Polydextrose as a functional ingredient and its food applications: A review

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Abstract: Polydextrose (PD) is a low calorie, sugar free, low glycemic carbohydrate that has a variety of functional properties including high water solubility, high glass transition temperature, prebiotic properties, good stability at elevated temperature and over a broad range of pH and is widely recognized as soluble dietary fibre. PD induces physiological effects, such as increasing fecal bulking, softening stools, decreasing fecal pH, increasing short chain fatty acid concentrations and reduces the concentration of carcinogenic substances in the colon. It also aids blood glucose homeostasis and can decrease low density lipoprotein (LDL) cholesterol and total cholesterol levels in blood serum. These functional and physiological benefits have led to considerable interest from the food industry to use PD in the development of new healthy products. PD is widely used in food applications such as baked goods, ice cream, beverages, confectionery, chocolate, yoghurt, and salad dressings, among many others. There is no maximum established limit for PD. However, good manufacturing practices (GMP) limit the quantity to the amount necessary to accomplish intended purpose in the food. This review describes the production process, chemistry, functional properties, physiological functions, food applications, safety and tolerance, and regulatory and labeling information of PD.

Keywords: Polydextrose, functional properties, physiological functions, food applications, safety and tolerance

Introduction

The level of health awareness among the consumers worldwide has increased and the concept of fibre-rich diet is gaining importance due to its well known digestive health benefits. In the recent years, many low-calorie fibre foods have become a part of the consumer’s daily diet. Among those, PD has been identified as a source of soluble dietary fibre in foods and beverages in many countries (Wang et al. 2014). PD is comprised of 90% soluble fibre and an energy value of only 1 kcal/g. It is a non-digestible polysaccharide composed of randomly cross-linked glucose. Due to its good processing performance and potential health benefits, it is widely used as low-calorie bulking agent in a variety of foods and a partial replacement for fat and sugar (Černá et al. 2003). PD has been approved as a direct food additive (21 CFR 172.841) by the US Food and Drug Administration for use as a nutrient supplement, texturizer, stabilizer or thickener, formulation aid and humectants (Burdock and Flamm, 1999). Previous clinical and in vitro studies revealed that PD induces physiological effects, such as increasing fecal bulking, softening stools, decreasing fecal pH, reduces transit time, increasing short chain fatty acid (SCFA) concentrations and the amount of beneficial bacteria (e.g. Lactobacillus and Bifidobacterium) (Jie et al. 2000; Probert et al. 2004; Lahtinen et al. 2010; Raninen et al. 2011; Tiihonen et al. 2011). In addition, PD fermentation reduces the concentration of certain putrefactive/carcinogenic substances (e.g. indole and p-cresol) in the colon (Endo et al. 1991). PD also aids blood glucose homeostasis because of its low glycemic index compared to the reference glucose (Foster-Powell et al. 2002) and can decrease LDL cholesterol and total cholesterol values in human blood (Liu and Tsai, 1995). The high tolerance and functional properties of PD allow the development of food products with a variety of nutritional improvements without compromising taste and texture profile (Tiihonen et al. 2011). The present review focuses on the structure, functional properties, physiological functions, food applications, safety and tolerance and regulatory and labeling information of PD.

Production process

PD is prepared by a vacuum melt process involving polycondensation of glucose in the presence of small amounts of
sorbitol and citric acid/phosphoric acid in the ratio 89:10:1, respectively. Sorbitol acts as a plasticizer and citric acid as a catalyst in the polymerization (Rennhard, 1973; Radosta et al. 1992). Typically, corn glucose is used. It is important that the molecular size of the polymer is controlled (MW about 5,000) during the manufacturing process in order to restrict the formation of large molecular weight molecules. This control prevents the formation of insoluble materials and results in the highly water soluble nature of PD (Beereboom, 1981; Allingham, 1982). The polymer is subjected to various clean-up procedures to produce several qualities of PD. The process was patented by Rennhard in 1975. It is available in two forms: PD-A (acid form) and PD-N (neutralised form), the latter being a practically neutralised product obtained by the addition of potassium hydroxide or carbonate to a solution of PD-A (Burdock and Flamm, 1999). It tastes bitter, astringent and sour and that is why it is modified by refinement (e.g. removal of citrate esters, neutralization and reduction) to remove undesirable characteristics. It may be neutralized with any food-grade base and/or decolourized and deionised for further purification. The bitter taste could also be remedied by passing the final PD, in aqueous solution, through an ion-exchange resin and this ion-exchange procedure removes the bound acid. Commercial PD is more purified form available under brand names such as Sta-Lite® by Tate & Lyle, Decatur; Litesse® by Danisco, New Century, Kan., now a division of DuPont Nutrition and Health; and Trimcal® from C&H Ingredients, Farington, UK.

Chemistry of polydextrose

PD is described in its Foods Chemicals Codex (FCC) monograph (Anonymous, 2004) as a randomly bonded condensation polymer of D-glucose, sorbitol and citric acid. Commercial PD also contains small amounts of free glucose, sorbitol, citric acid, and 1, 6-anhydro-D-glucose (levoglucosan). PD is highly branched, with a degree of polymerisation between 2 and 110 (on average approximately 12 glucose units), and with an average molecular weight of ~2,000 Daltons (Allingham, 1982; Murray, 1988). All possible linkages with the glycosidic carbon of glucose are present: α- and β-(1,2), (1,3), (1,4) and (1,6) with the (1,6) linkage predominating (Auerbach et al. 2007). A representative structure of PD is given in Figure 1 and its physico-chemical properties are summarized in Table 1.

Technical and functional properties

PD is an odourless, neutral taste, white to cream amorphous powder with virtually no sweetness. It is highly soluble in water (approximately 80% w/w at 20°C) and solutions have a higher viscosity than sucrose or sorbitol solutions at equivalent concentrations and temperatures. This characteristic enables PD to provide the desirable mouthfeel and textural qualities when replacing sugars and fats (Mitchel, 1996). PD can be used to replace both sucrose and fat in chocolate and toffee confectionery. This has led to the development of light, reduced calorie and tooth-friendly products which utilise hydrogenated PD that does not contain residual cariogenic monosaccharides. PD also exhibits excellent stability over a wide range of temperatures and pH conditions. Model system containing PD have indicated very good stability against hydrolysis over broad range of pH 4.5-6.0 and temperature making it ideal for use in many beverage applications, even those at lower pH. No significant hydrolysis would be expected at any storage temperature when pH is higher than 4.0 (Beer et al. 1991).

