducted on male Sprague-Dawley rats with streptozotocin-induced diabetes showed that the leaf extract resulted in a significant hypoglycemic effect, with fasting blood glucose levels decreasing from 236.8 ± 62.84 mg/dL to 171.8 ± 52.69 mg/dL by day 14, representing a 26% reduction. Groups in total for this study were 5: normal and diabetic controls, along with treatment groups receiving glibenclamide (2.5 mg/kg BW) and moringa leaf extract (300 mg/day) [147].

Few studies have established anti-diabetic effects of moringa seed powder in animal models, especially in streptozotocin or alloxan-induced diabetic rats. Animals were divided into 4 groups—control (both diabetic and normal) and treated with moringa seed powder (50 and 100 mg/kg body weight). The fasting blood glucose levels in animals fed with moringa seed powder (5%) were recorded at 174.17 mg/dl, while in Group 4, they were measured at 148.83 mg/dl. A dose-dependent relationship was observed [129]. Quercetin is reported to impart a hypoglycemic effect and is found to inhibit α-glucosidase activity. Similarly, when β-cell-specific toxin-induced diabetic male albino rats were administered an aqueous extract of drumstick seed, the sugar levels in blood were considerably lower in all groups in comparison to the control group. In addition, it was also found in the study that after drumstick seed extract administration, the levels of creatinine, urea, and albumin were also controlled and were effective against diabetic nephropathy [148].

Red bell pepper (Capsicum annuum L)

Red bell pepper belongs to the family *Solanaceae*. *Capsicum annuum* fruits contain a complex chemical makeup that includes capsaicinoids such as capsaicin and dihydrocapsaicin, which are responsible for their intense flavor. Leaves include alkaloids, tannins, and flavonoids, whereas roots contain steroids, alkaloids, coumarins, glycosides, and triterpenoids [149]. The extract of pepper shows the potential of decreasing postprandial hyperglycemia by delaying the production or absorption of glucose, and it has also been linked to the antioxidant property too [150].

In a study, male mice were divided into 4 groups, each containing 4 mice, and animals were divided into 4 groups: control (both diabetic and normal) and treated (red bell pepper seed extract—200 mg/kg body weight and metformin—150 mg/day). Group 3 fasting glucose was 429 mg/dl, whereas Group 2's fasting glucose was 544 mg/dl. Red pepper seed extract supplementation improved glycemic control, including regulation of insulin levels. The extract downregulated the gene expression of genes PEPCK and GP6Pase. These are involved in gluconeogenesis. This anti-diabetic effect was attributed to increased phosphorylation of transcription factors. Overall, RPSE shows promise in improving the control of glycemic index by inhibiting glucose formation in the liver in ObD mice [151].

Bottle gourd (Lagenaria siceraria)

Bottle gourd is a member of the *Cucurbitaceae* family and has huge applications in pharmaceutical and dietary developments [152]. The fruit is very rich in vitamin C; it also includes sterols, terpenoids, and flavonoids that have high medicinal properties [153]. The bottle gourd extracts inhibited alpha-amylase with an IC50 of 1.35 mg/mL, which is equivalent to that of the Acarbose (IC50-1.26 mg/mL). The study on the anti-diabetic potential of bottle gourd stalk showed that the aqueous extract has a strong inhibition capacity on α-amylase with an IC50 value of 1.35 mg/mL. This was higher than the inhibition observed for the antidiabetic drug Acarbose (IC50-1.26 mg/mL) [154].

In another study, six adult albino female rats with diabetes induced by alloxan (100 mg/kg BW) were chosen. Diabetic groups were treated with bottle gourd pulp extract (250 mg/kg BW) and seed extract (250 mg/kg BW). The study revealed that blood glucose went down to 112 mg/dl from 210 mg/dl after the treatment with bottled gourd seed extract [155].

