



REVIEW

Valorization of sugar beet pulp through biotechnological approaches: recent developments

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Abstract Sugar beet pulp (SBP) is a valuable by-product of the sugar beet industry and is predominantly composed of cellulose, hemicellulose, and pectin. It is commonly used as livestock feed because of its palatability, good energy levels, and highly digestible fibers such as pectins and glucans. However, the utilization of SBP for the production of value-added products via biotechnological approaches is gaining significance in recent years owing to its potential as a cost-effective nutrient source and technological advancements in its processing. SBP can be used as a substrate for bio-production of microbial enzymes, single cell protein, alcohols (e.g., ethanol), methane/biogas, hydrogen, lactic acid, ferulic acid, and pectic oligosaccharides. SBP can also be used as a carrier for cell immobilization in fermentation processes. This review focused on recent developments in biotechnological valorization of SBP.

Keywords Sugar beet pulp · Biogas · Enzyme · Ethanol · Fermentation · Valorization

Introduction

Sugar beet (*Beta vulgaris* subsp. *vulgaris*) is an important commercial crop that is cultivated primarily for the production of sucrose. After the extraction of sugars from the tap root, leftover processing waste [a.k.a. sugar beet pulp (SBP)] possesses a dry matter (DM) content of 18–23% w/w (Kuhnel et al. 2011). SBP is usually fed fresh to pigs and ruminant livestock because of its digestible fiber fraction (Joanna et al. 2018). SBP contains, on a dry weight (DW) basis, cellulose (20–25%), hemicellulose (25–36%), pectin (20–25%), protein (10–15%), and lignin (1–2%) (Zheng et al. 2013).

However, SBP as feed is an economically marginal part of beet processing in many parts of the world because of its low feeding value and high drying cost (Doran et al. 2000). Therefore, the beet industry seeks processes that add value to SBP without the requirement of drying. Bioconversion of SBP into value-added products like ethanol can be a suitable alternative since the substrate is fermentable to ethanol following pretreatment and hydrolysis without a drying step. Since SBP possesses significant levels of carbohydrates, it can potentially substitute pure sugars in different bioprocesses (Joanna et al. 2018). Further, due to its minimal lignin content and milder sucrose extraction conditions from sugar beet, SBP can serve as a potential feedstock for the production of value-added products via saccharification and

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subsequent conversion. However, SBP is not a cost-effective substrate for hexose-based fermentations since the proportion of cellulose is not high (Hamley-Bennett et al. 2016). The release of hydrolysis products, including glucose from cellulose along with xylose, glucose, galactose, arabinose, mannose, and rhamnose from hemicelluloses and pectin, is a crucial step towards valorizing SBP. To accomplish this, lignocellulosics (including SBP) are often structurally modified by a pretreatment prior to enzymatic release of fermentable monosaccharides (Kuhnel et al. 2011).

Significance of pretreatment

Despite the low lignin content, due to high physico-chemical integrity of SBP, pretreatment is needed to improve subsequent enzymolysis and fermentation yields (Bellido et al. 2015). Pretreatment is known to alter the structure of lignocellulosic biomass and increases its accessibility for hydrolytic enzymes. Commonly used methods for the pretreatment of SBP are shown in Fig. 1. Aqueous ammonia (AA) pretreatment can be used to decrease SBP recalcitrance. Li et al. (2017) showed the degradation of neutral detergent soluble fraction of SBP following AA pretreatment. In addition, softening and partly exposing of cellulose as well as enhanced enzymolysis

of SBP were observed following the pretreatment. Among pretreatments applied to SBP (AA, HCl, ammonium oxalate, and pectinase), AA pretreatment was found to be promising in terms of reducing sugar yield since it could cleave ester bonds between lignin and carbohydrates, increase cellulose content, expose crystalline region of cellulose, and modify and redistribute lignin functional groups (Li et al. 2018). Treatment of SBP using 10% wt AA at different temperatures had resulted in altered lignin distribution, exposed more hydroxyl groups in cellulose, and high adsorption of cellulase on cell wall (Li et al. 2020). Alkaline thermal pretreatment (especially using KOH) of SBP has been shown to be effective for the removal of cellulose, hemicellulose, and lignin (Şenol et al. 2019). Zhao et al. (2014) showed a significant increase in cellulose concentration and reductions in hemicellulose and lignin concentrations of SBP by aqueous NaOH pretreatment.

