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REVIEW ARTICLE OPEN ACCESS

Plausible Avenues and Applications of Bioformulations from Symbiotic Culture of Bacteria and Yeast

T. Jayalakshmi[1], G. Gayathry[2]*, K. Kumutha[1], K.G. Sabarinathan[1], R. Amutha[3] and P. Veeramani[4]

[1]Department of Agricultural Microbiology, Agricultural College and Research Institute, Madurai – 625104, Tamil Nadu, India.
[2]Agricultural Microbiology, ICAR-TNAU, Krishi Vigyan Kendra, Vridhachalam – 606001, Cuddalore, Tamil Nadu, India.
[3]Department of Crop Physiology, Agricultural College and Research Institute, Madurai – 625104, Tamil Nadu, India.
[4]Agronomy, ICAR-TNAU, Krishi Vigyan Kendra, Vridhachalam – 606001, Cuddalore, Tamil Nadu, India.

Abstract

Microbial cellulose, especially the bacterial cellulose produced by symbiotic co-cultures of acetic acid bacteria and yeast (SCOBY) that exists in a mutualistic interaction opens plausible strategies in the field of food as well as sustainable regenerative eco-system and waste management. Cultivated on sweetened black tea, the mutually proliferating bacteria (*Acetobacter xylinum, A. xylinoides,* and *Bacterium gluconicum*) and yeast strains (*Schizosaccharomyces pombe, Saccharomycodes ludwigii* and *Saccharomyces cerevisiae*) produces a fermented liquor along with the floating bacterial cellulosic pellicle called as Kombucha. This review explores the possible applications of kombucha SCOBY to use bacterial cellulose-based engineered living materials, commercial superabsorbent spheres by various marketing ventures like food, pharmaceutics, biomedical applications for bio-sensing and bio-catalysis, crop biostimulants, biocontrol agents in the management of plant and animal illnesses, post-harvest management in crops, water purification, pollutant detection, environmental biotechnology, and production of SCOBY from alternative substrates and agrarian waste management. The plausible use of bacterial cellulose hydrogels in dryland agriculture for their exceptional water-absorbing capability, eco-friendly nature, capacity to break down naturally, and compatibility with other living organisms is also elaborated in this paper. Furthermore, diverse microbial species to enhance the variety and functional properties of SCOBY, health benefits and its influence on human welfare is vividly discussed in the paper. The very in-depth study on the uses of SCOBY also paves way for the research exploration of this under-utilized microbial boon in food and farm sector for circular based regenerative agriculture in near future.

Keywords: SCOBY, Fermentation, Health, Industry, Agriculture, Applications

***Correspondence:** gayathryg@tnau.ac.in

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INTRODUCTION

Symbiotic co-cultures of cellulose producing acetic acid bacteria and fermentative yeast is popularly called as SCOBY in which mutualistic interaction between bacteria and yeast produces a tangy, flavoured tea like liqour called as Kombucha, a popular traditional fermented beverage in the world. Kombucha from SCOBY is known by several names including tea fungus, haipao, teakwass, comboutea, manchurian mushroom and kambotscha.[1]

In a sugar rich medium, *Acetobacter xylinum* and osmophilic yeasts produce a sour liquid broth beneath the cellulose layer of kombucha colonies. The reason kombucha is also called "tea fungus" is probably due to this bacterial and cellulose mixture that resembles fungus. In a symbiotic relationship, the acetic acid bacteria and yeast break down sucrose, with the yeast using its invertases to ferment the hexose units into ethanol and carbon dioxide. *Acetobacter* uses acetaldehyde to oxidize ethanol to acetic acid and appears as a membrane on the surface of fermented liquid, containing glucose that is converted to gluconic acid and cellulose.[2] An efficient strain, that produces soft textured, tender, juicy bacterial cellulose namely *Gluconacetobacter xylinum* was isolated from fermenting sugarcane juice by Gayathry and Gopalaswamy[3] showed maximum water holding capacity of 85%. High concentrations of antioxidants, B-vitamin complex, D-saccharic acid-1,4-lactone, glucuronic acid, phenols, and polyphenols are found in the liquid phase of fermentation, sometimes known as "soup" producing a pleasant flavour, tangy, and lightly carbonated appearance[4] (Figure 1).