An important characteristic of PD is that it has water activity closely resembling that of sucrose and can function as humectants helping to slow down undesirable changes in the moisture content of foods (Mitchel, 1996). This prolongs shelf-life and is especially important for baked goods. In short crust pastry, the fat content can be reduced by up to 50% with the addition of PD while maintaining the texture normally associated with traditional full-fat pastry (Murphy, 2001).

PD is a functional food additive due to its prebiotic properties (Kolida et al. 2002; Srisuvor et al. 2013). It contributes only 25 per cent of the calories of sugar (1 kcal/g versus 4 kcal/g) and only 11 per cent of the calories of fat (9 kcal/g). The low calorie content of PD is a result of its poor digestibility in the small intestine and incomplete fermentation in the large intestine (Oliveria et al. 2009). The random bonds in the PD polymer prevent mammalian digestive enzymes from readily hydrolysing the molecule (Murphy, 2001). This property has led to the acceptance of PD as a dietary fibre in many countries (Craig et al. 1999; Flood et al. 2004). The functionality of this prebiotic is beneficial to humans and includes such aspects as promoting the growth of healthy bacteria and stimulating the immune system (Gibson, 2004; Srisuvor et al. 2013).

The amount of water in a food system greatly influences PD functionality and its subsequent effect on the glass transition temperature (Tg) of the composite food. PD powder is an amorphous glass with an anhydrous glass transition temperature of 110°C, which is significantly higher than that of most other carbohydrates and is partly a function of its relatively low molecular weight. This high Tg of PD can be helpful in raising the composite Tg of foods (Stowell, 2009). When used in ice cream and frozen products, the freezing point depression factor permits the texture of the finished product to be balanced to create a rich, creamy smoothness. Products stored in a freezer can undergo deleterious changes in texture (e.g. ice- and solute-crystallization, starch retrogradation), structure (e.g. collapse and shrinkage), and chemical composition (e.g. oxidation flavor/colour degradation). PD may do this by interrupting sugar or polyol re-crystallization and/or starch retrogradation, by providing structure and/or raising the composite Tg which is the glass transition temperature of a maximally freeze concentrated solution (Craig et al. 1994). The Tg values (where ice can no longer form)
of lactose (-28°C), sucrose (-32°C), fructose (-42°C), glucose (-43°C) and sorbitol (-43.5°C) are all lower than PD (-24°C). This means that replacement of these sugars with PD raises the composite Tg of a food (Slade and Levine, 1995). It also improves storage stability by narrowing the difference between the storage temperature and the composite glass transition temperature of maximally frozen concentrated solutions for frozen desserts.

In transparent beverages, PD is a magnificent choice of dietary fibre. High solubility, clarity and rheological properties similar to sucrose make PD versatile enough to add a desirable texture to a variety of liquids, including dairy drinks and yogurts, sauces and dressings, while reducing calories from fat or sugar. PD works particularly well in foods that require bulking agents or those that are traditionally sweet or rich in fat. It is able to maintain the texture and mouthfeel that often is lost in the process of removing sugar and fat to reduce calories. Sometimes it helps to mask off-flavors that might be getting from vitamins or minerals (Beristain et al. 2006). Being a humectant, stabilizer, thickening agent, soluble fibre and a proven prebiotic substance, PD offers opportunities for creating new foods with more diverse sensory characteristics.

Physiological functions

Digestive health: fibre and prebiotic action

PD is hardly digested in the small intestine after oral administration, with 60% of the PD excreted in feces and 30% fermented in the lower gut by intestinal microflora (Figidor and Rennhard, 1981). The slow and incomplete fermentation of PD ensures minimal production of gas in comparison to other more quickly fermentable oligosaccharides (Hernot et al. 2009). PD produces volatile fatty acids (VFA) caused by microbial fermentation in the large intestine and lowers the pH of large intestinal contents. The unique arrangement of glycosidic linkages of PD makes it resistant to hydrolysis by human digestive enzymes. This has been determined using [14C] labeled PD in rat and human intervention studies (Figidor and Rennhard, 1981; Figidor and Bianchine, 1983). After ingestion PD passes intact into the colon where it is partially fermented by the colonic microflora. The slow and consistent fermentation of PD was first demonstrated using an in vitro colon simulator (Probert et al.)

### Table 1 The physico-chemical properties of generic PD

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight range</td>
<td>162-5000 (90%)</td>
</tr>
<tr>
<td>Appearance</td>
<td>White-cream amorphous powder</td>
</tr>
<tr>
<td>Odour</td>
<td>None</td>
</tr>
<tr>
<td>Melting point</td>
<td>130°C</td>
</tr>
<tr>
<td>Solubility (25°C)</td>
<td>80% w/w</td>
</tr>
<tr>
<td>Viscosity (25°C, 50% w/w)</td>
<td>33.3 centipoise</td>
</tr>
<tr>
<td>Heat of solution</td>
<td>9 kcal/g</td>
</tr>
<tr>
<td>Water activity (20% w/w)</td>
<td>0.992</td>
</tr>
<tr>
<td>pH in water (100 g/litre)</td>
<td>2.5-3.5</td>
</tr>
<tr>
<td>Titratable acidity</td>
<td>0.14-0.16 meq/g</td>
</tr>
<tr>
<td>Caloric value</td>
<td>1 kcal/g</td>
</tr>
<tr>
<td>Relative sweetness</td>
<td>None</td>
</tr>
<tr>
<td>Water</td>
<td>Max 4%</td>
</tr>
<tr>
<td>Sorbitol</td>
<td>Max 2%</td>
</tr>
<tr>
<td>(anhydrous ash free basis)</td>
<td></td>
</tr>
<tr>
<td>Glucose</td>
<td>Max 4%</td>
</tr>
</tbody>
</table>

### Figure 1. Chemical Structure of PD

![Chemical Structure of PD](image)

**Table 1** The physico-chemical properties of generic PD
2004; Mäkivuokko et al. 2005) and subsequently confirmed in a study on the effect of PD on intestinal microbes and immune functions in pigs (Fava et al. 2007). It has also been shown in vitro that the microbes that ferment PD prefer branched and especially single-branched PD residues over non-branched residues, especially the (1,6) pyranose moieties are subjected to microbial degradation over other types of glycosidic linkages in the molecule (Lahtinen et al. 2010).