The application of sonication, induced magnetic field, and pectinase pretreatments had substantially improved the production of biogas from SBP (Pessoa et al. 2020). Ozkan et al. (2011) demonstrated significant improvements in SBP solubilization following alkaline, microwave-alkaline, and thermal-alkaline pretreatments. Environmentally friendly hydrothermal pretreatment of SBP (at 160 °C) had led to the release of high concentrations of free glucose (Ziemiński et al. 2014). For selective fractionation of SBP, Hamley-Bennett et al. (2016) used a pressurized steam pretreatment. They observed the highest solubilization of pectin oligomers at a relatively low pressure whilst leaving the majority of the cellulose fraction intact. Moreover, the process required no addition of chemicals, milling of SBP or dilution.

Thermal-dilute acid pretreatment of SBP resulted in efficient solubilization of pectin and hemicellulose, and facilitated the residual cellulose more degradable during subsequent fungal hydrolysis (El-Gendy et al. 2015). Dilute acid (H_2SO_4 1% [v/v]) and butanol (1:3 [v/v] n-butanol/ H_2SO_4 1% [v/v]) pretreatments of SBP resulted in significant delignification and enhanced hydrolysis of cellulose (> 30%) was observed in the treated SBP (Schmetz et al. 2019). To achieve high carbohydrate yield from SBP, H_2SO_3 was used for pretreatment (Kharina et al. 2016). It also exerted a positive effect on subsequent enzymolysis. The predominant advantage of H_2SO_3 usage is the possibility of its regeneration. However, dilute acid pretreatment

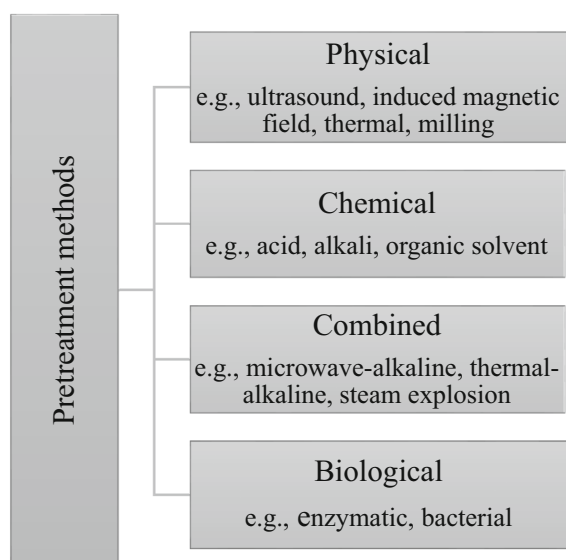


Fig. 1 Different pretreatments applied for enhanced bioconversion of sugar beet pulp

of lignocellulosics is generally reported to produce toxic furfural derivatives as a by-product (Zhao et al. 2014).

Biotechnological valorization of SBP

Enzyme production

SBP is a potential carbon source for enzyme production. It also served as an inducer of pectinase (polygalacturonase) enzyme. Olsson et al. (2003) showed the potential of SBP and alkaline extracted SBP as carbon sources for cellulases, hemicellulases, and pectinases production by *Trichoderma reesei*. The list of some enzymes produced using SBP as a substrate is given in Table 1. The supplementation of nitrogen sources may positively influence enzyme yields.

Bioethanol production

SBP is a promising feedstock for second-generation (2G) ethanol production because of its high content of cellulose, hemicelluloses, and pectin as well as relatively low levels of lignin. For fermentative conversion of 2G feedstocks including SBP, the efficient utilization of mixed substrates is crucial (Huisjes et al. 2012). Wild-type *Saccharomyces cerevisiae* strains are able to utilize glucose and galactose sequentially, but cannot ferment the pentoses (xylose and arabinose) and galacturonic acid. Rorick et al. (2011) investigated SBP potential as a feedstock for ethanol production using *Escherichia coli* alone and in combination with *S. cerevisiae*. They showed relatively higher total ethanol yield of 0.34 g/g sugar by starting simultaneous saccharification and fermentation (SSF) using *S. cerevisiae* (with pectinases, cellulases, cellobiases) and followed by a

second fermentation with *E. coli*. On the other hand, SSF using *E. coli* only exhibited relatively high ethanol productivity of 0.22 g/L/h (because of co-fermentation of glucose, arabinose, and galacturonic acid), despite lower yields. Efficient ethanolic fermentation of SBP-derived sugars (mixture) is challenging even without inhibitory compounds. For instance, galacturonic acid adversely affects the fermentation of xylose, galactose, and arabinose by *S. cerevisiae* (Huisjes et al. 2012).