Microbial epithets of Symbiotic Culture of Bacteria and Yeast

Several researchers have isolated and identified Symbiotic Culture of Bacteria and Yeast so as to produce bacterial cellulose or *nata* or kombucha. Anusuya *et al*. identified SCOBY like *Acetobacter senegalensis* producing bacterial cellulose in Hestrin Schramn medium.[5] The fungal genera *Zygosaccharomyces, Lachancea,* and *Starmerella* were identified as the main compensatory taxa for SCOBY, preventing an over representation of lactic acid bacteria.[6] Savary *et al*. called the cellulose as zooglea that consisted of *Dekkera bruxellensis, Hanseniaspora uvarum, Acetobacter okinawensis and Liquorilactobacillus nagelii.*[7] Bishop *et al*. indicated that kombucha tea resembling a fermented probiotic product can be made with cultured lactic acid bacteria and

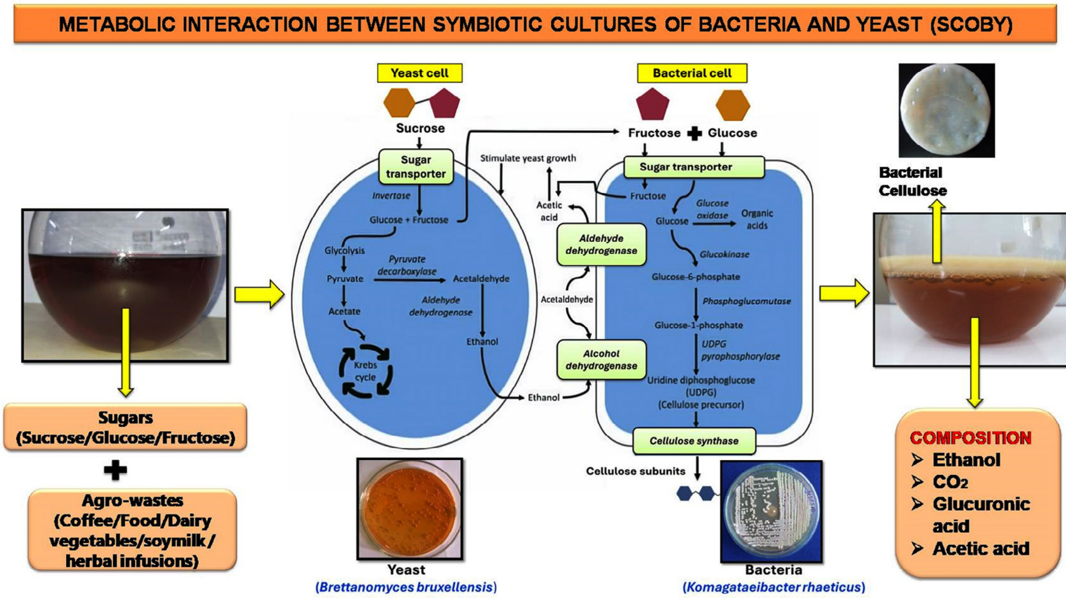

Figure 1. Metabolic interaction between Symbiotic Cultures of Bacteria and Yeast (SCOBY)[3,9]

probiotic yeasts like *Saccharomyces, Lachancea,* and *Schizosaccharomyces.*[8] Flyurik and Ermakova indicated that *Medusomyces gisevii*, is present in kombucha and known by various names in literature, as "Manchurian mushroom," "Japanese mushroom," "Japanese sponge," "sea mushroom," "kvass," "fango," and "kombuha,". The metabolic function of *M. gisevii* enzymatic systems relies on the functioning of microorganisms that are fixed in bacterial cellulose, a substance produced by the predominant generator of bacterial cellulose secreting acetic acid bacteria *Komagataeibacter xylinus* (also known as *G. xylinum/ Acetobacter aceti* subsp*. xylinum, Acetobacter xylinum*).[10]

Phisalaphong *et al.* described the jelly-like bacterial cellulose secreted by SCOBY in coconut water medium as *Nata-de-coco*, which means 'naturally obtained coconut cream' made purely of cellulose that is rich in organic dietary fibre, low in calories with zero cholesterol that is exclusively formed by non-pathogenic food-grade acetic acid bacteria that utilize sugars in coconut water to produce a dense fibrous mat called *Nata-de-coco*, and that which was produced from pine apples was called *Nata-de-pina*.[11,12] A very similar type of product was developed using cashew apple juice substrate supplemented with calcium alginate as a polymer additive for the production of bacterial cellulosic rich value-added edible product called as nata-de-cashew using *Gluconacetobacter oboediens* sju-1 (Figure 2).[13,14]

