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A critical review on the biotechnological potential of Brewers' waste: Challenges and future alternatives

Sourav Chattaraj [a,b], Debasis Mitra [a,c], Arindam Ganguly [d], Hrudayanath Thatoi [b], Pradeep K. Das Mohapatra [a,*]

[a] Department of Microbiology, Raiganj University, Uttar Dinajpur, Raiganj, West Bengal PIN - 733134, India
[b] Centre for Industrial Biotechnology Research, School of Pharmaceutical Science, Siksha 'O' Anusandhan University, Kalinga Nagar, Bhubaneswar, Odisha 751 003, India
[c] Department of Microbiology, Graphic Era (Deemed to be University), 566/6, Bell Road, Clement Town, Dehradun, 248002 Uttarakhand, India
[d] Department of Microbiology, Bankura Sammilani College, Bankura, West Bengal PIN - 722102, India

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ABSTRACT

In order to comply with the stringent discharge guidelines issued by governmental organizations to protect the ecosystem, the substantial amounts of effluent and sturdy wastes produced by the beer brewing process need to be discarded or handled in the most affordable and secure manner. Huge quantities of waste material released with each brew bestow a significant opportunity for the brewing sector to move towards sustainability. The concept of circular economy and the development of technological advancements in brewery waste processing have spurred interest to valorize brewery waste for implementation in various sectors of medical and food science, industrial science, and many more intriguing fields. Biotechnological methods for valorizing brewery wastes are showing a path towards green chemistry and are feasible and advantageous to environment. The study unfolds most recent prospectus for brewery waste usage and discusses major challenges with brewery waste treatment and valorization and offers suggestions for further work.

1. Introduction

There is currently a lot of societal and political impetus to lessen the pollution generated by commercial activity. By amending industrial operations so that their wastes may be recycled, nearly all developed and developing nations are attempting to adjust to this fact. As a result, the majority of large corporations no longer view leftovers as trash but rather as raw resources for other processing. Brewery by-product typically comprises two major components namely, Brewers' Spent Grain (BSG), and Brewers' Spent Yeast (BSY). However, hot trub and spent hops are also produced as byproducts of the brewing process but are of less significance due to their deprived quantity of production.

BSG makes up roughly 85 % of all byproducts produced during the brewing of beer. After the mashing stage and lautering (the extraction of sweet liquid wort), BSG stands as the remaining insoluble fraction of the barley grain. Aside from attached soluble components including maltooligomers, maltose and glucose, the dry matter of BSG also includes cellulose, lignin, proteins, lipids, hemicellulose, and ash fraction (Akermann et al., 2020). Hordeins, albumins, globulins, and glutelins are the main proteins found in BSG. Hordeins (prolamins), which are present in abundance, are further categorized as B (about 50 kDa), C (about 80 kDa), and D hordeins (about 95 kDa) as per molecular weights (Ikram et al., 2017). BSGs are nutrient-rich organic wastes containing 17 % cellulose, 28 % lignin, and 28 % non-cellulosic polysaccharides (generally arabinoxylans) and have negligible economic prospects (Mussatto et al., 2006). BSGs are currently utilized for animal feed (70 %), biogas production (20 %), and unutilized or disposed of for landfills (10 %) (Bianco et al., 2020).

BSY is rich in proteins, nucleotides, minerals, β-glucans and vitamins (B, C, and D) (Gokulakrishnan et al., 2022; Demirgul et al., 2022) and is utilized as feed additives for farm animals (Caruso et al., 2022). β-glucans of BSY act as Biological Response Modifiers in humans (Caruso et al., 2022). In the food sector, BSY has been most frequently employed as a flavor stimulator or as a health supplement. It also can be used as a bioadsorbent for heavy metals. Although it is rich in bioactive, its implementation in the pharmaceutical sector is almost negligible.

Currently, beer is the alcoholic beverage of choice, with yearly consumption hovering around 200 billion liters (Ambrosi et al., 2014).

* Corresponding author.
E-mail address: pkdmvu@gmail.com (P.K. Das Mohapatra).

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In the running year, the expected revenue in breweries will be US $610.00bn. For the period 2023–2027, the worldwide beer market is anticipated to expand at a 5.44 % annual rate. By 2027, it is anticipated that there will be 189,305.5 million L of beer produced worldwide. In 2023, the global market for bear is probably going to have a 2.2 % increase in volume. This year, it is projected that each individual will consume 22.67 L of beer on average (https://www.statista.com/outlook/cmo/alcoholic-drinks/beer/worldwide accessed 10/02/2023). Additionally, it is anticipated that the Indian beer market would expand at a rate of 8.17 % a year between 2023 and 2027. By 2027, it is predicted that India will produce 5807.0 million liters of beer. In 2024, the Indian market will be anticipated to have a volume intensification of 5.1 %. 3.39 L is the average amount of beer consumed per year per Indian, according to estimates and the expected revenue from breweries in India will be US$14.47bn in 2023. Globally, China ranks the top in revenue generation from breweries (https://www.statista.com/outlook/cmo/alcoholic-drinks/beer/india accessed 10/02/2023). Approximately 38.6 million tons of BSG were manufactured annually throughout the world (Mussatto, 2014). Crucially, 100 L of beer produces 20 Kg of BSGs (Fernandes et al., 2021). BSGs are widely accessible around the world and protein and amino acids contents are plentiful in them. However, due to the necessity of 30–60 % oxygen to completely oxidize, these nutrient-rich organic wastes are a threat to the environment. Janeeshma et al. (2023) reported on enzyme mediated managements of waste products. Again, inappropriate deactivation and discard of BSY also pose a menace to the environment (Caruso et al., 2022).

Pollution due to brewery waste is alarming as it has been reported to cause a significant deterioration in the flora and fauna. Alteration in the physicochemical attributes of water and an increase in heavy metal concentration highly impact the quality of life of the consumers (Sen et al., 2023). Again, the implementation of contaminated water in household appliances causes serious health hazards (Ipeaiyeda and Onianwa, 2009). Therefore, it is of utmost importance that brewery wastes are disposed of safely.

On the contrary, these readily available, inexpensive, underutilized wastes can serve as an ideal substrate for a variety of biotechnological processes. BSG is widely utilized in animal nutrition and only sporadically in human nutrition because it is high in protein, fiber, and other nutrients (Eliopoulos et al., 2022; Cuomo et al., 2022). It is also a fuel source; it has been claimed that the pyrolysis of BSG results in the generation of bio-oil, bio-char, and bio-gases (Bhakta et al., 2022). Synthesis of paper and pulp as well as using BSG as an adsorbent to remove colours from effluent or organic substances from waste gases are some of its other traditional applications (Puligundla and Mok, 2021). Potential benefits that can be obtained from BSG and BSY are enormous. The development of the circular economy paradigm and technological advancements in waste processing has given rise to an increased interest in alternative uses of BSG, particularly as a fermentative substrate. The nutrition, accessibility, and affordability of BSG make it a viable substrate in several biotechnological sectors.

This article aims to present the most recent knowledge on the biotechnological utilization of brewers' spent products, considering notable advancements in the exploitation of these residues through biotechnological approaches in recent decades. The study provides insights into the diverse applications of brewery wastes in various biotechnological sectors and elucidates the underlying mechanisms driving beneficial actions. Technological limitations and gaps in current approaches are systematically evaluated. Additionally, the study endeavors to outline the preliminary potential of brewery waste to contribute to the circular economy.

2. Brewery waste prospective

Globally, the lack of raw materials for biotechnological enterprises has created an environmental, economic, and societal imbalance that has led to the gratuitous abuse of natural resources, a spike in the price of essential commodities, and a drastic rise in the population of individuals living in severe poverty. The abundance of bioactives (Table 1), fibers, and bio-catalysts that are important for the formulation of functional products and medications against chronic and persistent disorders make brewery by-products beneficial. Bonifácio-Lopes et al. (2020) critically reviewed the bioactive components present in BSG. However, significant amendments in the breweries are required for the effective handling of the byproducts. The recent advances in the biotechnological utilization of Brewers' byproducts are mentioned in Table 2. In the medium and long term, the circular economy looks to be an effective choice for preserving natural resources by reusing or recovering resources from byproducts. The objective is to use sustainable technology to extract nutritious ingredients from the by-products and reinstate them to the manufacturing line as raw materials to create new products with significant physiological advantages and additional potentiality in the market.

2.1. Food

Brewery wastes are frequently associated with different sectors of the food industry as they play important roles as food ingredients and additives. BSG and BSY are good sources of proteins, amino acids, carbohydrates, fiber, vitamins, minerals, and other bioactives. Cheap and nutritious properties make them desirable candidates in food industries. The wet and dry forms of the spent grains are generally utilized as feed for ruminants and monogastric animals respectively. The high content of moisture eases the digestibility of the spent grains and makes them highly acceptable to livestock and fish. The implementation of brewery waste in the human diet still grasps the tag of novelty.

2.1.1. Animal feed

Proteinaceous products are the most costly ingredients in animal feed formulation. In recent years, the exploitation of brewery waste as a protein source in the feed of various animals has gained significant importance. The utilization of BSGs and BSYs as feed ingredients consequences in the improvement of growth, nutritional profile, fecundity, and overall health performance of fish and livestock. A replacement of 75 % soybean meal with BSGs in the diet of lactating cows enhances the feed digestibility and milk quantity of experimental cows (Faccenda et al., 2017; Overland et al., 2013). Additionally, the dietary inclusion of BSGs enhances the protein and fat content of bovine milk (Rachwał et al., 2020). BSG supplementation improves the growth and carcass composition of lamps. The carcass revealed an amplification of linoleic cis- 9 and trans-11 PUFA acids and a reduction of total fat (Radzik-Rant et al., 2018). Poultry and pigs are good acceptors of BSGs as feed (Pabbathi et al., 2022). Sorghum-barley BSGs have successfully improved the growth and feed conversion efficiency in broilers (Nortey et al., 2018). The application of BSGs in the aqua sector successfully reduces the exploitation of soybean meal during fish feed formulation. Dietary substitution of soybean meal with BSGs in the feed of *Cirrhinus reba* and Pangasianodon hypophthalmus consequences in a significant improvement of the growth parameters and reduces the cost of fish feed by 8.55 % and 27.56 %, respectively (Jayant et al., 2018; Chattaraj et al., 2023). The combined effects of BSGs and BSYs as a protein source were studied in Sparus aurata and the authors claimed that the waste products can successfully reduce the dependence on different animal and plant protein sources in feed formulation (Estevez et al., 2021). BSGs could act as an enriched source of polyphenols in animal feed (Stefanello et al., 2018). BSY has been evaluated to be a rich source of proteins, amino acids, B vitamins, and minerals. It can act as a promising substitute for soya products. The nutrient-rich product has good digestibility in fish, pigs, and rats (Overland et al., 2013). The residue has been applied as feed additives for ruminants, fish, poultry, horses, and swine for decades (Rachwał et al., 2020). However, the residual yeasts have to undergo inactivation steps either physically (heat) or chemically (organic acids) prior to their application. The inactivation process prevents

Table 1
Bioactives in brewers waste products, their extraction and utilization.