In a human intervention study by Endo et al. (1991) in which eight healthy volunteers were fed a diet rich in cholesterol and had a daily intake of 15 g of PD for 6 weeks, changes in colonic flora were accompanied by a decrease in fecal concentrations of Clostridium spp. In another human study, significant increases in the numbers of culturable Bifidobacteria and Lactobacilli together with decreased Bacteroides numbers have been demonstrated in a placebo-controlled, randomized, double-blind intervention study comprising 120 subjects (Jie et al. 2000). Improved bowel function was also demonstrated in the study with daily intake of 4-12 g PD with no adverse effects, such as abdominal distention, cramps or diarrhea reported. Supplementation with PD at 5 g/day and a probiotic mixture together was found to increase culturable fecal Bifidobacteria over supplementation with probiotic mixture alone when compared over a 2 week period in twenty human subjects (Tiithonen et al. 2008). Also, shortened oro-fecal transit time, implicating the role of PD in alleviating constipation, has been shown (Hengst et al. 2009). These findings suggest that dietary PD is a soluble dietary fibre-like substance and shown prebiotic properties like modification of the microbiota composition, activity and health benefits.

Digestive health: bowel function and fecal characteristics

Five human intervention studies (Tomlin and Read, 1988; Endo et al. 1991; Archour et al. 1994; Jie et al. 2000; Flood et al. 2004) and one study in rats (Oku et al. 1991) have all reported increased fecal weight in conjunction with dietary supplementation with PD. Nakagawa et al. (1990) and Tomlin and Read (1988) reported stool softening, and Jie et al (2000) reported improved ease of defecation in combination with PD supplementation. Two human studies have reported increased stool frequency on consumption of PD (Endo et al. 1991; Jie et al. 2000) while two other studies have shown no effect (Tomlin and Read, 1988; Nakagawa et al. 1990). A rat study (Oku et al. 1991) showed reduced transit time in association with PD consumption while two human studies showed no effect (Tomlin and Read, 1988; Archour et al. 1994). Decreased colonic pH, associated with the increased production of SCFAs, has been consistently reported in studies in human (Endo et al. 1991; Jie et al. 2000), rats (Peuranen et al. 2004; Yoshioka et al. 1994), and in two in vitro studies simulating human colonic digestion (Probert et al. 2004; Mäkivuokko et al. 2005). Hence, the ability of PD to favorably affect gut pH is well documented.

Serum cholesterol and triglyceride levels

PD is a fermentable non-viscous fibre, and has been shown to exhibit lipid metabolism regulating effects (Raninen et al. 2011). Typically these effects have been associated with two physico-chemical properties of soluble fibres: viscosity and fermentability. PD has been reported to confer lipid modulating effects in human clinical intervention studies, as well as in animal studies. In two rats feeding studies in which PD were accompanied with a lipid load, reduced lipid levels were reported. In one of the study, rats were given two different dosages of corn oil, 10% and 20%, to represent a moderate or high-fat diet, for 8 weeks, with or without 5% PD. Rats in the PD group showed decreased serum triglycerides as compared to a guar gum control in the high-fat diet, increased levels of serum HDL cholesterol both in the moderate fat and high fat diet (Choe et al. 1992). Another study has been done with gerbils for 4-weeks, the gerbils were fed with 0.15% cholesterol with 30% of the energy coming from fat and with inclusion of 6% PD. Liver and plasma total cholesterol as well as free and esterified cholesterol from liver decreased in the PD group (Prönzuk and Hayes, 2006). The acute response of PD on serum lipid values has also been studied in rats, but together with lactitol (Shimomura et al. 2005). The rats showed reduced serum triglyceride levels, and an increase in luminal triglyceride levels in the cecum after 150 minutes of ingestion of PD, which would indicate that the combination of PD and lactitol reduced either the level of fat absorption in the earlier part of small intestine or promoted the transit time of fat through the intestine (Shimomura et al. 2005).

In human study with normal healthy adults with no reported hypercholesterolemia a reduction in the amount of total HDL by administration of 15 g of PD for two months with concomitant decrease in apolipoprotein A-I, which is the main component of HDL cholesterol, has been observed (Saku et al. 1991). In another study with healthy adults, administration of 10 g of PD for 18 days was shown to decrease LDL cholesterol and total cholesterol values with no effect on HDL cholesterol or triglycerides (Liu and Tsai, 1995). There are also contradictory results with healthy humans, as administration of PD in an amount from 4 to 12 g per day for 29 days did not affect triacylglycerol, or cholesterol (Jie et al. 2000). Authors reported that due to relatively low fat content (20% of energy from fat) in Chinese diet, they did not expect to measure an effect of PD on blood lipids. In hypocholesterolemic individuals, the effect of PD has been studied in a 4-week study with administration of 15 g and 30 g PD daily (Prönzuk and Hayes, 2006). In this study it was noted that 5 of the 6 individuals ingesting 30 g of PD were in a separate responder group, and in third group the LDL cholesterol values declined significantly, and there was a tendency for reduced total cholesterol, but no change in HDL cholesterol. However, when all 6 individuals were studied together, no change compared to control was observed. Another study investigated the effect of PD on postprandial triglyceride (TG) responses in three independent trials including
The effect of PD on lipid values has been of interest in two studies with individuals showing abnormal glucose metabolism or type-2 diabetes. In subjects with impaired glucose metabolism, PD administered for 12 weeks at 16 g/day has been observed to lower LDL cholesterol, increase HDL cholesterol and cause no change in triglycerides (Schwab et al. 2006). In a combination study with 7 g PD and 3 g oligofructose administered daily for 6 weeks in adults with type-2 diabetes, a decrease in total cholesterol, TG, VLDL cholesterol, and ratios of total cholesterol to HDL cholesterol, and LDL cholesterol to HDL cholesterol was observed, while HDL cholesterol increased (Cicek et al. 2009). In a double blind and randomized study, nineteen healthy young adults consumed twice a standard hamburger meal with or without a cola drink containing PD (12.5 g). Postprandial triglyceride response was measured up to 360 min after the meal. The area under the curve was 25% in the PD trial than on the placebo trial (Vasankari and Ahotupa, 2005). As postprandial hyperlipidemia is believed to be an independent risk factor for the atherosclerotic vascular diseases, PD may provide new dietary concept to reduce risk factor.