Health-promoting and therapeutic characteristics of SCOBY bioformulations

Multiple medical investigations have demonstrated that kombucha exhibits medicinal properties, including antibacterial activity and favourable effects on gastrointestinal activities, arthritis, gout, haemorrhoids, cholesterol levels, arteriosclerosis, and the nervous system. Regular use of kombucha substantially decreases the likelihood of developing cancer. The fermentation process generates organic acids that protect the tea fungus symbiotic colony from being contaminated by undesirable alien bacteria that are not naturally part of it. The beverage contains not only tea and sugar, but also acetic acid, gluconic acids, L-lactic acids, amino acids, biogenic amines, vitamin C, and B-complex. Kombucha has been demonstrated to possess antibacterial properties against *Agrobacterium tumefaciens, Bacillus cereus, Escherichia coli, Helicobacter pylori,* and *Salmonella typhimurium*, *S. enteritidis, Shigella sonnei,* and *Staphylococcus aureus*.[15]

Anantachoke *et al*. conducted an analysis on co-cultures of acetic acid bacteria and yeasts that coexist in a mutually beneficial relationship in sweetened substrates. Through this analysis, researchers have observed the pharmacological effects of fermented kombucha beverages produced from different raw materials and mixtures, such as tea, coffee, herbs, milk, and fruits. These effects include antimicrobial, antioxidant, anti-hyperlipidemic, immunomodulatory, anticancer, antidiabetic, anti-inflammatory, and antihypertensive properties. The study invariably suggests that glucuronic acid is a crucial metabolite with significant medicinal value and serves as a carrier for the detoxifying qualities of kombucha. Also explores that extracts of kombucha have therapeutic qualities, including the capacity to prevent cancer, lower blood cholesterol levels, mitigate the nephrotoxicity of medications and hazardous metals, and offer protection against the detrimental effects of radiation.[16]

A study conducted by Murugesan *et al.* suggests that kombucha tea, produced through the fermentation of black tea with tea fungus, could be used as a curative as well as for preventive treatment of CCl_4-induced hepatotoxicity. Orally consuming kombucha tea showed stronger inhibitory efficacy against CCl_4-induced liver damage, serving as both a preventative and therapeutic strategy. Indicators such as aspartate and alanine transaminase, alkaline phosphatase in plasma, and the quantity of malondialdehyde in the plasma and liver tissues of albino rats in the experiment were used as supporting evidence.[17] Pioneering efforts to identify important volatiles/ metabolites by Jayabalan *et al*.[18] found that the ethyl acetate fractions of black tea kombucha contained two chemicals, dimethyl 2-(2-hydroxy-2-methoxypropylidene) malonate and vitexin, which have the ability to kill cells and prevent their invasion. These chemicals have shown anti-cancer effects in human lung carcinoma, osteosarcoma, and renal carcinoma cell lines. Studies have demonstrated that herbal SCOBY tea treatments effectively promote the expulsion of silica particles from lung tissues. Chinese herbal kombucha inhalation shows potential as an effective treatment for silicosis and other pneumoconiosis conditions. According to Fu *et al*. administering Chinese herbal kombucha to rats resulted in a significant decrease in the amounts of free silica in their lungs.[19] These innovative methods not only save waste but also demonstrate the adaptability of SCOBY beyond its conventional application in brewing. The laxative effect of fibrous bacterial cellulose was test verified through animal experimentation study using loperamide induced Dawley rats indicated that, oral administration of bacterial cellulosic solution increased weight of faeces, water content of faeces, and promoted satiety feeling, and acted as laxative agent by holding water inside the bowel lumen, inhibition of water absorption in the colon and stimulating colonic motility in the tested rats.[20]

The microbial makeup of kombucha varies based on the substrate, climate, and geographical region. The use of diverse initial substances, such as tea, fruit, fruit waste, and herbal extracts, along with a distinct starter culture, can result in variations in the fermentation process. Consequently, this will lead to the production of varied end products or metabolites, which may exhibit varying levels of activity. The study conducted by Silva *et al*.[21] aimed to compare the physico-chemical properties, *in vivo* toxicities, and antioxidant and antibacterial potentials of fermented SCOBY derived kombucha beverages prepared from *Malvaviscus arboreus* and *Camellia sinensis*. The SCOBY produced from green tea shown antibacterial efficacy against all fungi cultures, particularly the pathogenic fungus *Paracoccidioides brasiliensis*, as well as bacterial pathogens like *Staphylococcus aureus* and *Listeria monocytogenes*. Kombucha tea has been shown to decrease non-alcoholic fatty liver disease, specifically steatosis and steatohepatitis, by inhibiting the buildup of hepatic lipids. This is achieved by suppressing the beta oxidation pathway, which reduces the synthesis of triglycerides and the delivery of free fatty acids to the liver. These findings were demonstrated in obese mice during a study conducted by Hyun *et al*.[22]