Bioactives	Extracted from	Extraction process	Applications	Refs.
Fructooligosaccharides Galactooligosaccharides Inulin Lactulose	BSG	Autohydrolysis/ dilute acid alkaline hydrolysis/ enzymatic hydrolysis/ ultrasound aided extraction	Acts as prebiotics.	(Bonifácio-Lopes et al., 2020)
β-glucan			Acts as prebiotics for lactobacilli and bifidobacterium. Used in food and pharmaceutical industries	
Arabinoxylans		Autohydrolysis, Ultrasound/ Microwave assisted extraction	Controls blood glucose after a meal	(Li et al., 2017; Reis et al., 2015; Coelho et al., 2014)
Arabinoxylooligosacharides		Microwave assisted extraction	Used in food and pharmaceutical industries	(Coelho et al., 2014)
Phenolic compounds		Supercritical carbon dioxide extraction/ Autohydrolysis/ Solvent extraction	Used in food, pharmaceutical and cosmetic industries	(Bonifácio-Lopes et al., 2020)
Phenolics and flavonoids		Supercritical carbon dioxide extraction by ethanol as co-solvent	Used in food, pharmaceutical and cosmetic industries	(Spinelli et al., 2016)
Acetic acid Aroma compounds		Autohydrolysis Autohydrolysis in autoclave		(Bonifácio-Lopes et al., 2020)
Hydroxycinnamic acids (Ferulic acid and p-coumaric acid)		Alkaline hydrolysis, solid-to-liquid extraction	Used in food, pharmaceutical and cosmetic industries. Possess antioxidant, antiallergenic, anti-inflammatory and antimicrobial activities.	(Meneses et al., 2013)
Antioxidants (phenols, reducing sugars, flavonoids and proteins)		Solvent extraction (methanol, acetone, ethanol, ethyl acetate, hexane, water)	Substitute of synthetic antioxidants	
Proteins		Ultrafiltration + ultrasound aided extraction		(Tang et al., 2009, 2010)
Bio-compounds		Technologies based on electric-field (emergent and novel)		(Rocha et al., 2018)
4-hydroxybenzoic acid Ascorbic acid		Ohmic based hydro-ethanolic heating extraction	Can inhibit 50 % of angiotensin-I converting enzyme (ACE) enzyme and hence, can be used to control blood pressure and cardiovascular diseases. Inhibits biofilm produced by *Bacillus cereus* and *Listeria monocytogenes*.	(Bonifácio-Lopes et al., 2022)
Tryptophan, catechin, aminobutyric acid, lactic acid		Water extraction	Food and pharmaceutical applications. Aminobutyric acid controls anxiety, diabetes, stress, high blood pressure and insomnia	(Petrucci et al., 2023)
β1,3-glucans α1,4-Glc	BSY	Thermal autolysis, Hot water extraction, Subcritical water by microwave-assisted extraction	Food and pharmaceutical applications.	(Reis et al., 2023b)
Mannoproteins		Autolyzation, centrifugation and dialysis	Food production and conservation	(da Silva Araújo et al., 2014)

fermentation to protect animals from gastrointestinal (GI) ailments (Rachwał et al., 2020). A mixture of BSY and BSGs had been applied in inbreeding turkeys and hens and good effectiveness was observed in the productivity and fecundity of the experimental animals (Levic et al., 2010). The hot trub, another by-product of the brewing process, isn't generally utilized as feed ingredients for its bitterness. The presence of the spent hops in the hot trub is responsible for the characteristic unpleasant flavor. However, a mixture of dried trub-yeast has been accepted as a dried protein source in the feed for Swine (Russ and Meyer-Pittroff, 2003). Santos and Martins (2024) reported hot trub as a rich source of protein and different bioactives.

2.1.2. Human feed

There are affirmations that BSGs provide healthy nutrients that are safe for human consumption. Fibrous and proteinaceous components present in BSGs are crucial for the human diet and can raise the value of food items. Additionally, the inclusion of BSGs bestows advantageous attributes on food items. The waste grains can improve the gelling and emulsifying capabilities as well as the fragrance of food products. The high dietary fiber content of BSG-incorporated feed facilitates the body to avert chronic diseases like cancers, GI disorders, diabetes, and coronary cardiovascular ailments. The spent grains maintain the digestive organs and lower cholesterol and lipids. The BSGs act as a suitable alternative to synthetic antioxidants that are frequently applied during food processing (Aliyu and Bala, 2011). Bread and pastries supplemented with BSGs revealed an enhancement in protein, lipid, fiber, and minerals contents and endows food with satisfying flavor and better organoleptic properties. Flour made by the processing of BSGs has been highly appreciated in the food industry to make waffles, bread, pancakes, cookies, tortillas, breakfast cereals, and pasta. The incorporation of suitable enzymes in BSGs incorporated feed, enhanced the texture, and loaf volume and extend the shelf-life. Various bakery products experienced an improvement in sweetness, water-retaining capacity, and texture after being fortified with BSG flour (Ktenioudaki et al., 2013). Moreover, the physical qualities of cookies can be restrained by the addition of 40 % BSG flour and the nitrogen and fiber content will be subsequently enhanced. In recent decades many food industries apply BSGs as a chief ingredient to prepare ready-to-eat snacks like chickpeas (Stojceska et al., 2008). BSG can substitute animal protein or enhance meat products using dietary fiber, making it a useful additive to processed meat. BSGs are currently used to prepare smoked and low-fat poultry sausages (Choi et al., 2014). Brewer's wasted grain infusion does not have a detrimental impact on the qualitative attributes of foodstuffs, but it does boost the nutritional value of foods. BSY contains valuable nutrients and bioactives that are essential for different bioprocesses in humans. The enriched content of minerals makes BSY a promising candidate in the confectionery, dairy, beverages (juices), and mead (fermented honey and water) sectors of the food industry. It has also been applied in bakeries for flour production. Borchani et al. (2016) reported that BSY is enriched with prebiotic properties and exerts beneficial effects on consumers consuming BSY-incorporated feedstuffs. It can be used to enhance food items with B- complex vitamins, polyphenolics bearing antioxidative potentials, and minerals. Higher digestibility of the spent yeasts is another attractable attribute. Vegan

Table 2
Recent advances in the biotechnological utilization of Brewers byproducts.

Biotechnological utilization	Waste type	Employed in	Performance efficiencies	Mechanism of implementation	Challenges	References
Human food	BSG	Ćupter (Herzegovinian candy)	Ash, protein and sugar contents were enhanced. Reduce production costs	Partial replacement of semolina and flour	Recipes and desiccative processes should be customized to enhance consumer acceptance	(Lalić et al., 2023)
	BSG green extract	Simulation of Gastrointestinal digestion (GID)	The extracts act as potential prebiotic for *Bifidobacterium animalis* B0; *Bifidobacterium animalis spp. lactis* BB12; *Lacticaseibacillus casei* 01; *Lactobacillus acidophilus* LA-5. Catechin, vanillin and p-coumaric acid were available at the end of the GID	Extraction of bioactive compounds from BSG by solid-to-liquid conventional extraction and solid-to-liquid ohmic heating extraction	Extraction process is expensive. Formulation of the extracts as tablet or capsule is also a great challenge. Again shelf life enhancement of the extracts and protection from microbial attack is a matter of great concern.	(Bonifácio-Lopes et al., 2023)
	BSY	Eicosapentaenoic acid (EPA) production	EPA production of 155 mg L^{-1} had been observed.	EPA had been produced by *Pythium irregular* by utilizing BSY and expired orange juice as substrates.	Safety efficacy of the utilization of expired orange juice needs to be evaluated by clinical trials prior to human application.	(Russo et al., 2023)
Non-starch polysaccharides	BSG	Production of arabinoxylans	Proteolsis enhanced the purity and antioxidant capacity of extracted arabinoxylans	Extraction of arabinoxylans by CaO nixtamalization of BSG	Proteolysis affects the intrinsic viscosity and viscosimetric molecular weight of arabinoxylans and reduced the protein and lignin contents.	(Martínez-Encinas et al., 2023)
Organic polymer	BSG	Production of lignins	The extracted lignin have high purities, antioxidant activities and valuable attributes	Lignin had been extracted from BSG using Deep Eutectic Solvents (eco-friendly approach)	Efficiency of the process in practical field is to be established. Cost-effective analysis is required from a commercial point of view.	(Cassoni et al., 2023)
Pharmaceutical	BSY	Targeted Oral Carriers	The human Dectin-1 immune receptor detected the BSY microcapsules under *in vitro* condition. Several lectins of the immune system associated with (1–3) β-glucans, glycogen, and mannans variably identified the digested BSY microcapsules. The process can also modulate immuno responses.	Yeast microcapsules are recognized by Dectin-1, and may be internalized and employed for the specific and controlled delivery of anti-inflammatory medications. The association with key immunological receptors may be facilitated due to the enriched (1–3) β-glucans and α-glucan contents of BSY as well as the existance of residual mannoproteins.	Tolerance to *in vivo* digestion (IVD)of BSY microcapsules. Detection of IVD-solubilized BSY substances by several mammalian immune receptors. Detection of BSY by human Dectin-1 immune receptor.	(Reis et al., 2023)
	Spent Yeast Waste Stream	Skin care, cosmetics	The evaluated peptide fractions weren't cytotoxic for HaCat and HDFa cell lines. All peptide fractions demonstrated the ability to control the synthesis of the different target metabolites (pro-collagen IαI, fibronectin, hyaluronic acid, cytokeratin-14, aquaporin-9, and elastin).	The waste material contains phenolic compounds and peptides. Peptides have the ability to influence the epidermis by targeting skin metabolites like collagen synthesis and regulating immunological response.	The extraction of the phenolic compounds and the peptides still remains an expensive procedure. The incorporation of the bioactive compounds in emulsion may be a fruitful technique for ointment formulation.	(Costa et al., 2023)
Bioremediation	Brewery spent wash (BSW)	Wastewater treatment, Lipids and carotenoids production	The approach enables the operation to become profitable by lowering the price of the growth media and producing high lipid levels and other valuable components.	Pure cultures of Oleaginous yeast remove COD, N, P and NH_4+-N from BSW. Microalgae produces lipid from BSW. A combination of Yeast and microalgae is implicated in the production of carotenoids from BSW	Process standardization is desirable for *in-situ* application	(Dias et al., 2023)
Capacitor	BSG	Electrochemic-al and lithium-ion capacitors	The capacitors showed high energy, power densities and admirable cycling stability	Activated carbons possess large surface area and the electrodes prepared from it showed very high specific capacitance and capacitance retention when assessed in symmetric Electrical Double Layer Capacitors apparatus with organic electrolytes.	Stability of the material in long run. Thermo tolerance is essential for good performance of capacitors in electric circuits and stability in inorganic electrolytes is challenging.	(Magar et al., 2023)

cakes fortified with BSY were frequently found to have a good profile of protein, lipids, and saccharides (Coldea et al., 2017). In the food sector, hot trub with altered chemistry and functionality can be employed to enhance items that are high in lipids or as a substitute for plant protein (Saraiva et al., 2019).

Notwithstanding the benefits of utilizing BSG, its usage is still restricted, which is mostly due to preservation issues. The residues are prone to microbial infection owing to their high dampness. Wet grains are susceptible to mold attack and deterioration will take place within a short time of manufacture. Hence, preservation is essential for the effective usage of the by-products. The waste products may be dried by sun radiation or ensiled to enhance their shelf-life.