Bioethanol (final concentration = 5.54 g/L) was produced from alkali (2% NaOH)-pretreated and enzymatically (cellulase)-saccharified SBP (Zhao et al. 2014). Microbial decontamination of SBP through thermal pre-treatment (pasteurization or sterilization) has been shown to increase the yield of ethanol significantly (Gumienna et al. 2014). Their results showed that batch fermentation of sterilized SBP using *S. cerevisiae* yielded the highest concentration of ethanol (87.7% of theoretical yield). Bellido et al. (2015) used pretreated SBP for acetone–butanol–ethanol (ABE) production by *Clostridium beijerinckii*; the highest reported yield of ABE was 143.2 g/kg SBP. El-Gendy et al. (2015) employed response surface methodology to optimize thermal acid pretreatment of SBP. They showed that the integration of the pretreatment and fungal hydrolysis of the pretreated SBP with parallel batch fermentation processes of the produced hydrolyzates (using *S. cerevisiae*) yielded ≈ 0.32 g ethanol/g SBP.

Hydrolysis using dilute H_2SO_4 is an efficient approach for hemicellulose conversion. However, the process results in the formation of inhibitory by-products, including phenolic compounds, furan derivatives (furfural and 5-hydroxymethyl furfural), and weak acids, in addition to xylose, arabinose, glucose, galactose, and mannose sugars (Chandel et al. 2012). Yücel and Aksu (2015) detoxified acid hydrolysate of SBP using fly ash and activated

Table 1 List of some enzymes produced using SBP as a fermentation substrate

Enzyme produced	Microorganism used	Method	Yield	Reference
Alkaline pectinase	<i>Bacillus gibsonii</i>	SSF	3600 U/g	Li et al. (2005)
Exo-arabinanase	<i>Fusarium oxysporum</i>	SmF	0.25 U/mL	Cheilas et al. (2000)
Polygalacturonase	<i>Penicillium citrinum</i>	SSF	152.2 U/g	El-Batal et al. (2013)
Polygalacturonase	<i>Aspergillus sojae</i>	SSF	909.5 U/g	Heerd et al. (2014)
Exo-pectinase	<i>Bacillus pumilus</i>	SSF	12.68 U/mL	Tepe and Dursun (2014)
Dextranase	<i>Aspergillus awamori</i>	SSF	1057 U/g	Mouafi et al. (2016)

SSF solid-state fermentation, SmF submerged fermentation

charcoal obtained from SBP. They showed efficient removal of furan and phenol by SBP-derived charcoal and over-liming with CaO had enhanced their reduction, whereas fly ash treatment significantly decreased the concentrations of furans only. Neither of the treatments decreased the concentration of acetic acid significantly. The fermentation of the detoxified hydrolysates using *Pichia stipitis* resulted in ethanol yields of 0.108–0.122 g/g SBP and productivities of 0.119–0.286 g/L/h. Berłowska et al. (2017) investigated integrated approach to produce bioethanol, biomethane, and biohydrogen from SBP. Following enzymolysis of SBP, co-culturing with *S. cerevisiae* and *Scheffersomyces stipitis* yielded a final ethanol concentration of 12.6 g/L. The resultant stillage contained unfermented sugars, predominantly arabinose, galactose, and raffinose, and was found to be a good substrate for the production of methane (444 dm³/kg volatile solids [VS]) and hydrogen (252 dm³/kg VS) through anaerobic digestion and dark fermentation, respectively.

Ethanol fermentation of pectin-rich substrates by ordinary yeast has not been productive since arabinose and galacturonic acid are not fermentable by them (Doran et al. 2000). However, recently, Jeong et al. (2020) constructed an engineered *S. cerevisiae* (by in vivo assembly and integration technology using the CRISPR-Cas system) capable of fermenting pectin monomers. The engineered strain can metabolize galacturonic acid, arabinose, and xylose simultaneously. Moreover, xylose was fermented to ethanol and glycerol as the predominant products by the strain. Biz et al. (2016) have constructed an engineered *S. cerevisiae* capable of metabolizing D-galacturonic acid.