Glycemic control and insulin response

The effect of PD ingestion on glucose and postprandial insulin response has been investigated in several studies. PD has a very low glycemic index (4 to 7) with glycemic load of 1 compared to the reference glucose (100) (Foster-Powell et al. 2002). Based on a recent EFSA scientific opinion, PD is suitable for those who want to follow a low glycemic diet when it is used as a sugar replacer (EFSA, 2011). PD has been reported to attenuate the blood glucose raising potential of glucose, as the glycemic index of glucose was reduced from 100 to 88 when 12 g of PD was ingested together with glucose by healthy adults (Jie et al. 2000). Similar results were observed in a study with healthy adults when 14 g was ingested together with 50 g of glucose or 106 g of bread (Shimomura et al. 2004). Plasma glucose levels were decreased by 28% and 35%, compared to glucose and bread without PD, respectively with significantly reduced serum insulin levels in the glucose plus PD group. These observations indicate that PD could reduce the absorption of glucose. When the effect of PD was studied with human subjects with impaired glucose tolerance or impaired fasting glucose, no change in plasma glucose or insulin has been observed (Schwab et al. 2006). Diurnally PD did not seem to change plasma sugar levels, but a decrease in insulin after meals was noted (Ozawa et al. 1993). In dogs, PD showed an attenuated postprandial glycemic and lower relative insulin responses than the control sugar maltitol (Knapp et al. 2008).

In one of study investigated the effects of a lactose-free milk drink, PD-enriched milk drink (fat- and lactose free), and regular fat-free milk on fasting insulin and glucose levels in healthy subjects (Lummela et al. 2009). The insulin response was significantly lower for the fibre-enriched milk drink than it was for the other milk products and however, no differences in the response for glucose. PD has been also studied in trials in which the reference group received a normal meal/snack with glucose, and the intervention group the same but with the glucose, and the intervention group the same but with the glucose partially replaced with PD. In volunteers with type-2 diabetes, cranberries with 10 g of PD showed attenuated plasma glucose and insulin response compared to cranberries with glucose (Wilson et al. 2010). In one study with healthy adults, significantly lower postprandial glucose levels were observed after ingestion of strawberry jam with 40% PD than after ingestion of strawberry jam sweetened with sugar, corn syrup, or apple juice, but this study did not measure insulin (Kurotobi et al. 2010). These above results indicate that PD might have a role in decreasing postprandial glucose absorption and insulin response.

Anti-carcinogenic activity

Cecal fermentation may be an important factor in inhibiting cancer formation, because the fermentation product butyrate is anti-carcinogenic (Perrin et al. 1994). Animal study has shown that the ingestion of PD has significant suppressive effect on formation of aberrant crypt foci (ACF) induced by 1,2-dimethylhydraine (DMH). The inhibitory effect of dietary PD was significant only in the case that the PD was fed from 1 week before DMH indication when compared with day 0, 1 and 7, indicating the timing of intervention with the PD-containing diet is critical for the inhibitory effect on ACF development and the effect was most pronounced in the rectum (Ishizuka et al. 2003). These results suggest that the ingestion of PD may prevent colorectal carcinogenesis.

Balancing immune responses in the large intestine is especially important for reducing the risk of colon cancer development. A possible mechanism for reduction in cancer development involves the regulation of mucosal gene expression. Over expression of the cyclooxygenase-2 (cox-2) gene is related to early stages of colon cancer development and chronic inflammatory diseases in the intestine. Mäkivuoekko et al. (2005) combined two different in vitro systems, namely a four-stage simulator of colonic fermentation and a cell-culture-based model of human intestinal epithelial function, in order to study the effects of PD on colon cancer development. A dose-dependent decreasing effect on cox-2 expression was observed in Caco-2 cells (a human colon cancer cell line). This reduction of cox-2 expression associated with the
colonic fermentation of PD further suggests a protective role of PD against colon cancer. Recently, the effects of PD fermentation metabolites on colon cancer cells and their gene expression were investigated in whole-genome scale using Affymetrix gene chips (Putaala et al. 2011). In this study, it was observed that PD fermentation metabolites increased caspase-2 and caspase-3 activation, which is a hallmark of apoptosis, increased the level of apoptosis as well as diminished cell proliferation of colon cancer cells. These studies combined indicate that PD might be beneficial in preventing risk factors associated with colorectal carcinogenesis, which could relate to its ability to promote SCFAs production (Makelainen et al. 2007).

Mineral absorption

Prebiotics like PD contribute to a reduced pH of the colonic digesta through their fermentation and thereby to an enhanced solubilization to both calcium and magnesium. Animal studies have shown that PD improves calcium absorption both in gastrectomized rats and normal rats (Hara et al. 2000; Santos et al. 2009), where the former provide a model for severely hampered calcium absorption. In normal rats, PD increased the amount of calcium and magnesium in bone (Hara et al. 2000), with increase in total and femoral bone mineral density and cortical area and thickness (Weaver et al. 2010). Iron is normally absorbed in the small intestine with the stomach playing an essential role in improving the biological availability of iron. In gastrectomized rats, PD has been shown to improve apparent iron absorption to levels approaching those of normal rats. Also, in normal rats, iron absorption was shown to be improved by PD (Santos et al. 2010). The study demonstrated the effects of components from a typical Japanese diet (isoflavones, tea catechin or dietary fibre) on equol (is a metabolite of the isoflavone diadzein (Dz)) production and bone metabolism in ovariectomised (OVX) mice. Dietary fibre (PD or raffinose) increased equol production and inhibit bone loss in OVX mice. This effect was greater than that of Dz alone for preventing bone loss in mice. PD thus seems to be able to play a role in improving mineral status.