2.2. Production of organic acids

Waste products of the breweries can be utilized for the bio-production of organic acids. BSGs are recently exploited for the production of different organic acids. Dhillon et al. (2011) reported on the production of citric acid by *Aspergillus niger*. Utilizing BSG, organic acids notably citric and lactic acids have been synthesized by fermentation. By fermenting BSG hydrolysate with *Lactobacillus delbrueckii*, L-lactic acid had been synthesized (Mussatto et al., 2007). In the investigation, cellulase was used to saccharify BSG after chemical pretreatment; no additional nutrients were added to the medium. A maximum lactic acid output of 73 % was found (Mussatto et al., 2007). Since BSG contains modest amounts of free alpha-amino nitrogen, adding nitrogenous nutrients (BSG) may boost lactic acid productivity (Djukić-Vuković et al., 2016). Enzymatic hydrolysis and fermentation of BSG by *Lactobacillus sakei* and *Pediococcus pentosaceus* KTU05-9 (48.71 g per kg of BSG) produce L-lactic acid (Juodeikiene et al., 2016). Puligundla and Mok (2021) reported that the addition of yeast extract and MRS broth medium components (except carbon sources) to BSG hydrolysates increased the production of lactic acid. The addition of yeast extract and calcium carbonate to BSG also enhances lactic acid production (Pejin et al., 2015). Liang and Wan (2015) worked on the production of carboxylic acid from BSG by assorted culture fermentation. The inclusion of electron donors and optimization of pH greatly influences the formation of fermentation products. Lactic acid had been chiefly produced at alkaline and acidic conditions while volatile fatty acids (VFAs) were mainly produced at neutral conditions. The supplementation of ethanol as an electron donor greatly favored carboxylic acid chain elongation at neutral pH. Ethanol addition also enhances valeric acid (44 %) and caproic acid (167 %) production. The supplementation of lactic acid greatly influences the enhancement of the production of propionic acid (109 %) and butyric acid (152 %). The presence of lactic acid elongates the chain of carboxylic acid through reversed β oxidation by the anaerobic bacterium *Megasphaera elsdenii* (Weimer and Moen, 2013). BSG had been utilized as a substrate for acidogenic fermentation to produce biological monomers. BSG had been implemented in the pathways for the valorization of VFAs, like polyhydroxyalkanoates (Girotto et al., 2019). Citric acid had also been produced by *Aspergillus niger* utilizing BSG as substrate under solid state fermentation (SSF). The implementation of peptone and potassium dihydrogen phosphate enhances citric acid production (Pathania et al., 2018).

2.3. Pharmaceutical benefits

BSY contains vitamin D and nucleic acids. It can be applied as a cheap source for the enrichment of D2 (ergocalciferol) from its precursor (ergosterol) (Rachwał et al., 2020). Spent yeasts are also appreciated for

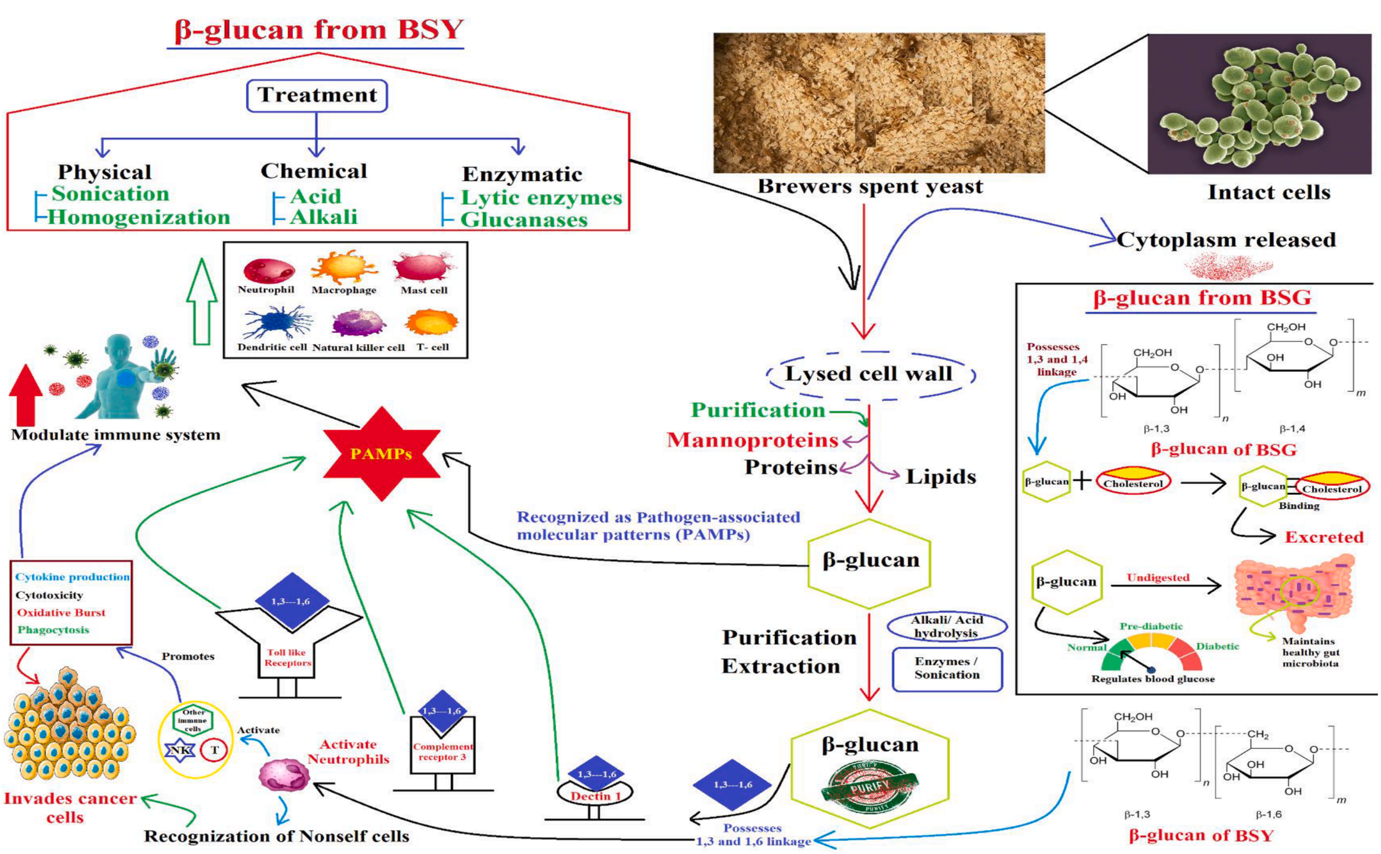

Fig. 1. Health stimulating effects of β- glucans produced from BSG and BSY. β- glucan is present in both BSG and BSY. β- glucan of BSG and BSY possesses 1,3-1,4 and 1,3-1,6 linkage respectively. β- glucan of BSG binds with cholesterol and excrete it from the body. Moreover, β- glucan of BSG maintains healthy gut flora and regulates blood glucose levels. β- glucan of BSY is to be extracted by different treatments and it acts as PAMPs to regulate the immune system. It can also activate neutrophils and invades cancer cells.

their capability of producing (1,3-1,6) β-glucan. β-glucans are frequently referred to as biological response modifiers (Caruso et al., 2022) for their potential in stimulating and amplifying immune responses in humans (Fig. 1). They have been shown to enhance disease resistance in humans and other animals (Varelas et al., 2016). β-glucans perform their immunomodulatory activities owing to the presence of Pattern recognition receptors (PRRs). Subsequently, the immune components stimulate the production of anti-carcinogenic and anti-microbial substances (Murphy et al., 2020). β-glucans also act as adjuvants for solid and hematological malignancies and are effective against different metabolic and respiratory disorders with allergic rhinitis (Murphy et al., 2020). The prebiotic, immunostimulatory, and antioncogenic properties of BSY are also highly appreciable (Cuomo et al., 2022). The yeast culture present in BSY can also act as a probiotic. Probiotics have immense importance in triggering different microbial infections especially viral ones (Chattaraj et al., 2022, 2023b, 2023c). The presence of (1,3-1,4) β-glucans in BSG has been established in previous studies (Eliopoulos et al., 2022). The component is closely associated to control blood cholesterol and glucose levels and maintain healthy gut microbiota (Murphy et al., 2020).

The hot trub has been applied as a carbon source for the production of Surfactin (Nazareth et al., 2020). Surfactin is a natural microbiocide competently applied to diminish the surface tension of liquid phases associated with gas, or interfacial tension among immiscible fluids. The properties of surfactant molecules, which possess a hydrophobic and hydrophilic moiety, allow the diminution of surface/interfacial tension. They may also alter the surface qualities that influence the adhesion of the microbes, disrupt membranes, trigger cell lysis, and interfere with the development of biofilms and quorum sensing. Surfactin produced from brewery trub has been shown to exhibit antibacterial effects against the pathogens Pseudomonas aeruginosa, *Escherichia coli, Staphylococcus aureus*, and *Staphylococcus epidermidis* (Nazareth et al., 2020). Hence, the waste trub can be applied in the pharmaceutical industries for cheap and easy production of Surfactin. Bacterial bio-surfactants are intricate assemblages of molecules with surface activity synthesized by microorganisms that attach to a particular cell membrane or are released

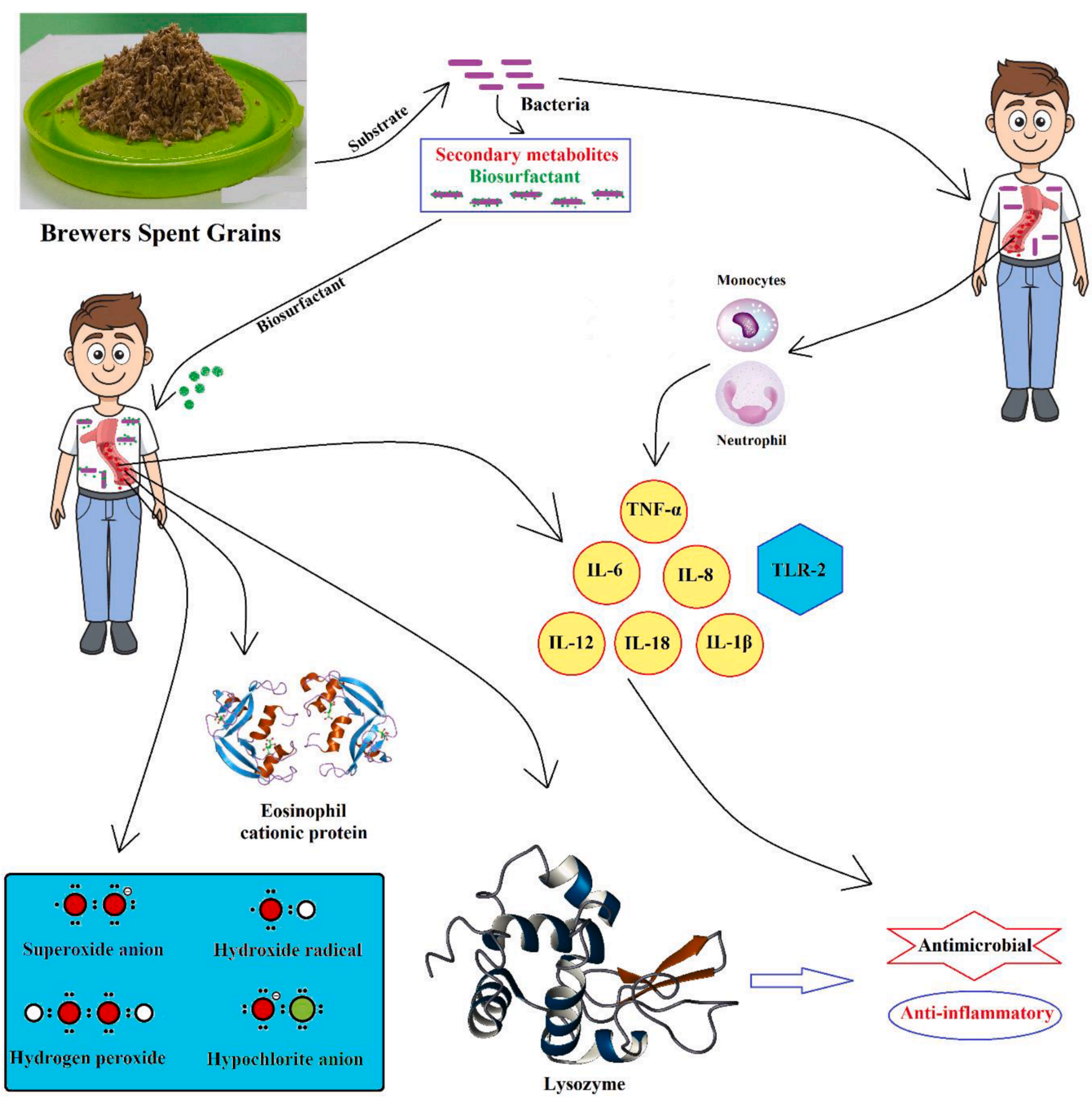

Fig. 2. Immuno-stimulative potential of biosurfactants. BSG can act as a substrate for bacteria capable of producing biosurfactants. These bacterial strains can modulate the immune system by activating neutrophils and monocytes and subsequently by releasing cytokines. Again, biosurfactants produced by the strains can trigger the synthesis of cationic protein, lysozyme and reactive oxygen species, thereby, bestowing anti-inflammatory and antimicrobial properties.