SSF process has a unique advantage (i.e., feedback inhibition of cellulolytic enzyme can be avoided since glucose is constantly removed by fermentation). Berłowska et al. (2016a) showed efficient ethanol production through SSF of SBP. The application of pretreatment followed by enzymolysis improved the effectiveness of SSF using *S. cerevisiae* and *P. stipitis*, resulting in an average ethanol concentration and efficiency of 26.9 g/L and 86.5%, respectively.

Single cell protein (SCP)

SBP can readily be bio-converted to SCP using *Candida* spp (Nigam and Vogel 1991). They observed

a maximum protein content of 43.4%, with a conversion efficiency of 46%, using *Candida tropicalis*. Yeast biomass containing significant amounts of SCP was successfully produced using SBP as a fermentative substrate (Patelski et al. 2015). Among tested yeasts, *C. tropicalis* exhibited the highest biomass yield (12.1 g DM dm⁻³) with a protein content of 52.3% of DM.

Methane (CH₄) and hydrogen (H₂) production

Anaerobic digestion (AD) for CH₄ production can be carried out either in the mesophilic (28–40 °C) or thermophilic (50–57 °C) temperature range. The advantages of thermophilic digestion include faster rates of degradation and biogasification. Tukacs-Hájos et al. (2014) showed thermophilic adaptation of mesophilic anaerobe fermentation of sugar beet pressed pulp. They showed 5% higher biogas yield and alterations in the microbial communities (predominantly hydrogenotrophic methanogens) in the thermophilic reactor. SBP has been bio-transformed into CH₄/biogas under both mesophilic and thermophilic AD conditions. Different pretreatment techniques, including physical, chemical, and enzymatic, have been shown to improve the yields of CH₄/biogas significantly (Table 2). The pretreatment of SBP with pectinase, xylanase, and endoglucanase prior to AD had improved the yield of biogas (Ziemiński et al. 2012). In H₂ production from lignocellulosics like SBP, pretreatment is critical to improve overall energy efficiency and enable economic feasibility. Ozkan et al. (2011) showed that alkaline-pretreated SBP exhibited the highest H₂ yield (115.6 mL/g COD).

Foaming is a serious issue for AD plants as it is associated with reduced biogas productivity and process efficiency (Moeller et al. 2018). Foam formation in the process of mesophilic AD of SBP, especially at high organic loading rates, has been shown (Suhartini et al. 2014). Suhartini et al. (2019) demonstrated that trace element addition was the most effective strategy for eliminating foaming and maintaining the digestion performance in mesophilic AD of SBP. Szabo et al. (2018) also showed increased specific methane yields ($\geq 11\%$) in semi-continuous AD processes of pressed SBP upon trace elements (Zn, Mn, B, Ni, Cu, Co, Mo, and Se) supplementation and with the trace elements + Fe supplementation compared to non-supplemented controls.

Table 2 Some pretreatments applied in the biological production of methane/biogas by anaerobic digestion of SBP

Product	Process	Yields	References
Methane/ biogas	Enzymatic pretreatment of SBP silage-vinnase (3:1) blend	Biogas yield was 765.5 mL/g VS	Zieminski and Kowalska-Wentel (2015)
Methane	Hydrothermal pretreatment	502.50 L CH ₄ /kg VS	Ziemiński et al. (2014)
Biogas	Alkaline (KOH) thermal pretreatment (3 N, 100 °C, 1 h)	458.4 mL/g TS (total solid)	Şenol et al. (2019)
Methane	Magnetic field pretreatment of mixture (Pectinase + SBP) Sonication prior to magnetization of the mixture	Enhanced production up to 62% Production increased up to 79%	Pessoa et al. (2020)

Methane production from mono-digestion of SBP stillage was not successful because of volatile fatty acid (VFA) accumulation and thereby dropping the pH (< 5.5). Therefore, anaerobic co-digestion (AcoD) with other organic wastes has been studied (Table 3). The addition of cattle liquid manure to SBP exerted a beneficial effect on methane production (Połec et al. 2017). Thermophilic AcoD with cow and pig manures (PM) significantly increased the yields of CH₄ (Fang et al. 2011; Gómez-Quiroga et al. 2019); an increase in the proportion of exhausted SBP (ESBP) in the ESBP + PM mixture led to acidification by VFA and, thereby distorted the process (Gómez-Quiroga et al. 2019). The increase of C/N ratio with increasing ESBP levels can be anticipated. In general, a C/N ratio between 20 and 30 is optimal for AD (Aboudi et al.