Bitter gourd (Momordica charantia)

Bitter gourds are vegetables that have been researched most for their health-benefiting properties. They contain triterpenes, phenols, flavonoids, isoflavones, terpenes, anthraquinones, and glucosinolates, all of which contribute to their peculiar bitter flavor. Major anti-hyperglycemic activity in bitter gourd is reported to come from charantins, insulin-like peptides, and alkaloids [156]. The fruit is rich in both fat-soluble and water-soluble vitamins and a variety of B vitamins, including B1, B2, B3, and B9 (folate) [156] (Table 5). Bitter gourd seeds contain polypeptide K and include nine necessary amino acids, with glutamic acid, aspartic acid, arginine, and glycine being the most prevalent. Stearic acid was found in abundance in the seed oil, as well as oleic and linoleic acids. Polypeptide K and seed oil inhibited pancreatic enzymes responsible for glucose absorption in vitro, which shows the capacity as hypoglycemic drugs [157]. Six adult albino female rats with diabetes induced by alloxan (100 mg/kg BW) were chosen for the study. Diabetic groups were treated with bottle gourd pulp extract (250 mg/kg BW) and seed extract (250 mg/kg BW). The study revealed that blood glucose went down to 112 mg/dl from 210 mg/dl after the treatment with bottled gourd seed extract [158].

Pumpkin (Cucurbita maxima)

Pumpkins belong to the family *Cucurbitaceae.* They cannot tolerate heat but contain plenty of beneficial components such as carotenoids, alkaloids, flavonoids, polyphenols, tannins, tocopherols, phytosterols, and cucurbitacin. These components have many therapeutic properties that also include the regulation of diabetes [159]. Pumpkin fruit contains vitamins niacin, phylloquinone, thiamine, riboflavin, and minerals including potassium, phosphorus, magnesium, iron, and selenium [160] (Table 5). Pumpkin seeds contain polysaccharides that improve insulin signaling, activate critical pathways, and reduce β-cell malfunction. These polysaccharides have significant anti-diabetic properties by controlling blood glucose in diabetic rats [3]. The bioactive compounds in pumpkin seeds, such as flavonoids, triterpenoids, and polysaccharides, contribute to their hypoglycemic effects by interfering with various methods in diabetes mellitus. Additionally, pumpkin seed polysaccharides and proteins have been implicated in lowering blood glucose levels. The presence of pectin, a dietary fiber, in pumpkin seeds regulates blood glycemic levels, making them beneficial for diabetic patients [161].

Diabetes was induced in male and female Wistar albino rats (150-180 g) using alloxan (150 mg/kg BW). In total, five groups were made, including control (normal and diabetic) and treated (metformin—65 mg/kg; ethanolic pumpkin flesh extract—150 mg/kg; and seed extract—150 mg/kg). The study reveals the very high anti-diabetic potential of pumpkin seed extract. The blood glucose levels were reduced from 304.67 mg/dl to 74.33 mg/dl on the 14th day [162] (Table 6).

Coriander (Coriandrum sativum)

Coriander is an annual plant in the *Umbelliferae* family that is valued for its spice, fragrance, nutritional, and medicinal qualities [163]. Coriander is regarded for its therapeutic characteristics, which include antibacterial, antifungal, and antioxidant activity, as well as its digestive effects. Coriander's phenolic chemicals have been found and investigated across the entire plant, including vegetative portions, leaves, stems, and seeds [164]. It contains 18% protein, 6.86% fat, 34.7% fiber, 2.77% moisture, and 9.83% ash (Table 4). Antioxidant and free radical scavenging properties are attributed to polyphenols, ascorbates, and flavonoids. The antidiabetic potential of coriander stem extracts is responsible for the overall oxygen scavenging activity and phenolic content, indicating that coriander stem is a valuable source of natural antioxidants with health-protective properties [163].