Food applications

The functional benefits of PD have led to considerable interest from the food industry, leading to the use of this ingredient in the development of new healthy products (Murphy, 2001). PD allows the development of food products with a wide variety of nutritional improvements such as prebiotic, fibre fortification, calorie reduction, reduced glycemic load as well as sugar and fat reduction. The technological properties of PD facilitate the production of products with a taste and texture profile similar to that of standard products. In United States, PD is approved by Food and Drug Administration (FDA) for use in the following product categories: Chewing gum, confections and frostings, dressings for salads, frozen dairy desserts and mixes, gelatins, puddings and fillings, hard candy, soft candy, baked goods and baking mixes, fruit spread, peanut spreads, toppings and sweet sauces.

Baked goods

PD is widely used as a low-calorie bulking agent that can replace part of the sugars and some of the fat in low-calorie foods while maintaining a pleasant texture and mouth feel of breads, rolls, crackers, flour tortillas, pita bread, pizza crust, and muffins (Mitchell et al. 2001; Chaudhary et al. 2013). It would function primarily as a humectant and water binding ingredient to help slow down the effects of undesirable changes in the moisture content and hence prolong the shelf life of these products.

Martínez-Cervera et al. (2012) evaluated the suitability of a mixture of sucralose and PD to replace different percentages of sucrose in muffins. Low-sucrose muffins in which the sucrose had been totally or partially replaced (25%, 50%, 75%) by a sucralose:PD mixture (1:1012). The structural characteristics of the muffins batters and of the baked muffins were studied through rheometry, microscopy, image analysis and texture analysis. Replacement of 25% sucrose by a mixture of PD-sucralose altered none of the eating quality properties of the reformulated muffins. Further replacement of sucrose by PD-sucralose progressively affected the batter structure, both before and during the baking process. The replacement of sucrose decreased the viscosity, viscoelasticity and specific gravity of the raw muffins batter. It further results in a muffins with less height and fewer final air cells as the sucrose was replaced, and with low hardness and springiness. For 50% sucrose replacement, the appearance, colour, texture, favour and sweetness and general acceptability were similar to those of the control. Significantly less acceptable muffins were obtained with 75 and 100% sucrose replacement. In a subsequent study, muffins were produced where 30% sucrose of the formulation was replaced against an iso-sweet amount of Steviol glycosides (or rebaudioside A from Stevia rebaudiana Bertoni leaves) in combination with several fibres (pea fibre, oat fibre, wheat fibre, wheat bran, apple fibre, cellulose, maltodextrin, PD and inulin) (Zahn et al. 2013). Multivariate analysis of instrumental and sensory data indicates that a combination of inulin or PD with rebaudioside A results in products with characteristics close to that of a reference. The use of wheat bran or apple fibre as bulk replacer for sucrose gives products which mainly deviate in crumb colour and are characterised by a whole meal off-taste, whereas increased crumbliness and reduced elasticity is the consequence of partial sucrose replacement by oat, pea or wheat fibre, cellulose or maltodextrin. Compared to the reference muffin with 1.3 g of fibre/100 g, the replacement of 30% sugar by inulin increases fibre in muffins to 4.6 g/100 g so that it allows the claim “source of fibre” (EC, 2006). Muffins with PD can be regarded as “high fibre” (7.1 g/100 g) source (Zahn et al. 2013).
PD can be used to make fat-reduced pastry. In shortcrust pastry, the fat content can be reduced by up to 50% with the addition of PD while maintaining the texture normally associated with traditional full-fat pastry. Studies have shown that the addition of PD to shortcrust pastry increased the crispiness; reduced pastry shrinkage; improved the machinability of very thin sheets of dough; caused browning under microwave reheat conditions; reduced amount of sugars and fats in shortcrust pastry without affecting the organoleptic quality of the product. Using PD, the fat content of shortcrust pastry can be reduced to as little as 13 to 15% of dough weight while maintaining acceptable sensory characteristics (Mitchel, 1996).

Beverages and dairy drinks

PD would be used to replace sugar and/or fat in these products as low calorie bulking agent to improve creaminess and mouthfeel. PD can be used in variety of beverages including carbonated and non-carbonated, concentrated and ready-to-drink, hot and cold beverages. It is used in dairy drinks; neutral or flavoured, or low pH, pasteurized, or UHT and in many other clear beverage formats. PD improve the mouthfeel, giving the taste experience of a product of a much higher fat content; this is particularly noticeable in low-fat dairy drink applications (Anonymous, 1991). PD is also added to beverages as a source of dietary fibre as it is very soluble, forming clear solutions, and is very stable over shelf life.