2015). On the other hand, single-stage mesophilic AcoD of SBP lixiviation and sewage sludge has been shown to be superior to thermophilic AcoD in terms of specific methane yield (0.63 vs 0.21 L CH₄/g total volatile solid (TVS)_{removal}), process stability, and effluent quality (Alonso et al. 2016). However, relatively higher TVS reduction was noted in the thermophilic digestion than in the mesophilic digestion. They have also shown that two-phase (thermophilic and mesophilic temperature phase) AcoD of the substrates was superior to the single-stage mesophilic AcoD in terms of specific methane yield (3.59 vs 3.42 L CH₄/d) and process stability, though not in terms of soluble COD or VFA. Improved biogas productivity and organic matter removal in mesophilic AcoD of sewage sludge and lixiviation of SBP were

Table 3 Some studies on methane/biogas production from anaerobic co-digestion of SBP with other substrates

Substrates	Product	Yield	References
SBP stillage + poultry manure	Methane	418 dm ³ /kg VS _{fed}	Borowski and Kucner (2019)
SBP stillage + municipal sewage sludge	Methane	357 dm ³ /kg VS _{fed}	Borowski and Kucner (2019)
50% of SBP + cow manure	Methane	280 mL CH ₄ /g VS-added	Fang et al. (2011)
Exhausted SBP + pig manure (25:75)	Methane	212.4 mL CH ₄ /g VS-added	Gómez-Quiroga et al. (2019)
Lixiviation of SBP + sewage sludge	Methane	0.64 m ³ CH ₄ /kg COD _{removal}	Montañés et al. (2013)
35% SBP residue + sewage sludge	Methane	348 dm ³ CH ₄ /kg VS _{fed}	Borowski and Kucner (2015)
Ensiled SBP + ensiled switchgrass	Biogas	Increased by 16.8% compared with mono-fermentation of switchgrass	Kupryś-Caruk and Podlaski (2019)

also shown earlier by Montañés et al. (2013). Montañés et al. (2015) showed relatively high methane productivity under mesophilic AcoD of sewage sludge and SBP lixiviation compared with thermophilic regimen. They observed an increased VFA accumulation, which reduces microbial activity, under thermophilic conditions. The optimum pH for most anaerobic microorganisms is 7.0–7.5, and pH values < 5 are considered inhibitory. Acidogenic activity (VFA production) is stimulated by low pH and inhibits methanogenic activity (VFA consumption). Montañés et al. (2014) showed that initial pH adjustment resulted in total biodegradability of sewage sludge and SBP lixiviation at mesophilic range (35 °C).

Pytlak et al. (2020) showed that biochar addition stimulated CH₄ production in AD of SBP through reshaping of microbial communities, especially enrichment of *Bacteroidales* and *Clostridiales*. Tomita et al. (2019) used co-cultivation approach (with cellulolytic bacterium *Clostridium cellulovorans* and methanogens) for CH₄ production using SBP as a carbon source. They observed simultaneous utilization of CO₂ and H₂ for methanogenesis in the coculture, resulting in an efficient degradation of SBP (87.3%) without any pretreatment and the generation of 34 L of CH₄/kg SBP (DW). Among different biomasses, the highest H₂ yield was observed for SBP (19.87 mL/g) and the maximum biogas yield for SBP was 387.86 mL/g (Aslan et al. 2020).

Cieciura-Włoch et al. (2019) developed a process for simultaneous processing of SBP for H₂, CH₄, and furfural production via dark fermentation. They showed that thermal pretreatment of SBP yielded high levels of biogas (945 dm³/kg VS) and CH₄ (374 dm³/kg VS), a moderate level of H₂ (113 dm³/kg VS), and a low concentration of furfural (1.63 g/L). On the other hand, pretreatment with 2% H₂SO₄ resulted in a moderate furfural production (4 g/L) and a high H₂ yield (220 dm³/kg VS). Cieciura-Włoch et al. (2020b) showed the production of both H₂ (17–37 cm³/g VS) and CH₄ from hydrolyzed SBP, despite a low pH. They found that methanogens (which could grow at pH below six and produce CH₄) activity lowered the hydrogen yield. Cieciura-Włoch et al. (2020a) produced H₂ and CH₄ from hydrolyzed SBP via dark fermentation. They found substantial increase in H₂ yields with the addition of Fe₂O₃; the highest yields of H₂ and CH₄ obtained in semi-continuous experiments

were 52.11 dm³/kg VS and 19.5 dm³/kg VS, respectively.