Evaluation of the anti-diabetic properties of coriander leaf extract showed significant results in insulin-deficient mice induced by alloxan. The leaf extract regulated the levels of blood sugar, and further study showed that it also maintained the β cell levels of the islets of the pancreas. In the in vitro study, coriander leaf extract demonstrated an IC50 value of 32.376 ppm for inhibiting α-glucosidase activity, compared to 82.272 ppm for acarbose, the standard drug [165].

Diabetes was developed in male and female Wistar Albino rats that weigh between 150 and 180 grams by using alloxan (150 mg/kg BW). There were 5 groups for the study: normal and diabetic controls, as well as treatment groups given glibenclamide (5 mg/kg/day), coriander leaf extract (150 mg/kg), and coriander stem extract (200 mg/kg). The results show that the coriander stem extract has hypoglycemic properties, as evidenced by the blood glucose level of 124.40±1.66 mg/dl. (group 4), while group 2's positive control group's glucose level is 256.47±1.61 mg/dl [166] (Table 6).

Onion (Allium cepa L.)

Onion is a member of the family *Amaryllidaceae*, and it is the second most-grown vegetable globally [167]. Onions, which have been known for their therapeutic virtues from ancient times, have been historically used to cure a variety of diseases. Experimental studies show that they have a variety of pharmacological actions, including lowering cholesterol, preventing platelet aggregation, and acting as a neuroprotective and anti-carcinogenic drug. Onions have anti-inflammatory qualities, activate the immune system, and have been shown to help prevent osteoporosis [168]. Onions contain a wide range of phytochemicals, which include sulfur-containing organic compounds, compounds that have phenol groups, etc. [169].

Peels are the major waste from onions. The nutritional content of onion peels is presented in Table 4. Apart from its good nutritional value, it is a rich source of polyphenols, including anthocyanins. The hypoglycemic effect of onion peels was observed in the administration of onion peel extract in different concentrations [170]. Onion peel extracts exhibited inhibitory activity against tyrosine phosphatase, alpha-glucosidase, xanthine oxidase, and alpha-amylase [171].

A study included seven groups of overnight fasting Sprague Dawley rats that have been supplied with alloxan (120 mg/kg BW) to develop diabetes. The groups were normal and diabetic controls, as well as treatment groups that received 1%, 3%, 5%, or 7% onion peel extract (OPE). From day 0 to day 56, the 3% OPE group had the greatest reduction in blood sugar levels, going from 289 mg/dL to 205 mg/dL, respectively, among all. This final blood sugar level was significantly lower than in the 1% OPE (234 mg/dL) and 7% OP (230 mg/dL) groups [172].

UTILIZATION OF FRUIT AND VEGETABLE WASTE IN THE PRODUCTION OF FOOD PRODUCTS

Utilization of fruit and vegetable waste is a challenge due to poor consumer acceptance of its primary form and the collection of huge quantities of waste for processing. The process is even more complicated as the waste collection and segregation require much energy and manpower. The chance of microbial contamination increases spoilage and leads to the risk of developing foodborne illness if not properly processed. Utilization of this waste not only helps generate a secondary income for the company but also increases the wide production of nutraceuticals [180]. Most by-products are nutritionally superior and can be excellent low-cost sources of protein and other bioactive compounds [181]. There are different methods for utilizing fruit and vegetable waste to produce functional foods or to incorporate peel/pomace or seed powder into a product as a functional ingredient.

Herbal infusions and drinks

Herbal teas are one of the most important types of tea made from different ingredients that may contain therapeutic properties. It contains antioxidants, polyphenols, and so many flavonoids [202]. Herbal tea is commonly referred to as any beverage plant that doesn't belong to the *Camellia* genus. Tea prepared with dehydrated avocado peel showed high antioxidant activity, and it also had good sensory acceptability [182]. In a study conducted by Ubbor *et al*., herbal teas were developed from pure blends of moringa leaves, dried lemon peel powder, and a mixture of moringa leaves and lemon powder. It's been shown that the results of the proximate analysis were comparable with the control, but the vitamin C content and the phytochemical content showed a relatively high concentration [183].