Chocolate confectionary

The development of chocolate and composite chocolate products with reduced calories, sugar and fibre enrichment is possible with PD. PD functions to replace sugar and provide warm, creamy texture in the chocolate matrix without contributing mouth cooling effect or scratchy after taste (Mitchel, 1996). PD completes the chocolate flavor through the formation of small amounts of caramel during processing. Its low residual acidity ensures that the delicate cocoa and sweet flavors are brought forward and maintained (Renauld et al. 2003). PD may be added to chocolate as an edible carbohydrate and intense sweetener (Afoakwa et al. 2007). Gomes et al. (2007) obtained a diet chocolate using various bulking agents as sucrose substitutes. The bulking agents in the study were PD (24.14–48.27%), inulin, fructooligosaccharides, lactitol and maltitol and sucralose used with a high intensity sweetener. The formulations containing PD, PD and lactitol, and PD and maltitol were evaluated for a sensory analysis due to their good technological performance and adequate machinability of the chocolate mass at different stages of the process. The sensory analysis revealed no significant difference in the three evaluated formulations in terms of aroma, hardness, melting in the mouth and flavor and there was no significant difference in the intention to purchase the three chocolate formulations, although a preference was shown for the formulation containing PD (32.60%) and maltitol (15.57%). The production of a low-sugar milk chocolate with prebiotic properties of inulin was evaluated by Farzanmehr and Abbasi (2009). Various ratios of inulin, PD and maltodextrin (MD) along with sucralose (0.04% w/w) were used instead of sucrose. In general, formulations with high ratios of PD and MD were moister and softer than control. The lowest moisture content and highest hardness were observed for the moderate ratios. In addition, MD induced the least desirable sensorial effects, whereas PD and inulin pronouncedly improved the overall acceptability. PD has been reported as a good options as bulking agent to improve the overall acceptability of low-sugar milk chocolates (Farzanmehr and Abbasi, 2009). The diabetic prototypes of milk-chocolates were prepared by substituting sucrose with high-intensity sweeteners, sucralose or stevioside, and a PD/lactitol (60/40) blend as a bulking agent (Melo et al. 2010). PD and lactitol are usually well tolerated but may also have some dose-related undesirable effects owing to their natural osmotic potential and/or excessive fermentation (Marteau and Flourié, 2001). Shah et al. (2010) studied the development of a sucrose-free chocolate sweetened with Stevia rebaudiana extract and containing PD and inulin as a bulking agent. Aidoo et al. (2014) examined optimum conditions for the use of inulin and PD mixtures as sucrose replacers in sugar-free chocolate, and effects on rheological, physical properties and microstructure was also studied. The Casson plastic viscosity increased with increasing inulin concentration and reduction in PD, whilst Casson yield stress was reduced. The properties of chocolate formulated with 100% PD or 100% inulin were compared. Chocolate formulated with 100% PD revealed large crystals with dense smaller particles and minimal interparticle spaces compared to large crystals with more void spaces in chocolates formulated with 100% inulin. Chocolate formulation consisting of 75.3594% PD and 24.6406% inulin was found as the optimum concentrations producing the most acceptable rheological and physical quality characteristics. In a subsequent study, Aidoo et al. (2015) investigated the rheological properties, melting behaviours and other physical quality characteristics of sugar-free chocolates processed from inulin and PD mixtures (36 and 12,%w/w) (ratio of 25:75) as bulking agents sweetened with stevia (0.24 %w/w) and thaumatin (0.06 %w/w) extracts. The sugar-free chocolates (stevia and thaumatin) showed similar flow (rheological) and melting properties as compared to the reference chocolate containing 48 per cent sucrose. Sugar-free chocolates showed significantly higher viscosity than the reference chocolate. There were however no significant differences in the melting behaviour and texture of the sugar-free chocolates and the reference. Chocolates containing the sugar substitutes recorded lower onset temperatures and higher peak widths than the reference sample. Authors concluded that inulin and PD mixtures could be used for sugar-free chocolate manufacture with satisfactory physico-chemical properties when sweetened with stevia or thaumatin extracts.
Pasta and noodles

Fibre enhancement of noodle and pasta products is possible with PD as well as some process improvement benefits to mechanical properties of the dough. The addition of PD to the dough improves the firmness that can aid forming noodle or spaghetti strands or pasta shapes. The texture of the cooked product is not significantly altered by addition of PD and 95% of the added PD remains in the pasta or noodles after cooking (Matsuda, 2006).

Fish and meat applications

PD would be used to replace nutritive sweeteners or polyols in surimi (myofibrillar protein concentrate) and other comminuted fish and meat products such as chicken fingers, salmon patties, etc. It is an effective cryoprotectant, which unlike sorbitol or corn syrup does not add sweetness to the product (MacDonald and Lanier, 1991). To protect the muscle proteins from denaturation and so improve the technological properties of frozen muscle tissue cryoprotective substances are often used. PD can be used in meat products such as chicken nuggets to bind moisture in the meat patty. Moisture loss is reduced during cooking as well as moisture migration to the batter and breadcrumb coating. This has the effect of keeping the chicken nugget moist and juicy while the crispness of the coating is improved and stays crispier for longer after cooking (Satsuba and Okuma, 1995). Park et al. (1993) found that the functional quality of salted pre-rigor mince treated with PD as cryoprotectant and stored for 6 months at -28°C was about equal to that of post-rigor fresh muscle. It is possible that cryoprotectants could help maintain the functional properties of pre-rigor salted mince during long-term chilled or frozen storage. Sadler and Swan (1997) investigated the functional properties of minced beef that was salted pre-rigor with or without added PD, then stored, chilled in a vacuum pack or a carbon dioxide controlled atmosphere pack, or stored frozen. Adding PD (2.6%) to salted mince improved batter strain and stress compared with the non-additive and salt-only samples and thus helped in maintaining the meat’s functionality. Tomaniak et al. (1998) studied the effects of cryoprotectants (sucrose, D-sorbitol, maltodextrin and PD) on frozen red meat from slaughtered domestic mammals. They suggested that PD as the cryoprotectant of choice in red meat. Due its least sweetness, taste was distinctly suppressed by meat, its duration of sweetness was the shortest and its total flavour impact (the total area under the time intensity curve) was the smallest.

In surimi and reformed meat products, PD may be used as a cryoprotectant to modify the glass transition (Tg) of the frozen matrix and protect myofibrillar proteins from cold denaturation during frozen storage (Okada, 1992). Kovačević et al. (2011) investigated the cryoprotective effects of PD on chicken surimi using two different thermal analysis techniques. The samples of chicken surimi were mixed with different mass fractions of PD (w = 2 - 10%) plus κ-carrageenan (w= 0.5%), PD (w= 2 - 10%) plus sodium chloride (w = 2%), and PD (w= 2 - 10%). The addition of PD results in stabilization of myofibrillar proteins. The shift in the thermal transition temperatures of myosin and actin to higher temperatures, increase of enthalpies of myosin and actin transition, and shift of initial freezing point to lower values as the mass fraction of PD increases, indicating that PD acts in accordance with cryoprotecting mechanism and interacts with proteins in chicken surimi. Nopianti et al. (2012) used different types of low calorie sweetness sugar (lactitol, MD, palatinit, PD and trehalose) as a cryoprotectant on physico-chemical properties of threadfin bream (Nemipterus spp) surimi during six months of storage was investigated. They reported that surimi treated with a cryoprotectant exhibits better physicochemical properties compared with raw surimi. PD was able to maintain better physico-chemical properties (water holding capacity, folding test, gel strength etc.) than the other low sweetness sugars and sucrose during six months of frozen storage and hence suggested that, PD as a potential alternative cryoprotectant to replace other low-sweetness sugars (Nopianti et al. 2012).