extracellularly in the growing media. The implementation of a suitable carbon source is highly desirable for biosurfactant production. The carbon source should be capable of providing sufficient calories to fuel up the bacteria for synthesizing biosurfactants. In this scenario, BSGs are highly potential to be used as a carbon source supplying adequate metabolic energy. Additionally, the enriched content of different minerals, growth stimulatory bioactives, and lack of toxic compounds make BSG a suitable substrate for bacteria-producing biosurfactants. Brewery waste had been employed for the development of Bacillus subtilis N3-1P and the synthesis of biosurfactants (Moshtagh et al., 2019). The conditions optimum for the synthesis of biosurfactant were brewery waste (7 % v/v), ammonium nitrate (6.22 mg/L), pH (6.41), agitation speed (150 rpm), and temperature (27 °C) (Moshtagh et al., 2019). Biosurfactants had also been produced by utilizing brewery waste (trub) as the carbon source of B. subtilis ATCC 6051 (Nazareth et al., 2021). Biosurfactants have applications in the medical, food, and cosmetic industries. The biosurfactants are used for drug delivery, function as anti-viral face-masks, and are incorporated with hand cleansers to limit the transmission of disease (Smith et al., 2020; Subramaniam et al., 2020). The modes of antimicrobial actions of biosurfactants are depicted in Fig. 2. Hence, through the utilization of brewery waste as substrate, expenses for biosurfactant synthesis can be reduced and a more ecologically acceptable method of disposal and treatment of the hazardous component can be developed.

Hops (Humulus lupulus) used in breweries are reported to contain aromadendrene oxide which is an oxygenated sesquiterpene having anticancer potentialities. It can also induce apoptosis by ROS-intervened mitochondrial pathway (Pavithra et al., 2018).

The polar lipid constituents of hops and BSG possess antithrombotic activities and had been evaluated on human platelets (Lordan et al., 2019). The polar lipids can inhibit platelet-activating factor and thrombin-induced human platelet aggregation and eventually functions as antithrombotic agents. Not only the waste products, the malted grain, wort, and bottled beer also provide evidence of antithrombotic activities (Lordan et al., 2019). The polar lipids of the breweries contain cardioprotective lipids. Hence, the functional components can be purified and may be applied as drugs to control cardiovascular disorders and thrombosis. The antithrombotic activities of brewers' raw materials, products, and byproducts may have some correlation with fibrinolysis as fibrin is chiefly associated with thrombosis. However, the fibrinolytic ability of the waste products of breweries has remained unexplored and is a considerable knowledge gap.

Brewery wastewater contains polyphenols, especially flavonoids, which are often implicated in antitumor and antioxidant properties. The obtained flavonoid improved mitochondrial oxidative activity, which is probably associated with a reduction in oxidative stress and an augmentation in mitochondrial biogenesis (Tatullo et al., 2016). Brewers spent grains act as a carbon source for cellulose production by different bacteria. Ha et al. (2008) reported on the production of bacterial cellulose by Gluconacetobacter hansenii utilizing the beer culture broth trash. Bacterial cellulose has immense importance in wound healing and designing regenerative medication for the skin. Bacterial cellulose has a porous configuration that can mimic the skin's extracellular matrix. The hydrophilic property of bacterial cellulose has been applied in wound healing (Kucińska-Lipka et al., 2015). Brewery waste-derived bacterial cellulose will possibly possess a good profile of hydrophilicity and may restore moisture. The technology can be applied on wounds as cuts and injuries heal faster if optimum moisture has been maintained.

Hence, the active pharmaceutical ingredients present in the waste products of breweries may stand as a functional ingredient in the pharma sector to design different therapeutic agents and may contribute to a great extent to diminishing environmental concerns and upgrading the financial status in the context of the circular economy.

2.4. Production of quantum dots

The application of brewery waste grains for carbon quantum dots (C-dots) fabrication is novel in the sector of cell imaging. Brewers' waste products have been applied as a rich source of carbon for the fabrication of fluorescent C- dots (Rodrigues et al., 2015). The quantum dots possess admirable features like tunable emission, optical stability, and brilliant luminescence which facilitate their incorporation into medical science. Small size, optical features, and non-toxic nature of C- dots make them more suitable. The potentialities of the C- dots in cellular imaging have been demonstrated (Rodrigues et al., 2015). The oxidation of brewery waste generated C- dots to produce sp3 domain on its surface which decorates the surface with various functional groups (such as carboxyl, carbonyl, hydroxyl, and epoxy). The inclusion of these oxygenated functional groups influences the hydrophilic characteristics of the C-dot derivatives significantly and also enables the development of more focused bioprobes through basic chemical reactions. Down-and up-conversion photofluorescence of C-dots from brewing industry waste has potential application in live cell imaging (Rodrigues et al., 2015). Hence, the utilization of the brewery waste for C- dots production may build a sustainable way of reducing the cost of different cell imaging techniques regularly prescribed for diagnostic purposes in medical science. As the source of the brewery waste generated C- dots are totally organic, the toxicological effects of the conventional C- dots may be triggered. However, it is a great challenge to design and fabricate the total system for commercial utilization in diagnostic sectors. Again, standardization of the entire process welcomes comprehensive studies and clinical trials are required for the sustainable implementation of the technology. A model for the production of quantum dots from BSG by lyophilization and pyrolysis has been postulated in Fig. 3.

2.5. Bioremediation

2.5.1. Heavy metals

Siddiquee et al. (2015) reported on the heavy metal contaminants removal efficacy of fungal biomass. Yeast cell possesses a high surface area to volume ratio that facilitates a large area of interaction with heavy metals. Owing to the effectiveness of heavy metal exclusion, yeast cells gain high acceptability to the environment. Waste yeast biomass has been emphasized as a promising biotechnological strategy in combating metal pollution due to its effectiveness in removing heavy metals, compatibility with the ecology, and accessibility. Soares and Soares (2012) reported on the heavy metal bioremediating abilities of brewers' spent yeast. The utilization of BSY in the detoxification of effluents containing heavy metals has extensive benefits over chemical compounds (Soares and Soares, 2012). Again, BSG was developed into a cellulose adsorbent for effective Mn and Pb elimination from polluted water (He et al., 2022). The mechanisms led behind the metal detoxification properties include intracellular metal immobilization, biosorption to the cell wall, metal transformation, metal mobilization, and metal uptake (Fig. 4a) (Siddiquee et al., 2015).

2.5.2. Hydrocarbon

Bacterial bio-surfactants are surface-active substances needed for the breakdown of hydrocarbons. Oil is disseminated into extremely small droplets by bacterial cells using a combination of biosurfactants, increasing the bioavailability of Crude Oil. The interfacial tension at oil/water interfaces and the surface tension at air/water interfaces are both decreased by these amphiphilic biomolecules. *In vitro* and field studies have demonstrated that organic brewing waste boosts the activity of enzymes produced by microorganisms that oxidize hydrocarbons, speeds up the reduction of oil content, and enhances the chemical and physical characteristics of chernozemic environments (Strizhenok et al., 2021). BSG includes complexes of nutrients and physiologically active chemicals that support the growth of hydrocarbon oxidizing microorganisms and consequently result in the degradation of hydrocarbons in

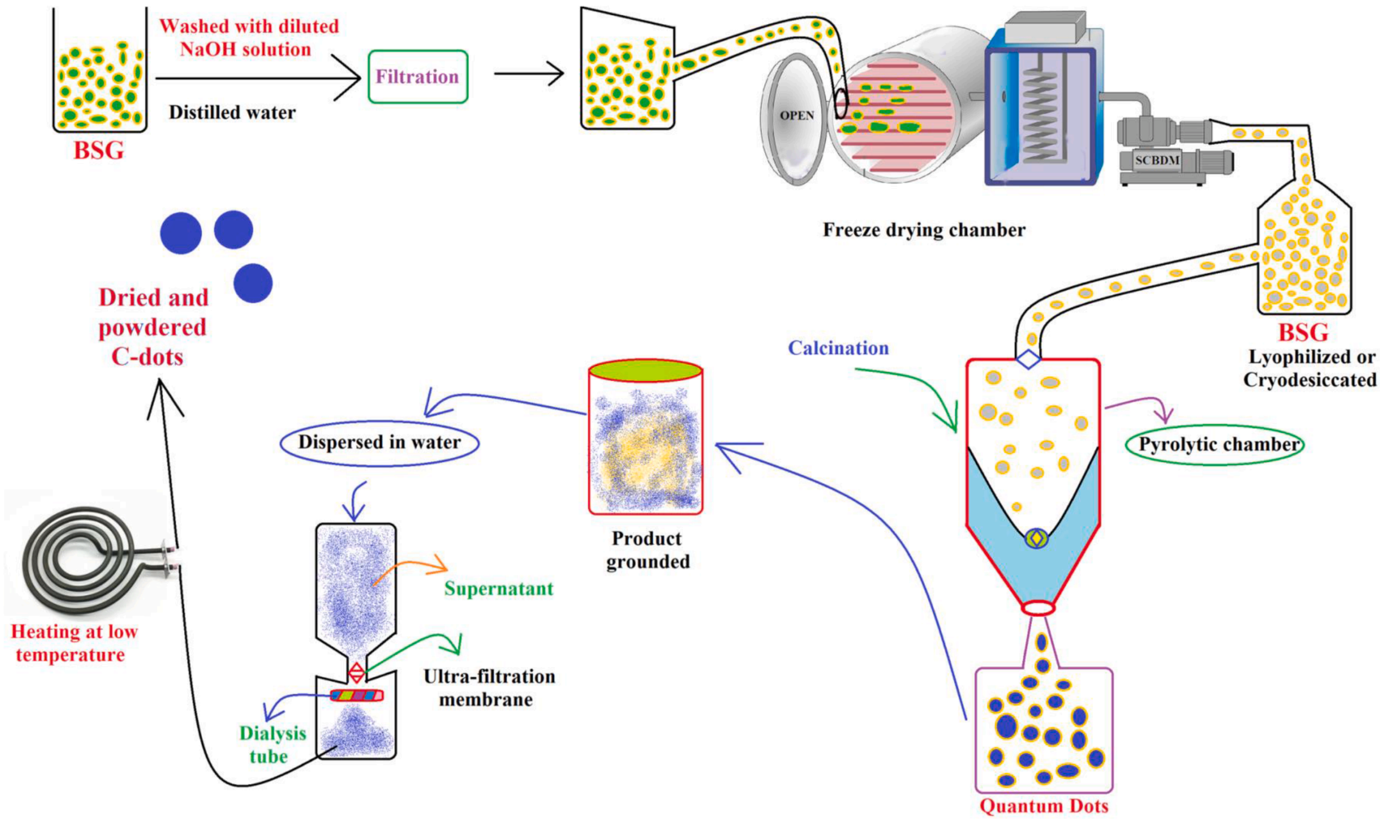

Fig. 3. Model for quantum dot production using BSG. BSGs are to be washed, filtered and then to be lyophilized to enhance the colloidal stability. Heat treatment is to be applied in the pyrolytic chamber to achieve pyrolysis and carbonization of the BSGs. Calcination alters the amino acids and peptide sequences to concrete quantum dot. After that, purification of the product is required to eradicate the unwanted aggregates.

the soil ecosystem (Fig. 4b) (Strizhenok et al., 2021).