Not only tea but also research done on developing herbal drinks based on fruit and vegetable waste has been carried out. An herbal extract called 'Tisane' has been developed using pomegranate seed powder and pomegranate peel powder in different ratios. The study showed that the blends of these powders had great antioxidant capacity and retained most of the flavonoids that were originally present in the raw materials [203]. Kombucha is a fermented drink prepared from a symbiotic culture of bacteria and yeast called 'SCOBY'. The ingredients of Kombucha involved are black tea, sugar, and fruit pulp [204]. Kombucha prepared from banana peel showed high antioxidant capacity and acted as a suitable ingredient [205]. Kombucha prepared from orange and pomegranate peel also showed good sensory and antioxidant properties [206].

Preparation of edible coatings

Edible coatings can enhance the sensory properties of the product and increase the microbial stability of the product by acting as a packaging material. Usually, polysaccharides and chitin are used as coated material. Apple pomace polyphenol is incorporated into standard coating material and was found to be very effective in increasing the shelf life of strawberries. It also showed that it has good antioxidant capacity [207]. In another study, they incorporated pomegranate peel powder with gelatin and found it to have increased water permeability and antioxidant properties [208]. An edible coating made from whey protein concentrate and apple pomace extract to extend the shelf life of fresh-cut apples. The coating was found to have good antioxidant properties and increased freshness of the product [209].

Functional ingredient in food

Fruit and vegetable pomace acts as a novel ingredient in bakery products to increase the functional properties, and they also increase the sensory properties. They increased the shelf of these products with the increased antioxidant contents in them. [210]. Raw and de-fatted flour from mango kernels used in bread as flour substitutes showed high levels of phenolic compounds [211]. Cake incorporated with apple pomace showed a good number of phenolic compounds and good functional properties [212]. Biscuits enriched with pearl millet flour and pomegranate peel showed high levels of total dietary fiber [213].

The sprouted pumpkin seeds showed an increase in phenolic content as compared to the raw ones. The amount of phenolic content from control to germinated ranges from 24.16 (control) and 215.01 mg GAE/100 g (germinated) to 57.14 (control) and 185.72 mg/100 g (germinated) [214].

Value-added products

Value addition is an effective methodology to increase the value of a product and a new possibility to increase the sustainability of a product. "USDA defines value addition as a change in the physical state or form of the product (such as milling wheat into flour or making strawberries into jam [215]). Food supplements, nutraceuticals, and oleoresins are examples of value-added products. Fruit and vegetable peels can act as a great source for producing value-added products.

Table 7. Studies depicting the valorization of fruit and vegetable waste into different products

S. No.	Ingredients used	Processing conditions	Benefit	Ref.
A	HERBAL INFUSIONS AND TEA			
1)	Avocado peel	Peels are chopped and dried in an oven at 60°C and dipped in hot water. It is then compared against Mate tea, Apple tea which was available in the market.	-Antioxidant activity was comparable with Mate tea (1954.24 a±87.92) -High level of phenolics (123.57a±4.64)	[182]