Frozen dairy desserts

PD replaces the bulk, creaminess, smoothness, and mouthfeel of sugar and fat and enabling the formation of high-quality, low calorie and reduced-fat products (Kappas, 1998). It has greater viscosity in solution than sucrose or sorbitol at equivalent concentrations and its role in freezing-point depression helps in achieving creamy, palatable frozen desserts. A dessert can readily be formulated with PD to achieve a 50% calorie reduction when used with a high intensity sweetener. Goff and Jordan (1984) used PD and aspartame (0.06 to 0.1%) as sugar substitutes in a frozen dessert system. Smoothness and acceptability, as evaluated by sensory methods, indicated that substitution of PD for no more than 12% of the 14% total carbohydrates in the mix produced acceptable products. Layered desserts and yoghurts have been successfully formulated using PD as a low-calorie bulking agent (Barranates and Tamime, 1993). Specter and Setser (1994) studied the effects of milk fat and sucrose substitutes on physical and sensory properties of a frozen dessert system by sensory and instrumental methods. Two complex carbohydrate fat replacers, tapioca dextrin and potato maltodextrin, and a PD-aspartame sweetening system were evaluated. PD-aspartame effectively compensated for functional properties that normally were conferred by sucrose and milk fat. Replacement of milk fat with tapioca dextrin or potato maltodextrin increased coarseness and wateriness and decreased creaminess relative to the control. Roland et al. (1999) demonstrated the effects of fat replacers on the physical and sensory properties of fat-free ice cream. Ice creams (≤ 0.5% milk fat) were formulated with maltodextrin, milk protein concentrate, or PD. Lactose-reduced, freeze-concentrated skim milk was used to prepare a ice cream mix. Ice creams with 10 or 0.1% fat were prepared as controls. The addition
of fat replacers to fat-free ice cream decreased the amount of ice in the product. When compared with 0.1% fat ice cream, these fat replacers improved the appearance and texture of the ice cream but did not match the attributes imparted by 10% milk fat. The sample containing only maltodextrin had the greatest cream flavor and the best textural characteristics compared to sample containing PD or milk protein concentrate. In a subsequent study, low calorie ice cream samples were produced by mixing milk powder (2, 4, 6 or 8%) with either maltodextrin (10%), PD (10%) or a mixture containing equal ratios of maltodextrin-PD (5% + 5%) on weight basis and artificial sweeteners (aspartame and acesulfame-K) were added to mixes with reduced fat content (Güzeler et al. 2011). Maltodextrin added ice cream samples melted late or did never melt. However, melting of samples with PD takes place earlier. Therefore, PD has a positive effect on the physical properties of ice cream than maltodextrin. But sample containing PD received lower sensory scores than others. Authors demonstrated that the use of equal mixture of PD and maltodextrin had positive impact both on the physical and sensory properties of ice creams.

Cultured dairy products

Yoghurt is a healthy food due to the beneficial aspects of its high protein and calcium contents (McKinley, 2005). PD can be used as fat and sugar substitutes in low-fat dairy products owing to their advantageous functionality. Numerous researchers have tried to improve textural and functional properties of low-fat yoghurt by using this fat replacer. When used as fat replacer, they give fat-like mouth feel and texture (Helland et al. 2004). Allgeyer et al. (2010) demonstrated the effect of adding prebiotics and probiotics into yoghurt drink (stirred yoghurt) system. The prebiotics inulin, soluble corn fibre, and PD were shown to alter the sensory properties of the yoghurt drink when incorporated at different levels. When probiotics (Bifidobacterium lactis Bb-12 and Lactobacillus acidophilus LA-5) were incorporated, additional sensory changes were identified. Total variance explained by the principal component analysis biplot of factors 1 and 2 was 65%, which showed yoghurt drinks with soluble corn fibre and inulin varying by the sweet versus sour attributes and yoghurt drinks with PD varying by the mouth feel attributes. Based on the results of this study, only the PD treatment would be an acceptable vehicle to deliver the probiotic health effects at the end of the 30 days storage period. Srisuvor et al. (2013) studied the effects of two prebiotics (inulin and PD as fat replacer, each at 1, 2 or 3 g/100 mL of reconstituted milk) on physico-chemical and sensory properties of low-fat set yoghurt. The addition of each prebiotic could improve physical and sensory properties of the yoghurt and 2 g of PD/100 mL was the most suitable level. Further, the probiotic-cultured (with Lactobacillus paracasei Lpc-37) banana purée was prepared and used as fruit base of the product and some physicochemical and microbiological characteristics were monitored during 21 days of storage. The number of the probiotics was still highly acceptable at 8.86 log CFU/g during the entire storage period; however, its physical properties gradually deteriorated after 14 days. Authors concluded that the use of banana purée as a source of nutrients for the probiotic and the PD as a fat substitute in the set yoghurt was beneficial both for the consumers and the manufacturers.