2.6. Recycling agriculture

The lack of attempts to address farmers' perceptions of the economic benefits of BSG in agriculture, and the technical use of brewer waste sludge in crop production was virtually nil in most developing nations. Because it has a high organic content and easy availability, BSG can be utilized in agricultural strategies to boost crop yield. Again, BSG is a vital organic fertilizer and soil conditioner for sustainable agriculture. Typically, the implementation of BSG has been shown to have favorable effects on natural vegetation. Reusing this waste material has the potential to reduce raw materials required in conventional farming, boost efficiency and profitability, and eventually aid in environmental sustainability. BSG was generally applied before, during, and after the sowing of seeds. The application of the spent grains successfully enhanced the yield of maize, sorghum, and khat crops (Merga et al., 2020). Kopeć et al. (2021) reported on the potentiality of spent hop sediments for composting. The authors concluded that the total nitrogen content of spent hops is very high (50 g/kg) and can affect composting. Hence, the composting of nitrogen-rich hop sediments requires a structural substrate with considerably greater C:N ratios like sawdust or straw. With the proper quantitative and qualitative allocation of substrates, stable composting with spent hop deposits may be produced after 60 days of extensive aerobic decomposition (Merga et al., 2020). Hence, the scientific and judicious implementation of BSG and spent hops to the soil at the proper times can replace the exploitation of conventional fertilizers. Farmers may be able to affordably nourish their fields with the organic matter by using brewery trashes. Sludge recycling for agricultural use thus appears to be a desirable option for the long-term management of soil. It can enhance the level of organic content and can also enrich the soil with macro- and micronutrients. An increase in the amount of organic matter can rejuvenate the soil parameters and may promote bioactivity. Moreover, it has been reported that Brewery waste biomass and the microalgal culture of Scenedesmus obliquus improved the ability of wheat and barley seedlings to germinate and develop (Ferreira et al., 2019). The germination index (GI) of 85 had been observed for barley seeds supplemented with pellet from brewery effluent and was found to be higher than the GI for control seeds (35) cultured with tap water (Ferreira et al., 2019). Culturing S. obliquus in brewery effluent results in the release of different bioactives including phenols and flavonoids. Flavonoids have been found to play significant roles in mitigating stress in plants. The antioxidative activities of flavonoids aid plants in repairing damage brought on by uncontrolled ROS production and balancing it out (Shomali et al., 2022). The four following routes are used by flavonoids to reduce ROS production: Singlet oxygen is restricted, ROS-producing enzymes (lipoxygenase, cyclooxygenase, xanthine oxidase, and monooxygenase) are inhibited, transition metal ions are chelated, and other antioxidants are recycled (Mierziak et al., 2014). Again, flavonoids can quench free radicals and protect the cells from oxidative damage (Shomali et al., 2022).

2.7. Antibiotic removal from water

The antibiotic absorptive efficacy of activated carbon produced from BSG has tremendous applicability in the field of medical science research. The abundance of lignocellulosic fibers makes BSG an admirable precursor used for the fabrication of activated carbon. The adsorption of carbamazepine and acetaminophen (paracetamol) by activated carbon generated by pyrolysis of BSG had been described in the specific circumstance of pharmacological effluents (Sousa et al., 2020; de Araújo et al., 2020). The rapid and easy approach of microporous activated carbon production from BSG using one-step biochemical stimulation and microwave pyrolysis has been illustrated (Sousa

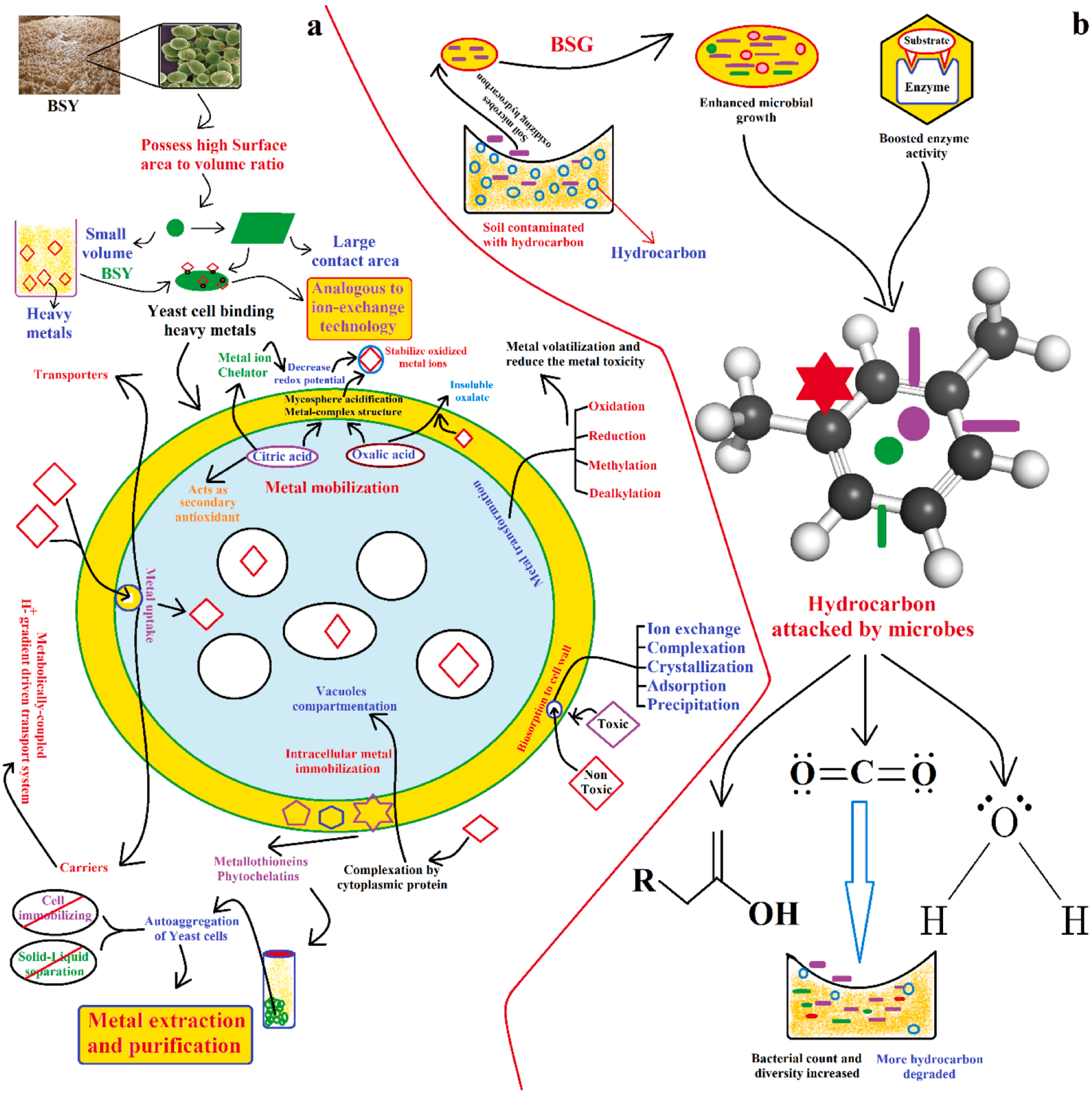

Fig. 4. Mechanism of bioremediation by BSG and BSY. (a) Role of BSY in heavy metal remediation. Yeast cells have large surface area compared to the volume. This property helps yeast cells to engulf and detoxify heavy metals by different mechanisms. Moreover, autoaggregation of yeast cells facilitates cell harvesting without any cell immobilizing or solid-liquid separation technique. (b) Role of BSG in remediating hydrocarbons. BSG enhances the diversity and growth of microorganisms. It stimulates microbial enzymatic activities and facilitates the microorganism to degrade hydrocarbon and produce free fatty acids, carbon dioxide and water.

et al., 2022). The three antibiotics namely, sulfamethoxazole, trimethoprim, and ciprofloxacin been used as the adsorbates. The optimal activated carbon, produced using K2CO3 and BSG (1:2) during pyrolysis (800 °C) for 20 min, had a well-microporous structure with impressive adsorptive elimination (84–92 %) on the experimental antibiotics (Sousa et al., 2022). Again, Sousa et al. (2023) produced activated carbon from brewers waste by single-step microwave pyrolysis and assessed its efficacy in the removal of sulfamethoxazole, trimethoprim and ciprofloxacin from antibiotic contaminated water. The technology can be utilized for the purification of drug-contaminated water. Additionally, it will reduce the overexploitation of antibiotics by recovering the antibiotics and consequently will reduce the cost of pharmaceutical drugs. Moreover, the eradication of antibiotics from effluent will restrict the interaction of the drugs with the microbes, and eventually, the environment will be protected from antibiotic-resistant strains.

2.8. Bioinsecticide production

The bio-insecticide Bacillus thuringiensis Serotype H-14 had been cultured in an assortment of BSY and trash cassava starch. The formulated medium supported the growth of the species up to 4.4×10^{10} cfu ml^{-1} and above 95 % sporulation and crystallization were achieved. After sporulation, crystals develop, and these crystals are the main components of the strain's larvicidal activity. The lethal concentration 50 (LC50) of the culture was 12 and 14.8 ppm (Ejiofor, 1991).

2.9. Bioelectricity generation

Distillery spent waste water is the combined waste water generated during the brewing of beer and from washing and chilling the fermenting equipment. Distillery spent waste water is alarming to the environment for the presence of organic components, dark colour and obnoxious odor. The waste wash has been found to be enriched with potassium, nitrogen, phosphorus and sulphur along with Ca, Zn, Mn, and Cu as micronutrients (Acharya et al., 2010). The organic matters act as oxidizing agent in Microbial fuel cells (MFCs) for the production of bioelectricity. Previous studies reported that brewery spent waste wash can produce an utmost open circuit voltage of 745.13 mV (Nayak et al., 2018); 0.578 V (Wen et al., 2009); 305 mV (Miran et al., 2015) and power density of 836.81 mW/m^2 (Nayak et al., 2018); 38.34 ± 16.45 mW/m^2 (Mshoperi et al., 2014); 48.47 mW/m^2 (Mohanakrishna et al., 2010); 264 mW/m^2 (Wen et al., 2009); 269 mW/m^2 (Miran et al., 2015); 669 mW/m^2 (Wen et al., 2010); 0.8 W/m3 and 0.35 W/m^3 (Negassa et al., 2021), 0.23 MWh t^{-1} (Buller et al., 2022). The composition BSG may be better amenable for anaerobic digestion after being ultrasonically processed. Ultrasonication of BSG prior to anaerobic digestion yields more electrical energy (Buller et al., 2022).