In a clinical research conducted by Mendelson *et al*. the frequent consumption of kombucha tea by human volunteers with type II diabetes resulted in notable anti-hyperglycemic effects in adults. Regular use of sweetened kombucha did not result in a significant increase in fasting blood glucose levels among individuals with diabetes. However, it significantly decreased the average fasting blood glucose levels in the fourth week in comparison to the initial values. Surplus SCOBY can be repurposed in a multitude of innovative ways. SCOBY jerky is a snack made by dehydrating the extra SCOBY, which can be seasoned and flavoured according to personal preference. SCOBY candy can be created by submerging them in a solution of sugar syrup or honey and then dehydrating them to produce a chewy and sweet snack. They can also be utilized in skincare products, such as facial masks, where the probiotics and organic acids are thought to have advantageous effects on the skin. Additionally, SCOBY can be used as a hair conditioner to enhance shine and softness.[23] In their work, Pakravan *et al*. identified the cosmeceutical properties of SCOBY through a clinical trial conducted on elderly rats. The intradermal administration of the ethyl acetate fraction of kombucha tea extract in mice resulted in improved thickness and flexibility of aged skin. This effect can be attributed to the high levels of flavonoids and NADH makers present in the extract, which aid in mending connective tissue in naturally aged skin.[24]

The study conducted by Simoes *et al*. systematically reviewed and documented the functional benefits of SCOBY derived kombucha in various experimental scenarios. These scenario included the prevention or treatment of hepatotoxicity, hyperglycemia, nephrotoxicity, steatosis, silicosis, fatty liver disease, transient cerebral ischemia, reperfusion injury, myocardial injury, steatohepatitis, hypercholesterolemia, induced cytotoxicity, exposure to irradiation or electromagnetic fields, biocompatibility with the sciatic nerve, hyperuricemia, cancer, oxidative stress, age-related abnormalities, autoimmune encephalomyelitis or multiple sclerosis, and post-operative intraperitoneal adhesion formation in the abdomen.[25]

Practical implications of kombucha SCOBY

This section of the review is intended to present details on the recently developed bacterial cellulose from SCOBY based bioformulations that are commercially available in the marketplace. The world trade for kombucha SCOBY is projected to reach $7.05 billion USD by 2027. The introduction of organic acids, flavonoids, and tea polyphenols brings in a new era for powdered SCOBY. The global manufacture of popular herbal tea and ready-to-drink beverages was facilitated by employing spray drying technology using additives such as maltodextrins and arabic gums to microencapsulate SCOBY organisms in fermented kombucha.[26] Introducing InstaKOMBU™, the latest powdered kombucha product brought to the market by an innovative Taiwanese provider of nutritious components. Using an exclusive method, we produce microencapsulated goods that contain abundant probiotics such as *Saccharomyces cerevisiae, Lactobacillus plantarum,* and *Acetobacter aceti*. To preserve the inherent nutritious characteristics of kombucha, a recently developed powder accentuates the distinct taste of the plant while maintaining its manifold benefits.[27]

Gilbert *et al*.[28] investigated Syn-SCOBY, a living substance created using laboratory yeast and bacteria. This material serves as a versatile framework for developing robust bacterial cellulose-based engineered living materials. These materials have the potential to be used in various fields such as biomedical applications[29] for bio-sensing and bio-catalysis, food industry, water purification, and pollutant detection. The production of enzyme-functionalized bacterial cellulose materials can be achieved by cultivating a stable co-culture of *Saccharomyces cerevisiae* and bacterial cellulose-producing *Komagataeibacter rhaeticus*. This process allows for the growth of self-assembled bacterial cellulose materials with desired functionalities, using simple substrates and under mild conditions. Yeast strains were genetically modified to produce enzymes that were released into bacterial cellulose. This enabled the modification of DNA and the creation of self-generated catalytic materials, resulting in enhanced overall properties of the bacterial cellulose. Yeast that has been modified through engineering can be incorporated into the growing cellulose structure to produce living materials that have the ability to detect and react to chemical and visual signals.