2)	Moringa leaves and lemon peel powder	3 Formulations – 100% moringa leaves, 100% lemon peel powder, Different ratios of Moringa leaves and lemon peel powder in the ratio 50:50, 30:70, and 60:40 respectively	-Tea with 100% lemon peel showed high carotenoid content (5.52µg/100g) -Tea with 100% moringa leaves showed high values of saponins and phytates 1.5 and 1.25mg/100g, respectively -Blend having 70: 30 also showed good alkaloid and tannin content, i.e, 1.29±0.01 and 11.50 ±0.01	[183]
3)	Mango leaf tea supplemented with moringa and ginger powder	3 Formulations – 100% mango leaves -A 60% mango leaf, 30% moringa leaf and 10% ginger - B 40 % mango leaf, 30% moringa leaf and 30% ginger -C Infusing 3g of tea powder into a tea bag and dipping it in hot water.	Showed a good number of glycosides. 1.89b ±0.1 1.86b ±0.15 and 1.08b ±0.2 for A, B and C respectively	[184]
4)	Herbal Tea prepared from orange peel	Orange peel was dried using different methods i.e. sun dried, oven dried, and air dried was ground and sieved. 2g peel powder added to 100ml	Catechin tannins are found to be present in all combinations	[185]
5)	Addition of Jamun seed powder in orange, ginger, and anola juice	Jamun seed powder extract at 5,10,15, and 20% of different concentrations with 10% anola fruit juice, 5% orange juice, and 2% ginger juice were	Among all the combinations, T3C7, ie, 15% JSE, 10% Anola Juice, 5% Orange juice, and 2% ginger juice, got the highest sensory acceptance	[186]
6)	Development of functional drinks from melon by-products	Melon seed powder and extract, melon peel extract, and powder were prepared separately. Different concentrations of this are mixed with 1L water, 13% sugar, 0.3-0.4 % citric acid 0.20% CMC	High phenolic and anti-oxidant capacity was observed for a 3% Melon peel extract-based drink (2.51 GAE/mg and 62.10 %)	[187]
B)	USES IN EDIBLE COATING			
1)	Edible films and coatings based on mango peel and seed kernel	Mango peel flour dissolved in citrate buffer, mixed thoroughly and then glycerol was added. Constantly agitated and and temperature lowered to 5°C. Films made by casting technique	Showed good polyphenol content of 14.7 GAE/mg and great protection to coated peaches	[20]
2)	Anti-microbial edible films from chitosan incorporated with guava leaf extract	Different ratios of vacuum filtered Guava leaf extract are added to a mixed solution of 2% chitosan and 2% acetic acid solution, stirred for 5h	Polyphenols in guava helped to increase the anti-microbial properties of chitosan.	[188]
3)	Potato Peel Extract based edible film	5g Potato peel powder is mixed with 93g of distilled water and 1.5g of glycerol. Poured on a labeled dish and dried	The phenolic component in Potato peel helped to reduce the oxidation and microbial activity (39 ± 0 mg of GAE for ethanolic extracts)	[189]
4)	Edible coatings Citrus limon peel extracts and *Ocimum tenuiflorum* leaf extracts	Limon peel and Tenuiflorum leaf extract were added to glacial acetic acid (100ml) and glycerol (0.75%) and coated on bananas.	Bananas with coating showed lowered weight loss but increased phenolic content as to non-coated ones. (4.9 % and 90.76%)	[190]