MFCs are hybrid biochemical devices designed to generate renewable energy from organic wastes. Microorganisms present in the system act as a mediator to convert biodegradable organic wastes into carbon dioxide, water, and energy (Pandey et al., 2016). The metabolic pathways present in the microorganisms facilitate the conversion of chemical energy to electrical energy. A modified design of a two-chambered MFC has been proposed in Fig. 5. Exoelectrogenic bacteria are employed in MFCs as biocatalysts for catabolizing composite organic compounds in the existence of electrodes for gathering electrons generated from the microbial catabolic pathways. In the anodic chamber, the substrate (brewery spent wash) undergoes oxidative conversion with the aid of microbial activities. Chemical reductive alteration instantaneously takes place in the cathodic section. Electrons generated in the anodic chamber pass through an exterior circuit and the protons simultaneously pass through a proton exchange membrane and react with oxidizing elements (preferably oxygen) at the cathodic section leading to a closure of the circuit (Nayak et al., 2018). Standardization of the system is highly required for the commercial and industrial employment of this technology. Modification of the electrodes by new elements and valorization of BSG by ultrasonication to obtain more electrical energy invites more research in this field. Strain development of bacteria and alga is also an effective way to get more voltage output.

2.10. Substrate for microbes

BSG has been vastly reported to support the growth of different bacteria, algae, and fungi. On the contrary, the prices of culture media used in laboratories are increasing day by day. BSG can act as a potential substitute for different conventional ingredients of culture media as the waste product has been found to be enriched with proteins,

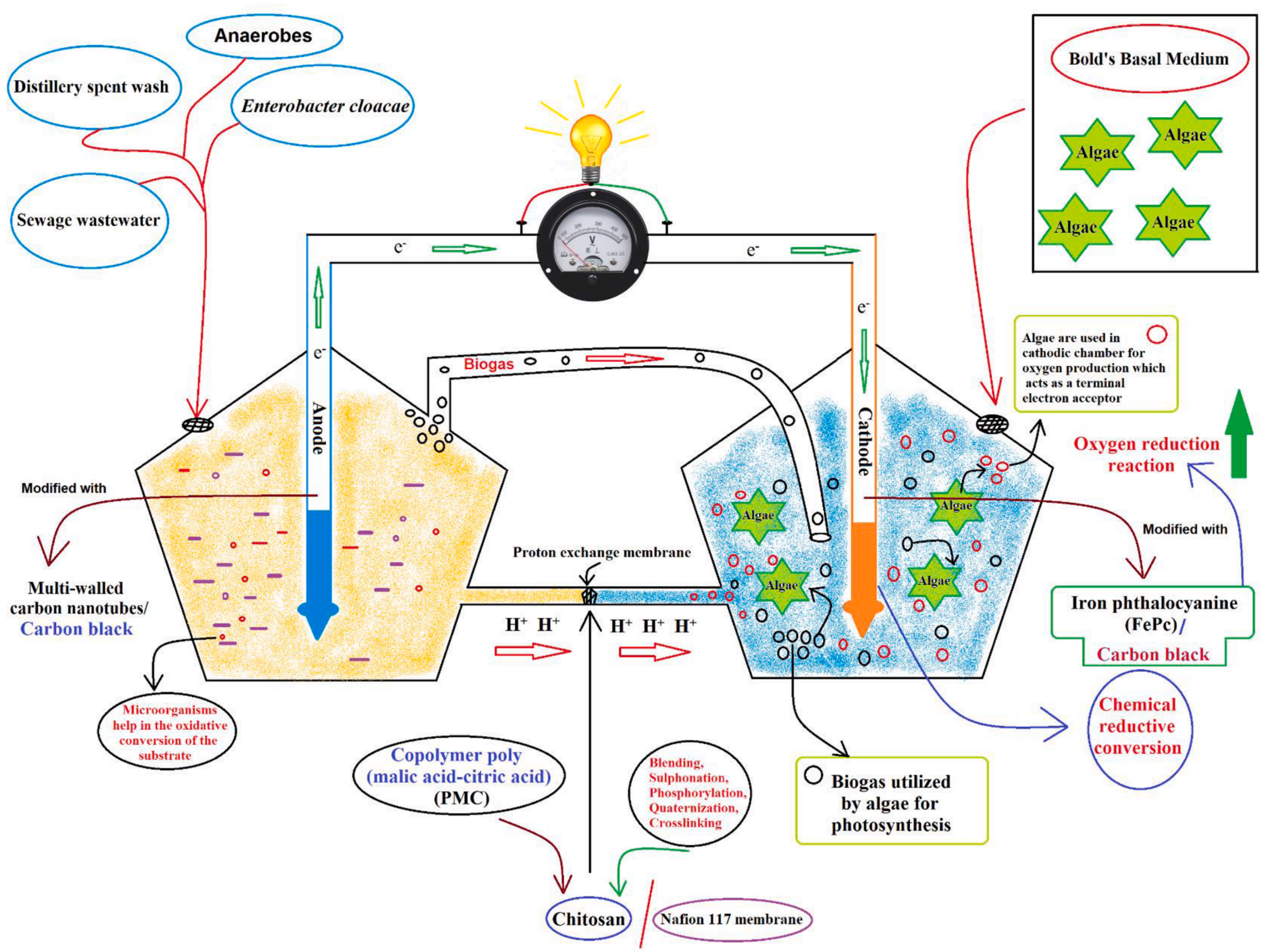

Fig. 5. Model for bioelectricity generation using brewery spent wash. Microorganisms present in anode chamber helps in oxidative conversion of the brewery spent wash. The anode chamber that can be modified with multiwalled carbon nonotubes attracts the electrons. Green algae are there in the cathodic chamber modified with FePc and chemical reductive conversion occurs there. Oxygen is produced by the green algae by utilizing biogas produced from the anode chamber. Oxygen acts as the terminal electron acceptor. Again protons from the anode chamber move through the proton exchange membrane and reach the cathode thereby completing the electrical circuit. The proton exchange membrane can be constructed with PMC-Chitosan.

carbohydrates, free amino acids, etc. Hence, BSG may be used as an active ingredient for laboratory scale culture media formulation but only after proper scientific processing. Standardization of the media formulating process is a great challenge and invites further studies. Again, BSY contains different growth-stimulating macro and microelements and can act as a substitute for yeast extract in media formulation. Hence, scientific and judicious utilization of the technique may trim down the cost of culture media.

2.11. Biogas

The technique of producing biogas by anaerobic digestion of biomass or trash substrate is widely established. Biogas generation from BSG has enormous potential. Ultrasonication and anaerobic digestion of BSG generated 56 % methane (Buller et al., 2022). Brewery waste grains are required to have lignocellulosic fibers degraded using hydro thermolysis in order to produce more methane. Macellibacteroides, Sphaerochaeta, and Archaea (Methanosaeta) were found in the optimized methanogenic fermentation conditions of processed BSG, preferring the acetoclastic methanogenic mechanism (Gomes et al., 2022). Panjičko et al. (2017) designed a two-stage platform for the anaerobic digestion of BSG. Phase separation of anaerobic digestion by acidogenesis and microbiological hydrolysis took place in a solid-state anaerobic digester, and secondly, methanogenesis occurred in a granular bioreactor. The authors documented that biogas formation had been 414 ± 32 L/kg and the content of biomethane was 224 ± 34 L/kg of entire supplemented solids (Panjičko et al., 2017). *Ruminococcus flavefaciens, Fibrobacter succinogenes, Clostridium cellulovorans,* and *Pseudobutyrivibrio xylanivorans* were implicated in the digestion of the lignocellulosic biomass for biogas production (Čater et al., 2015). The biochemical methane propensity screening was used to assess the impact of bioaugmentation by anaerobic hydrolytic bacteria on biogas formation. The use of lignocellulose in the biogas sector may be expanded by bioaugmentation, a potential technique for enhancing methane output from BSG (Čater et al., 2015). A biorefinery's two-stage thermal pretreatment emerged as a compelling substitute for fractionating BSG and has been successfully implemented in biogas production (de Camargos et al., 2021). Torrefaction (chilled pyrolysis), a unique and effective approach for increasing biogas output, can be achieved with the addition of biochar (Dudek et al., 2019). The biogas produced from BSG can be used as a renewable source for the production of cooking gas, bioelectricity, and fuel for vehicles. However, the risks concerning safety efficacy and environmental issues are to be weighed against the benefits. As methane is a greenhouse gas, comprehensive investigations are awfully required to assess its suitability.

2.12. Bioethanol

A renewable fuel, ethanol may be manufactured from a wide range of plant components collectively referred to as "biomass." Non-food biomaterials including lignocellulosic biomass and biowaste have been employed more and more recently as raw materials for the manufacture of second-generation (2G) ethanol. BSG may be employed to generate bioethanol since it contains a lot of fermentable carbohydrates. The considerable lignin concentration of BSG causes issues during enzymatic hydrolysis. To liberate carbohydrates, the lignin wall must be broken down. Treatments with acids or alkalis are common methods for delignifying BSG. It had been observed that pretreatment of BSG with NaOH was efficient for releasing glucose, and fermentation of resulting hydrolysates produced an adequate amount of ethanol (Puligundla and Mok, 2021). Wagner et al. (2022) studied the one-pot production of bioethanol from BSG by implementing the recombinant ethanologenic strain *E. coli* MS04. A systematic approach that included preprocessing, saccharification, and fermentation phases despite solid elimination had been proposed by the authors for 2G bioethanol production. Puligundla and Mok (2021) mentioned the application of Pichia stipitis, Kluyveromyces marxianus, and Trametes hirsute to produce bioethanol from BSG. Barampouti et al. (2022) achieved high ethanol yields by recovering and extracting the oil content of BSG and Spent Coffee Grounds. The previous studies showed the possibility and efficacy of enzymatic hydrolysis, acid pretreatment, and ethanologenic microbial strains for bioethanol synthesis employing BSG as the only substrate despite the requirement for hydrolysate detoxification. The application of bioethanol will possibly protect the environment from the toxic effects of conventional fossil fuels.

2.13. Biodiesel

Potential sources for the generation of biodiesel include microbial lipids. BSG was employed by Sae-ngae et al. (2019) to cultivate oleaginous yeasts. Trichosporonoides spathulata, one of the evaluated yeasts, produced a significant amount of lipid (62.9 mg/g of BSG). For the culture of the oleaginous yeast, Rhodosporidium toruloides organosolv-preprocessed hydrolysates of BSG had been employed (Puligundla and Mok, 2021). Darpito et al. (2015) utilized the microalgae Chlorella protothecoides in brewery wastewater treated anaerobically for biodiesel production at a cost-effective approach. Brewery waste wash that had undergone anaerobic treatment was utilized to cultivate *C. protothecoides* at a cheap cost. 1.88 g/L of biomass was accumulated by C. protothecoides. Improvements in cell volume and cell aggregation were seen in C. protothecoides cultured in the waste wash, which led to a harvesting efficiency improvement of about 80 % in 20 min. Additionally, the alga reflected a 1.84-fold increase in the content of total fatty acid (Darpito et al., 2015). Hydrogen production by photobiological reaction and transesterification methods is generally implicated in biodiesel production. Hence, microbe-derived lipids can be utilized as a renewable source of diesel in the upcoming future.