Cakes

There are some studies reported the replacement of sucrose in sponge cakes by PD, with or without nonnutritive sweeteners. The texture of yellow layer cakes was optimized by Frye and Setser (1991) using six bulking agents: sorbitol, hydrogenated starch hydrolysate mixture, lactitol, isomalt, 18-dextrose-equivalent maltodextrin and PD in combinations to totally or partially replace sucrose. Sorbitol at 100% level resulted in moderate mouth drying compared to PD which caused long and severe mouth drying, while a less prolonged drying occurred from the mixture of the PD with maltodextrin, sorbitol or isomalt. Attia et al. (1993) studied the effect of replacing sucrose with fructose, acesulfame-K or aspartame, with or without the addition of PD, on the physical properties of cakes. The results indicated that adding PD caused an improvement in textural properties which led to sponge cakes with similar acceptability to that of sugar cake with a 40% reduction in calories. Pateras et al. (1994) demonstrated the effect of sucrose replacement by PD on foam characteristics of cake batters. PD caused an increase in the mean size of air bubbles, and introduced a larger variation in bubble size distribution in the cake batter. Hicsasmaz et al. (2003) studied the effect of PD substitution on a high-ratio cake system. Authors found the same increase in the mean bubble size and showed that PD was capable of imitating the sucrose cake batter in terms of bubble size distribution. Also, they found that increase in PD resulted in a significant decrease in cake height and a sensible change in the lightness and in the crumb colour hue. Ronda et al. (2005) evaluated the effect on sponge cake volume, colour and texture properties of total replacement of sucrose by seven bulking agents. Several polyols - maltitol, mannitol, xylitol, sorbitol, isomaltose and two oligosaccharides - PD and oligofructose were tested as bulking agents. Best results were obtained with xylitol and maltitol, leading to sponge cakes more similar to the control ones manufactured with sucrose and with the highest acceptance level in sensory evaluations. Panelists assigned the lowest score in overall acceptability to mannitol cakes, followed by oligofructose and PD ones. The poor sensory scores given to the oligofructose and PD cakes were mainly related to taste and aftertaste. Siti Faridah and Noor Aziah (2012) prepared reduced calorie chocolate cake with jackfruit seed flour and PD. Optimized product was obtained by partially replacing sucrose with PD at 11% and resulted in 34% calorie reduction as compared to the control cake.

Safety
The safety of PD in the human diet has been comprehensively demonstrated (Burdock and Flamm, 1993). Both the Joint FAO and WHO expert committee on food additives (JECFA) and the European Commission, Scientific Committee on Food (EU/SCF) have assigned an acceptable daily intake (ADI) “not specified”, meaning that neither agency found it necessary to stipulate an upper level of safe intake because excessive consumption is a matter of tolerance rather than safety (JECFA, 1987; EC/SCF, 1990). Therefore, PD is permitted for use in any food at any level without restriction other than GMP in most markets. While PD is not considered toxic at high dosages, laxation effects have been observed when intakes are elevated, similar to other nondigestible carbohydrates. Children are considered no more sensitive than adults to PD when given at the same level on a per body weight basis (Flood et al. 2004). As reported in a compendium by Burdock and Flamm (1999), an extensive array of toxicological studies, conducted in a variety of animal models (i.e. mice, rats, rabbits, dogs) for extensive periods of time (3–24 months), have fully supported the safety of two forms of PD (acidic and neutralized forms) as food ingredients.

Tolerance

Flood et al. (2004) have reviewed nine clinical studies in adults and children who were conducted with PD to evaluate the extent of gastrointestinal symptoms. These studies demonstrated that PD is not likely to induce diarrhea in adults at doses less than 50 g per day (a practical no-effect dose), and most individuals may only experience diarrhea from much higher doses. These studies showed that PD is better tolerated than most other low-digestible carbohydrates. The fact that less gas is produced during fermentation is likely a contributing factor (Hernot et al. 2009; Vester Boler et al. 2009). The diarrhea induced by PD is isolated and transient. Clinical chemistry and metabolic balance studies have shown no treatment related effect from ingestion of high doses of PD (Flood et al. 2004). PD is well tolerated, and a mean laxative threshold of 90 g/day (1.3 g/kg bw) or 50 g as a single dose has been given (JECFA, 1987). The SCF rapporteur pointed out, however, that such estimates are only provided as a guide and should not be used to establish maximum levels of use (Van Esch, 1987).

Regulatory and labeling guidelines

The use of PD in foods has received approval in numerous countries. It is approved for use in foods in 57 countries, 56 of whom permit use of 1 kcal/g energy value for labeling (Auerbach et al. 2006). PD has been approved as a food additive in the US since 1982 (Food and Drug Administration 21 CFR 172.841). In the EU, PD is approved under the Miscellaneous Additives Directive - Annex I, permitting the use of PD in virtually all foodstuffs following the quantum satis principle and is listed as E1200. In Japan, the Ministry of Health and Welfare (MOHW) recognizes PD as a food (Mitchell, 2001; Stowell, 2009). In India, according to the Food Safety and Standards (Food Products Standards and Food Additives) Regulations (2011), PD (INS No. 1200) may be used as bulking agent, stabilizer, thickener, humectant and texturizer in ice cream, frozen desserts, cakes, biscuits, yoghurt, whip topping, sugar boiled confectionary, jam, fruit jelly and traditional Indian sweets (carbohydrate based and milk based) as per GMP levels (FSSA, 2006).

Foods containing PD designed for special dietary use, such as reduced or low calorie foods, must be labeled in accordance with 21 CFR Part 105. The ingredient statement of foods containing PD (either the powder or the 70% solution partially neutralized with potassium hydroxide) should include the official recognized name of the ingredient PD. Foods containing in excess of the 50 mgs potassium per serving must also declare potassium hydroxide in the ingredient statement. A clarifying statement must also follow such as “for neutralization” or “to adjust pH”. FDA recognizes that PD contains only one calorie per gram and does not object to the use of this value for purpose of determining the caloric content of foods formulated with PD (Smiles, 1982). The US, however, allows PD use as a food additive in specific foods only, and requires that ‘The label and labeling of food, a single serving of which would be expected to exceed 15 g of the additive’ shall bear the statement: ‘Sensitive individuals may experience a laxative effect from excessive consumption of this product’ (Flood et al. 2004). According to FSSAI regulations in India, food containing more than 10% PD shall bear the label on package “PD may have laxative effects”.

Conclusions

PD is added to foods for its physiological and technological reasons. Its high stability in heat and acidic environments, low viscosity, high solubility in water, and bulking and texturing properties and bland taste lends itself to a wide variety of food and beverage formulations. PD can improve mineral status, attenuate postprandial blood triglycerides, maintains blood sugar levels, regulates bowel function, softened the feces, improves the ease of defecation and helps in prevention of colon carcinogenesis. In this regard PD allows the development of food products with a wide variety of nutritional improvements such as prebiotic, fibre fortification, calorie reduction, reduced glycemic load as well as sugar and fat reduction. Hence, PD is a versatile food ingredient that can be used to improve the nutritional profile of a wide range of processed foods.

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