5)	Edible coatings Moringa leaf extract	2% moringa leaf extract + 0.5% chitosan extract and (CN 0.5%), M + CN 1%, M + CMC 0.5%, M+ CMC 1%) of chitosan concentrations. Fruit is dipped in the treatment solution	Moringa with 1% CMC extract lowered the ripening rate and also reduced the lipid peroxidation rate	[191]
C)	AS A WHOLE INGREDIENT			
1)	Mango peel powder	Washing, disinfection, blanching, drying (lyophilization, infra-red drying, oven drying, etc.), blending	Novel non-thermal methods retained the phenolic contents, and the peel powder works as a source to produce commercial pectin	[192]
2)	Pumpkin peel and seed powder	Parts were cleaned and dried in a hot air oven at 60ºC until constant weight and blending of the dried parts.	Peel powder showed good levels of antioxidant activities (DDPH - 13.00±0.08b mg AAE/100g)	[193]
3)	Guava leaf powder	Leaves were cleaned and dried in a hot air oven	Leaf extracts lowered post-prandial blood glucose levels in diabetic rats	[194]
4)	Jamun Seed Powder	Seed powder at a dose of 5g twice daily was given before meal was given to patients having Type 2 Diabetes and the control group was those who type 2 diabetes patients who got placebo powder.	Fasting plasma glucose reduced from 143 mg/dl to 131mg/dl	[195]
5)	Pomegranate peel powder	Peels and arils are cut into small pieces and dried at 38°C for 48h in a dryer. And is added to fruit salad at different concentrations (2.5: 2.5% & 5:5%)	The microbial colony was less as compared to the control one log reduction ie 4CFU/g for 5:5% and control 5 CFU/g in 1 week.	[196]
D)	AS AN INGREDIENT IN BAKING			
1)	Avocado seed powder in cupcakes	Seed powder is added to cupcakes at different concentrations like 0,5, 30 & 50 %	The total phenol content of cupcakes increased with increasing seed powder concentrations (5% -2.5, 3-30%, and 4 for 50%)	[197]
2)	Mango seed kernel on muffins	Dried mango seeds are separated from the stone, the kernels removed, and dried in an oven at 60ºC for 5 h, grinding and adding the powder to the muffins in different ratios ie 0%, 10%, 20%, 30%, and 40%	30% mango kernel increased the sensory qualities. It also increased the ash content from control -1.56 to1.82%	[198]
3)	Pomegranate seed powder in gluten-free bread	Pomegranate seed powder was added to bread ingredients in different ratios ie. 2.5%, 5.0%, 7.0%, and 10%, and baked at 230ºC for 20 min.	The total phenolic content of bread increased 2.8 times as that of control when 10% PSP was added (0.88 to 2.47 Mg/g)	[199]
4)	Watermelon rind flower in wheat flour cookies	Rinds are dried and milled by an attrition mill, sieved, and added to cookie flour. The combination ratio of wheat flour in the ratio of 100:0% (sample A [control]), 97.5:2.5% (sample B), 95:5% (sample C), and 92.5:7.5% (sample D).	The ratio 97.5: 2.5% was more accepted. Showed a significant increase in vitamin C content as of control 2.72 to 7.23 mg/g	[200]
5)	Potato peel in fabricated potato snack	15g potato flour and peel of combined weight is maintained using different formulations. Spices and oil are added and baked.	The developed snack had a good amount of fiber content (9.82%)	[201]

A study of the production of single-cell protein from peels of orange, pineapple, and banana and wastes from garlic and sugar cane was conducted by Ahmed et al. using fungi under liquid fermentation. And it's been found that the substrates are suitable for producing SCP using *A. niger* [216]. Dietary fiber extracted from mango peel has great hydration capacities and antioxidant capacities due to the presence of phenolic compounds in the peel [217]. Soluble dietary fiber from orange peel showed a good extraction rate with an increase in temperature. The soluble dietary fiber content of orange peel is approximately 5%, and when the extraction temperature is increased to 135°C, the extracted fiber content reaches 24.28 percent. An approximate five-fold increase in extraction recovery was observed with raised temperature [218].

DISCUSSION

The current study gives an overview of the anti-diabetic activity of fruit and vegetable waste highlighting the presence of bioactive compounds such as polyphenols, flavonoids, carotenoids, and other phytochemicals. Through various mechanisms like the inhibition of carbohydrate-digesting enzymes, which include α-amylase and α-glucosidase, improvement in insulin sensitivity, regulation of oxidative stress, and upregulation of glucose transporters such as GLUT4, these compounds display their hypoglycemic activities.

Various fruit and vegetable by-products, including mango peel, pomegranate seeds, guava leaves, and orange peel, have shown promising anti-diabetic effects *in vitro* and *in vivo* models. For example, the extract from pomegranate peel has shown tremendous potential in inhibiting α-glucosidase which was like drug-like potency of pharmaceutical drug acarbose ($p=0.0295$) [107], whereas the onion peel extracts polyphenols significantly decreased the blood glucose levels from 289 mg/dL on day 0 to 205 mg/dL on day 56, in diabetic rats [172]. However, there are some gaps in this research. Even though various bioactive compounds have been identified, the molecular mechanisms through which they exert anti-diabetic activity require more biochemical and genetic research.