2.14. Prebiotic oligosaccharides production

Xylooligosaccharides and arabinoxylooligosaccharides are highly appreciated for their potential in enhancing the load of beneficial gut microbiota. BSG serves as a good raw material for the production of the prebiotic arabinoxylooligosaccharides. Enzymatic cleavage of BSG-derived arabinoxylan yields arabinoxylooligosaccharides of desired chain length (Sajib et al., 2018). Different types of xylanases were preferred for enzymatic hydrolysis. BSG had been exploited as a substrate for the production of arabinoxylooligosaccharides by one-step fermentation using *B. subtilis* (Amorim et al., 2018). Amorim et al. (2019) also produce xylooligosaccharides from BSG by single-step fermentation using Trichoderma reesei.

2.15. Building material

Thomas et al. (2017) reported on the utilization of BSG as a building material. BSG can act as a partial substitute for cement. The tensile strength of cow dung and local BSG mortar is significant to a great extent and is more than the minimum needed strength of mortar for low-cost buildings, indicating the possibility of utilizing cow dung and local BSG in partial substitution of cement used for plastering low-cost buildings.

2.16. Seed germination

Brewery waste biomass and the microalgal culture of Scenedesmus obliquus improved the ability of wheat and barley seedlings to germinate and develop (Ferreira et al., 2019). The germination index (GI) of 85 had been observed for barley seeds supplemented with pellet from brewery effluent and was found to be higher than the GI for control seeds (35) cultured with tap water (Ferreira et al., 2019). Culturing S. obliquus in brewery effluent results in the release of different bioactives including phenols and flavonoids. Flavonoids have been found to play significant roles in mitigating stress in plants. The antioxidative activities of flavonoids aid plants in repairing damage brought on by uncontrolled ROS production and balancing it out (Shomali et al., 2022). The four following routes are used by flavonoids to reduce ROS production: Singlet oxygen is restricted, ROS-producing enzymes (lipoxygenase, cyclooxygenase, xanthine oxidase, and monooxygenase) are inhibited, transition metal ions are chelated, and other antioxidants are recycled (Mierziak et al., 2014). Again, flavonoids can quench free radicals and protect the cells from oxidative damage (Shomali et al., 2022).

3. Nutritional enhancement of Brewers waste

There are different techniques to enhance the nutritional contents of brewers' waste products for sustainable application in food industries. Considering edible filamentous fungi have great potential as a source of protein, fatty acids, and micronutrients, they can be utilized in food (Puligundla and Mok, 2021). BSG was employed to produce Aspergillus oryzae biomass with a higher content of protein and polysaccharides (Serba et al., 2020). The authors demonstrated that fungus produced by SSF on a medium supplemented by this byproduct had a protein concentration that was three times more than fungus cultivated by submerged fermentation. In addition, it had been observed that SSF (35 days) of BSG by A. oryzae significantly increased protein content as compared to the unfermented control (Ogunjobi et al., 2011). In contrast, it was discovered that the fermented BSG had significantly less carbohydrate and fiber and more ash. Ibarruri et al. (2019) explored the SSF technique employing Rhizopus sp. to improve the nutritional value of BSG. They discovered that the concentrations of total protein and soluble protein in the biomass were significantly raised when BSG had been fermented at 30 °C for 9 days. A modified amino acid profile having a high percentage of essential amino acids and total polyphenol content was observed in the biomass with increased antioxidant activity. In a different investigation, nutritional grade Rhizopus oligosporus was employed to increase the nutrient value of BSG using SSF (Cooray and Chen, 2018). It had been noticed that after fermentation, the amounts of amino acids, vitamins, citric acid, and antioxidants in BSG increased. SSF of BSG by Bacillus subtilis also results in an enhancement of amino acids, unsaturated fatty acids, and antioxidant content of BSG (Tan et al., 2019). The edible fungus Pleurotus ostreatus was used to demonstrate protein enrichment of BSG (Aggelopoulos et al., 2018). The authors identified BSG as a component that encourages the proliferation of fungal cells. The produced fermented product enriched with mycelium is a good source of protein, minerals, and aromatic volatile components. However, recovery of the edible compounds from the microbial cultures is again a great challenge and requires expensive downstream processes. Future researches are desirable to design cheap approaches for sustainable and commercial application of the products.

4. Brewery waste concerns

The residual brewer's waste products pose a significant environmental risk since they need approximately 30–60 % of oxygen to get completely oxidized, and the proper disposal of these products is a serious environmental concern (Jayant et al., 2018). Wastewater from distilleries is concerning to the ecosystem since it contains organic materials and has an abhorrent odor with a blackish texture. It supports the growth of bacteria (Bianco et al., 2024). Again, BSY poses environmental hazards if it has been inappropriately deactivated and discarded (Caruso et al., 2022). Harikrishna (2008), Ipeaiyeda and Onianwa (2009) and Senthilraja and Jothimani (2014) reported on the consequences of improper ejection of brewery wastewash on the surface and groundwater quality. As the brewing effluent makes its way to the aquatic environment, the oxygen balance in the receiving stream has frequently been found to be decreased owing to the organic load of brewery waste, which may result in tremendous loss to aquatic organisms. Brewery effluent contains a high proportion of sodium, therefore if it is disposed of improperly in the soil, it might cause salt to build up and cause groundwater pollution through leaching (Harikrishna, 2008). Lower pH and reduced dissolved oxygen were observed on the water downstream of the brewery effluent discharge spot of Olosun river in Ibadan, Nigeria (Ipeaiyeda and Onianwa, 2009). Due to the influx of brewing effluent, the concentrations of nitrate, chloride, dissolved solids, ammonia, turbidity, and BOD were noticeably high. The quantities of Cr, Zn, Co, Cd, Cu, Pb, and Ni downstream surpassed the freshwater and drinking water standards in large part due to the brewing discharges (Ipeaiyeda and Onianwa, 2009). Furthermore, the total levels of these heavy metals were much higher than the concentration found at the upstream site of discharge (Ipeaiyeda and Onianwa, 2009). When combined with effluents, the byproducts (such as mash or yeast excess) produced during those processes cause pollution. Additionally, cleaning floors, equipment, tanks, and containers generate a significant amount of polluted water. Brewing effluents, which contain chemical (with extremely high organic load) and microbiological pollutants, cause the receiving river's amenities to be set up in a disorganized manner. The natural vegetation and soil qualities may also face deterioration. Furthermore, Harikrishna (2008) studied the impacts of brewery waste discharge on the water quality of the Cauvery River, India. The authors reported that a significant increase in Na and Cl had been observed in the water sampled downstream of the effluent disposal site. Level of water, clarity, turbidity, depth, dissolved oxygen, color, total hydrocarbon, nitrite, nitrate, and biochemical oxygen demand all exhibited remarkable spatial variation (Harikrishna, 2008). There had been a poor diversification of fauna and a detrimental effect on the biotic and abiotic ecosystem was observed as a consequence of the detrimental effects of brewery effluent discharge (Harikrishna, 2008). Brewery effluent is thus one of the main contributing factors to the decline in the quality of river water. Importantly, antibiotic-resistant *E. coli* had been isolated from energy-processed hop sediment (Wolny-Koładka and Zdaniewicz, 2021). The strain showed significant resistance to aztreonam, ticarcillin, tetracycline, ceftazidime, and ampicillin. The gene blaTEM has been commonly found to encode beta-lactamase (Wolny-Koładka and Zdaniewicz, 2021). According to the study, the brewery waste was colonized by numerous drug-resistant strains of E. coli, which are dangerous for the general well-being framework. Furthermore, the drug-resistant isolates have the potential to pass on genes of resistance to a variety of strains and against a variety of widely used antibiotics, making it challenging to administer sensible antimicrobial treatment and encouraging the concurrent establishment of cross-resistance to various antibacterial drugs. So, it is high time to develop a technique for the safe disposal of the waste products of breweries.

5. Remedial measures

An innovative biotechnological procedure that is ecologically benign uses microalgae, bacteria, and fungi to remediate wastewater (Chattaraj and Das Mohapatra, 2023). As a result of ingesting organic material and turning them into usable biomass, the organisms thrive in nutrient-rich effluents. Scenedesmus obliquus microalga was used to treat brewery effluent, and the technique was successful in removing phosphate, ammonia, Nitrogen, and COD at the rate of 30, 81, 88, and 71 %, respectively (Ferreira et al., 2019). Chlorella protothecoides also hold the ability to remove total nitrogen (96 %) and phosphorus (90%) from anaerobically treated brewery wastewash (Darpito et al., 2015). Aerobic management uses aerobic bacteria to break down organic materials in the effluent in the presence of oxygen. More microorganisms and inorganic byproducts like carbon dioxide, ammonia, and water are produced by them. Pollutant digestion is more effective when carried out by aerobic mechanisms. As part of the aerobic biological treatment, microorganisms modify non-settleable materials into settleable solids, which are then accompanied by sedimentation that enables the settleable solids to descend and segregate (Amenorfenyo et al., 2019). The three most popular aerobic wastewater treatment techniques are the trickling filter process, attachment growth (biofilm) process, and activated sludge process. The severity of the contaminants in the effluent, however, has a significant impact on the selection of aerobic treatment procedures. Mostly activated sludge methods are employed in the treatment of wastewater. Due to the significant organic contaminants in the effluent, activated sludge and trickling filter techniques are typically utilized in the treatment of brewery wastewater. Activated sludge is used as a primer in an aerated, agitating tank where the wastewater is being processed. Aeration systems actively mix the suspension of aerobic bacteria in the aeration basin while supplying oxygen to the biological culture (Simate et al., 2011). The use of algal-bacterial aggregates can diminish the need for aeration and also the high biomass harvesting expenses linked with algal monocultures can be greatly reduced (Papadopoulos et al., 2023). The authors designed a bioethanol synthesis process combined with a semi-continuous algal-bacterial wastewater treatment plant. A similar plant for bioethanol production can be developed by utilizing the brewers' spent wash. Nayak et al. (2018) designed an innovative way for reducing the COD of brewery waste by utilizing Scenedesmus abundans, Pseudomonas aeruginosa, and Bacillus cereus and ultimately producing bioelectricity. Hultberg and Bodin (2017) reported on the use of nontoxic filamentous fungi (Trametes versicolor, Trichoderma harzianum, and Pleurotus ostreatus) to remediate brewery effluent which additionally can produce biomass and reduce nutrient levels of brewers' waste washes. A significant reduction of chemical oxygen demand (89 %), total nitrogen, phosphorus, and ammonium were observed after the utilization of the fungal species. Hence, the environmental concerns of brewery waste can be eliminated by these biological approaches and subsequently will aid in sustainable environmental protection. The breweries should construct a waste treatment plant by scientifically implementing the potential microbial cultures to reduce the environmental hazards associated with brewery waste disposal. A schematic idea has been proposed in the form of a flowchart (Fig. 6) for sustainable management of the waste products produced in breweries. Brewery waste extrapolates to the broader context of waste disposal in a city or country by providing a microcosm of the challenges and opportunities inherent in managing organic waste streams. In a city or country, like in brewing, there is a pressing need for efficient and sustainable waste disposal strategies to adhere to environmental regulations and mitigate ecological impacts. The substantial volumes of brewery waste underscore the importance of addressing waste at its source, promoting the adoption of circular economy principles. Similarly, cities and countries grapple with large volumes of diverse waste types, necessitating integrated waste management systems. The biotechnological methods applied to brewery waste offer a valuable parallel, showcasing how innovative approaches can transform waste into resources, aligning with the broader goal of sustainable waste management. Lessons learned from brewery waste valorization, including technological advancements and circular economy principles, can inform and inspire waste disposal practices on a larger scale, potentially contributing to more environmentally friendly and economically viable solutions for cities and countries.