Lactic acid (LA)

SBP is a potential substrate for second-generation LA production. A maximum LA concentration of 59.57 g/L was produced from enzymatically pretreated SBP using a mixed culture of *Lactobacillus* spp. (as they ferment both pentoses and hexoses) under SSF conditions (Berłowska et al. 2016b). Comparison of the efficiency of LA production from SBP between separate hydrolysis and fermentation (SHF) and SSF processes showed that SSF was advantageous over SHF, including higher productivity and lower processing costs, with LA yield of ~ 30 g/L, which was 80–90% more than the SHF process (Berłowska et al. 2018). De Oliveira et al. (2020) produced LA (2781.01 g) using hydrolyzed SBP in a continuous fermentation (by *Bacillus coagulans*), with a highest productivity of 18.06 g/L/h. Diaz et al. (2020) used fed-batch SSF strategy instead of SHF to attain higher productivity using ESBP pellets as a substrate. They achieved the highest LA concentration of 27 g/L and a maximum productivity of 0.63 g/L/h using *Lactobacillus casei*.

Pectic oligosaccharides (POS)

SBP is a potential raw material to obtain POS through enzymatic or chemical methods. SBP-derived POS mainly consisted of partially acetylated rhamnogalacturonan oligosaccharides and partially methyl-esterified/acetylated homogalacturonan oligosaccharides; these POS can be completely fermented by pig and human fecal microbiota, thereby producing butyrate yet mainly acetate and propionate (Leijdekkers et al. 2014). An investigation into prebiotic potential of SBP-derived POS indicated that they increased the populations of bifidobacteria and lactobacilli significantly (Gómez et al. 2016; Gómez et al. 2019); a rise in *Faecalibacterium* and *Roseburia* counts was noted as well. Their prebiotic potential was found to be similar to that of commercial fructooligosaccharides (Gómez et al. 2016). The combination of pectin hydrolysis and yeast cultivation has been shown to be effective for POS generation (4.2 g/100 g DW) (Wilkowska et al. 2020). The obtained POS yields were similar to those obtained by chemical processing, while avoiding the

generation of new waste and additional energy consumption during the extraction.

Biomass production

SBP has been shown to be suitable for the cultivation of different strains of endophytic fungi. Cultivation on medium prepared with SBP: water (1:2 ratio), containing calcium sulfate and carbonate, generated high yields of fungal biomass (100–500 g kg⁻¹ dry SBP) (Vázquez-de-Aldana et al. 2020). Microalgae *Chlorocella* was successfully cultivated in acid-rich hydrolysates, which were prepared by non-airtight fermentation of SBP with digested dairy manure (Wang et al. 2019). Results showed that hydrolysis and acidification process of the fermentation led to production of 8.1 g/L VFA; and *Chlorella* exhibited best growth and nutrient reduction in threefold diluted hydrolysate, with a final biomass density of 2.17 g/L.

Other value-added products

Ferulic acid (FA)

SBP is rich in FA. Sato et al. (2013) used a hydrothermal treatment for FA recovery from SBP as ferulate esters of oligosaccharides. They showed that > 80% of arabinan content of beet fiber can be recovered as arabino-oligosaccharides (AOs) and feruloylated arabino-oligosaccharides (FA-AOs) under optimal reaction conditions. Alkaline hydrolysis was used for the extraction of FA from SBP (Aarabi et al. 2016). Under optimum conditions, the highest FA content of 1.29 g/100 g was extracted and the isolate exhibited antioxidant capacity. For the extraction of FA-AOs from SBP, a thermophilic endo-1,5- α -L-arabinanase (TS-ABN)-secreting *Pichia pastoris* was successfully developed (Zhang et al. 2020). They showed that, under optimized enzymatic (TS-ABN) digestion condition, FA-AOs with an average seven arabinose residues per FA could be extracted from SBP-polysaccharides, reaching a FA-AO recovery yield of 1.52% (w/w). Their research established that SBP can be better utilized to produce value-added bio-products for potential nutraceutical applications.