Secondly, most studies rely on *in-vitro* and animal models, with limited human clinical trials available to validate their efficacy and safety. Most studies are conducted on *in vitro* and animal models with very few human clinical trials that can confirm their efficiency and safety. Finally, although natural products are generally considered safe, long-term toxicity studies are necessary to evaluate their potential risks at higher doses. Several issues must be resolved to take full advantage of fruit and vegetable waste for diabetes management.

Consumer perception is another key hurdle, since the idea of incorporating waste-derived materials in nutraceuticals may be met with suspicion and opposition due to safety and hygiene concerns. Regulatory clearances are also a barrier because the items must undergo extensive testing and validation before they can be launched. Scalability, processing, and storage of massive amounts of fruit and vegetable waste are further logistical problems. Stability difficulties also arise with bioactive substances. Most phytochemicals deteriorate due to heat, light, and oxygen, necessitating improved formulation procedures to increase the shelf life.

Pharmaceutical applications include the potential for bioactive molecules to be developed as supplementary therapy to standard diabetic medications. Future research should focus on improving extraction and processing technologies, such as supercritical fluid extraction and enzyme-assisted extraction, to increase active ingredients, yield, and bioavailability. Rigorous clinical trials are required to establish dose recommendations and determine long-term safety. Encapsulation and delivery technologies, such as nanoencapsulation, should be investigated to improve the stability and bioavailability of these drugs. Furthermore, incorporating fruit and vegetable waste into functional food production chains has the potential to speed up large-scale integration. Finally, approaches to customized nutrition will adapt diabetic interventions based on genetic diversity.

In conclusion, fruit and vegetable waste is a valuable yet underutilized resource in the battle against diabetes. There has been significant progress in clarifying its bioactive potential; nevertheless, there is still an urgent need for more research, regulatory clearances, and smart commercialization activities to put this knowledge into practical, consumer-friendly health solutions.

CONCLUSION

The fruit and vegetable processing industry generates a substantial amount of waste, including peels, seeds, pulp, and discarded pieces that are rich in vitamins, minerals, and bioactive compounds. Many bioactive compounds, such as quercetin, fiber, naringin, peptides, and fatty acids, have demonstrated hypoglycemic potential. In-vitro and in-vivo studies indicate that supplementation with fruit and vegetable waste can exert anti-diabetic effects through various metabolic, enzymatic, and molecular mechanisms. These include enhanced insulin production from β-cells, suppression of apoptosis, pancreatic cell regeneration, improved peripheral glucose uptake, controlled glucose release, and activation of antioxidant enzymes like catalase and glutathione peroxidase. Additionally, reduced activity of glucose-metabolizing enzymes such as α-amylase, upregulation of PPARγ and PPARα, and enhanced transcription of Nrf2 have been proposed as contributing factors.

Along with these promising findings, further research is needed to fully elucidate the mechanisms of action and optimize extraction techniques to enhance the bioavailability and effectiveness of these bioactive compounds. Innovations such as nano-encapsulation, green extraction methods, and AI-driven personalized nutrition strategies could address existing research gaps. Furthermore, large-scale human clinical trials and regulatory support will be critical for the commercial development of functional foods, nutraceuticals, and pharmaceutical applications. By integrating scientific advancements with sustainable waste utilization practices, fruit and vegetable by-products can be effectively transformed into valuable therapeutic resources for diabetes management.

Statements and Declaration

- *Author contribution- VT- Study conception and design, written, edited, and supervised the manuscript. NV, RS, JK, KA, TP, and AM- collection of data and drafting the manuscript. AK, VS, and PP have edited and improvised the final draft. All authors reviewed the manuscript and approved the final version of the manuscript.*
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