6. Potential of brewery waste to contribute in circular economy

The present economic system (linear model), which is based on the idea of a continual supply of commodities with a limited shelf life that forces producers to increase output in order to meet consumers' ongoing demands, was developed during the Industrial Revolution. A serious ecological and socioeconomic disaster would result from the escalating unrestrained plunder made by the linear economy (extracting, manufacturing, and disposing of) for finite environmental assets (Osorio et al., 2021). The demographic study states that there are currently 7625 million people living on this planet, with a rising rate of almost 74 million each year. According to UN predictions, 9.2 billion individuals will inhabit the planet by 2050 (Haseeb et al., 2019). The linear economy that currently governs the country has facilitated swift industrial and cultural growth. The abundance of environmental sources that feed the global inhabitants is severely impacted by the architecture of the extraction, use, and disposal. The demand for natural materials and foodstuffs increases along with the demographic rise. Despite this, there aren't enough resources available to feed the world's expanding population and to deal with the massive amounts of waste being produced (Maqbool et al., 2020). Each year, BSGs are hauled to municipal landfills, limiting the amount of land that can be used for agriculture and degrading the ecosystem and human health. In order to solve the issue, utilizing waste would make it easier to provide sustenance to the expanding population and lessen the wasteful exploitation of resources for human use. The circular economy fundamentally modifies the civilization and the concept of linear economy and implements an idea to restore and regenerate the worth of environmental resources (Del Borghi et al., 2020). It thereby minimizes the wasteful use of resources and raw ingredients and averts the needless accumulation of waste. Different societal, financial, and ecological domains are involved in the shift to a circular economy, which may create a potential for innovation, rejuvenation, and restoration in the brewery sector while preserving resource depletion. Requirement, availability, and pricing would be impacted by

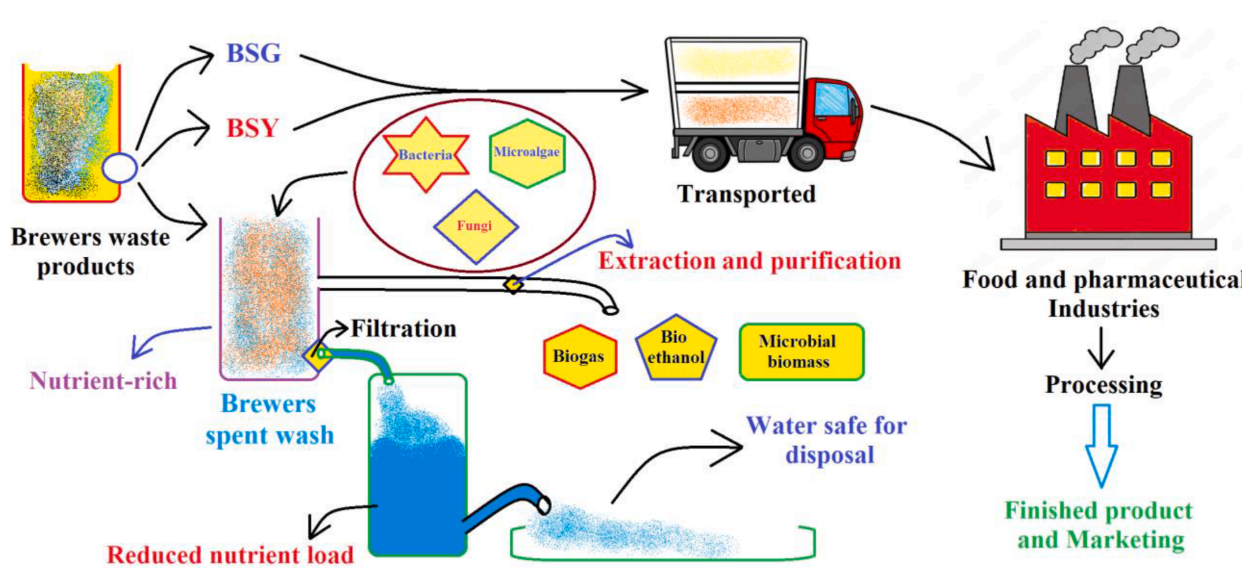

Fig. 6. Sustainable management of brewery waste products.

the incorporation of increased revenue from circular enterprises. The reduction of manufacturing costs may produce secondary impacts that speed up the economy's overall growth and contrast favorably in terms of GDP. Additionally, developing local reverse logistics with Small and Medium Enterprises and producing significant savings in raw material prices by implementing a circular model, high-quality recycling initiatives, and skilled services in the transition and reprocessing of resource depletion and wastes may create employment (Genovese et al., 2017). The intense use of synthetic materials, such as fertilizers, pesticides, fuel, and non-renewable power, which cause major harm by contaminating the air, land, and water, is directly influenced by the circular economy in terms of the environment and may be gradually reduced to zero. The circular economy also results in a decrease in leftovers in the food chain, and a decrease in greenhouse gas emissions (Ingrao et al., 2018). With less waste generated in breweries and more efficient use of the resources, the social features of the circular economy may have a significant influence on the way of resource utilization. Geissdoerfer et al. (2017) commented on the employment opportunities offered by a circular economy. In this scenario, the brewery industry may stand as a potential candidate to uplift the financial strength by means of the circular economy. The routes by which brewery wastes can be implicated in the circular economy are depicted in Fig. 7. New circular technical innovations in the brewery sector and the establishment of businesses in collaboration with local industries may congregate the issue of social stratification brought on by hunger and poverty. It will possibly make food more accessible and jobs more readily available while enhancing the caliber of food products and customer satisfaction. The utilization of the spent products of the breweries will additionally protect the environment from their concerning activities.

The current study is likely to encompass both research-oriented findings and potential translational applications. By exploring the biotechnological aspects of brewers waste, the review is expected to explore the scientific research underpinning its utilization. Additionally, it may explore the practical applications and translational possibilities of these findings, suggesting potential ways in which the knowledge derived from the research can be applied in real-world scenarios. This dual focus on research and translational aspects would provide a comprehensive overview of the biotechnological opportunities associated with brewers waste.

7. Conclusion

Biotechnology has the potential of lowering agribusiness trash and enhancing sustainability since the circular economy conception has gained popularity recently. Additionally, the utilization of trashes will reduce water, air, and soil pollution. BSG is a perfect substrate for the bio-aided technological development of value-added commodities since it is a ubiquitous agro-industrial by-product and consist rich supply of fermentable carbohydrates and other elements. When compared to their chemical process equivalents, the commercial feasibility of biotechnology processes is what determines their accomplishment. Processing stages and resource usage may be decreased by co-using sugars from BSG hydrolysate as well as by integrated bioprocessing techniques. However, developing potential strains for executing these purposes continues to be challenging. Utilizing a biorefinery strategy might greatly lower the costs associated with producing value-added goods; nevertheless, for optimal product yield, the approach might necessitate cheap and accurate downstream processing techniques for the extraction of finished goods. Moreover, the biotechnological approaches mentioned in the current study have to undergo comprehensive trials before their implementation on a commercial basis. Dose standardization of the waste products required for different bioprocess invites more research.

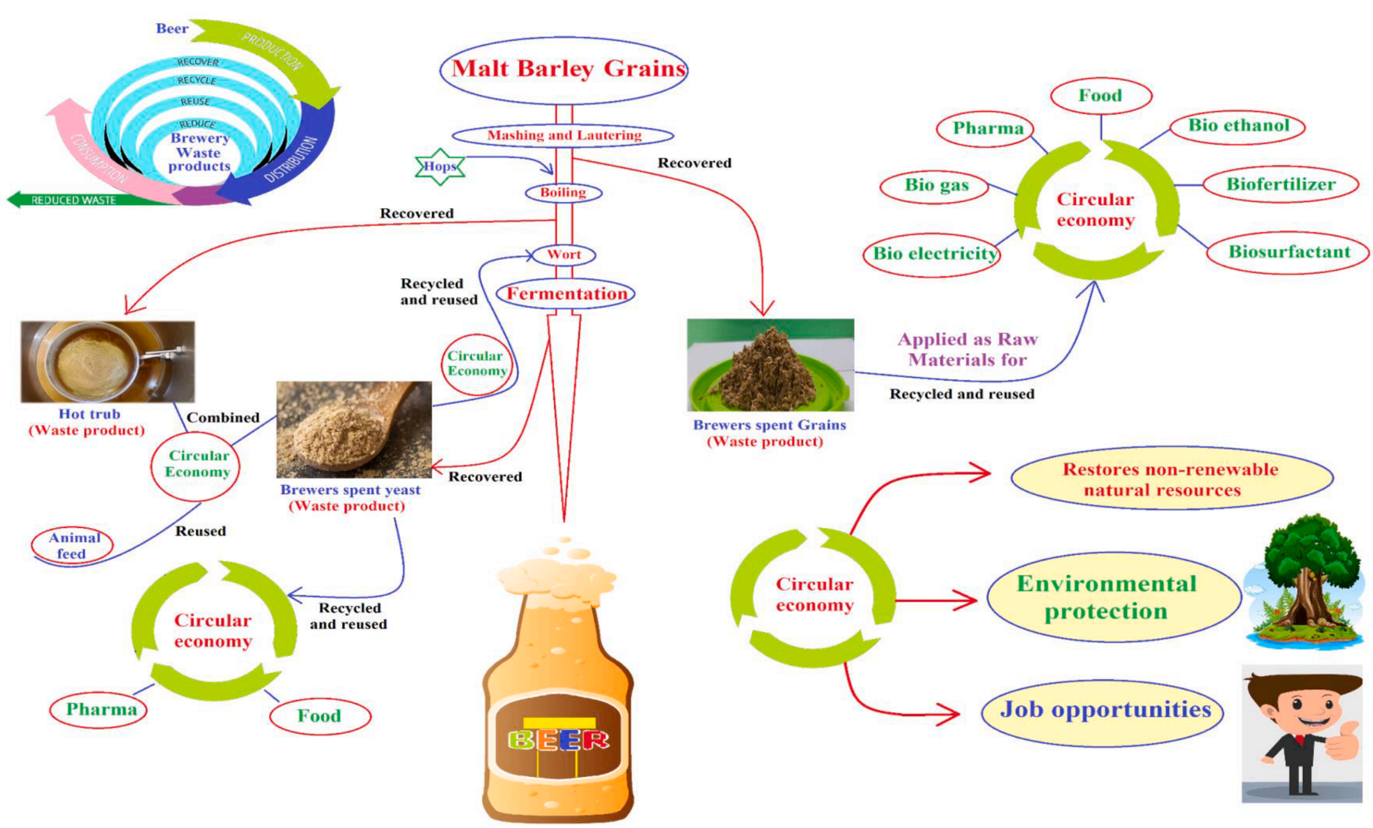

Fig. 7. Potentiality of brewery wastes for contributing in circular economy.

CRediT authorship contribution statement

Sourav Chattaraj: Conceptualization, Writing – original draft, Formal analysis. **Debasis Mitra:** Writing – review & editing. **Arindam Ganguly:** Writing – review & editing. **Hrudayanath Thatoi:** Writing – review & editing. **Pradeep K. Das Mohapatra:** Formal analysis.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

Data availability

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Ethics approval

The present study does not involve experiments involving human or animal.

Consent to publish

All authors are aware of this submission and have consented to the publication of this study.

Code availability

Not applicable.

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