Valorization via biorefinery approaches

Waste biomass refining complies with circular economy initiative and bioeconomy. Some recent research efforts are aimed at complete utilization of SBP components. Hamley-Bennett et al. (2016) have achieved the selective fractionation of SBP into solubilized pectin and enriched insoluble cellulose by steam pretreatment, fitting perfectly into the concept of a sugar beet bio-refinery. The cellulose-rich fraction could be effectively fermented into ethanol by yeast after enzymolysis, since no inhibitory compounds are produced during this process. The isolation of component sugars from biomass is an important step in further bioprocessing. Following the hydrolysis of SBP pectin, component monosaccharides were isolated from the crude hydrolysate by centrifugal partition chromatography (Ward et al. 2015). These monosaccharides can be separated into 3 main fractions: a mixed L-arabinose/D-galactose fraction, a pure L-rhamnose fraction (> 90%) and a pure D-galacturonic acid fraction (> 90%). Cárdenas-Fernández et al. (2018) has shown a continuous bioprocess sequence to obtain L-arabinose (Ara) from SBP within the context of integrated sugar beet biorefinery. They showed the selective hydrolysis of pectin derived from SBP using an immobilized α -L-arabinofuranosidase to yield monomeric Ara and a galacturonic acid rich backbone. A subsequent tangential flow ultrafiltration allowed 92% Ara recovery. Alexandri et al. (2019) successfully fractionated SBP into phenolic compounds, pectins, and a fermentable hydrolysate. The hydrolysate was subsequently used for succinic acid production using *Actinobacillus succinogenes*, resulted in a maximum concentration of 30 g/L, a yield of 0.8 g/g, and a productivity of 0.62 g/L/h.

Carrier for cell immobilization

SBP is a potential carrier for yeast immobilization because of its biocompatibility, renewability, inexpensiveness, porosity, high cell retention capacity, and high water swelling capacity. Vučurović et al. (2013) employed SBP as carrier for the immobilization of *S. cerevisiae* in a continuous ethanol fermentation process. The maximum cell retention was 1.7×10^{11} cells/g dry SBP and the yeast-SBP system exhibited stable performance at a dilution rate of 0.025 h⁻¹ over

a 15-day period. SBP was used as a support for *Leuconostoc mesenteroides* immobilization in the process of fermentative production of dextransucrase using molasses (Miljković et al. 2016). The maximum dextransucrase yield was 2.02 U/mL and they suggested that the yields of the enzyme could be improved by using NaOH-treated SBP as a carrier. For β -amylase production using molasses, Mihajlovski et al. (2016) successfully used SBP as immobilization support for *Paenibacillus chitinolyticus* cells. They observed an effective immobilization of the cells onto NaOH-pretreated SBP and a maximum β -amylase activity of 2.237 U/mL was noted. SBP was found to be a superior carrier material for the immobilization of *Lactobacillus paracasei* in LA production using beet molasses-enriched potato stillage (Mladenović et al. 2018). The carrier material exhibited higher water absorption index and lower critical humidity point, leading to the highest cell attachments. They also noted the highest LA concentration (80.10 g/L) and productivity (1.48 g/L h) using SBP as a carrier. Mladenović et al. (2019) reported simultaneous production of LA (the highest concentration: 399 g L⁻¹; productivity: 1.27 g L⁻¹ h⁻¹) and probiotic-enriched livestock feed using a combined substrate based on molasses and potato stillage by *L. paracasei* immobilized onto SBP.

Conclusions

Biotechnological utilization of SBP is rapidly gaining prominence. Biotechnological intervention offers the potential to improve value, quality, and safety of SBP even as animal feed (e.g., protein- and probiotic-enriched SBP for animal nutrition). Enzymes used for biomass hydrolysis are generally expensive and it is a bottleneck in the production of value-added products from SBP. To decrease the cost, the use of fermented ESBP pellets obtained by fungal SSF as an enzyme source has been recommended (Marzo et al. 2020). These pellets can be directly added to fresh ESBP pellets for their hydrolysis, without the need of enzyme extraction and purification. For realization of the concept of circular economy, advanced processing, which allow to combine different agro-wastes and integrates them into a biorefinery process, could play a significant role through improving productivity and the overall profitability. SBP carbohydrates can be

selectively extracted for feed, food, and industrial applications using biorefinery approaches. Cascade processing of SBP through a biorefinery approach renders maximum utilization of components.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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