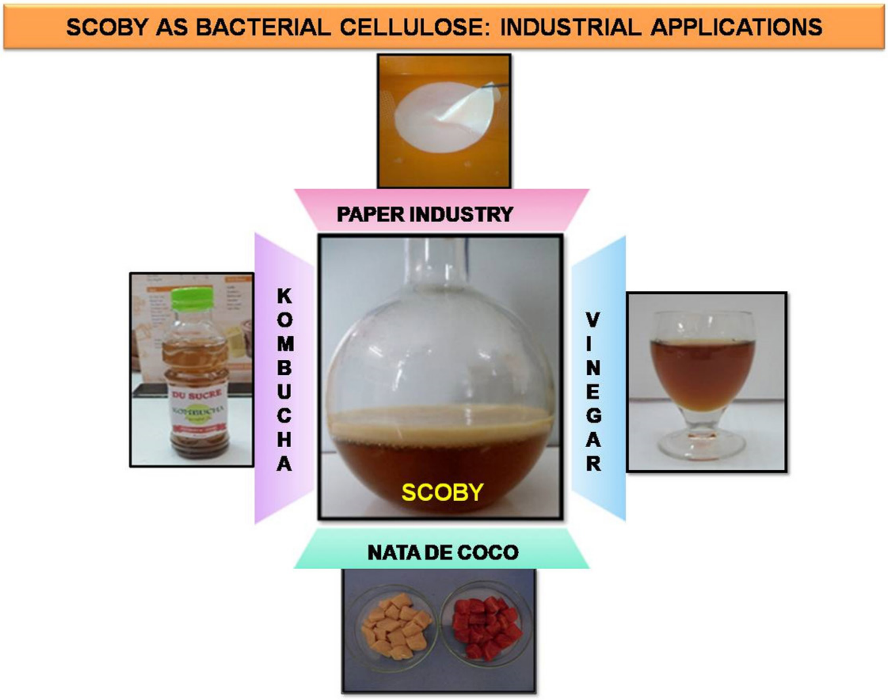

Figure 2. SCOBY as bacterial cellulose: industrial applications

Another benevolent introduction of kombucha is 'Borecha' which is India's pioneering and premier brand specializing in tailor-made functional beverages. Borecha has collaborated with 'Akasa Air', the rapidly expanding airline in India, to introduce kombucha on their flights, thereby establishing Akasa as the pioneering Indian airline to provide this probiotic refreshing, healthy and delicious beverage as a part of their in-flight beverage selection. Borecha's probiotic mango kombucha, offers a delightful and nourishing taste, as well as gut friendly qualities.[30]

A promising finding of biodesign using bacterial cellulose, that integrates biology into design practices was deliberated by Cogdell[31] in New York. Use of bacterial cellulose as a material for textile production in the field of fashion design, biodegradable packaging, feminine hygiene products, diapers, air filtration panels, water filters, shopping bags, armbands, and fast-fashion footwear that feature biodegradable soles is a path breaking inventions made in this line. Scientists have devised a technique to make bacterial cellulose resistant to water by applying corn zein protein, layering and drying bacterial cellulose sheets to enhance their strength, and investigating the impact of dyes on the fabric's softness and flexibility. In addition, leftover citrus juice were used to produce cellulose sheets, and also employed a DNA plasmid to bind arsenic, a microbe to break down 1,2-dichloroethane, a chemical found in PVC and vinyl for developed of eco-friendly biodesigns. In addition, the team of researchers developed bacterial cellulose aerogels that are both lightweight and absorbent, specifically for use in packaging and nappy designs.

Researches investigating on the principles of "green chemistry" evidenced that hydrogel bacterial cellulose (HGBC) materials can be used to create a range of clothing using sewing techniques that are widely available. Seminal contributions have been made by Kaminski *et al*.[32] and Gayathry *et al.*[33] in the process of producing and altering bacterial cellulose derived from kombucha to fabricate ecologically friendly HGBC textiles possessing necessary mechanical and physicochemical properties and the synthesized materials were tested on volunteers by using them as bracelets and T-shirt components and with greater ideas that led to an innovative discovery of HGBC fabric and textile.

SCOBY in food and agro-waste management

A large number of existing literature studies on bacterial cellulose strongly suggest that they are utilized as hydrogels in agriculture for their exceptional water-absorbing capability, environmentally friendly nature, capacity to break down naturally, and compatibility with living organisms. The presence of both physical and chemical cross-linking structures gives the cellulose hydrogel its exceptional absorbency. Gayathry and Gopalaswamy[34] experimented on the development of highly fibrous bacterial cellulose from coconut liquid endosperm using *Acetobacter xylinum* sju-1 isolated from sugarcane juice. Gayathry and Gopalaswamy[35] developed thin sheets of highly viscous microbial cellulosic biopolymer with good degree of polymerization, tensile strength and Young's Modulus using *Acetobacter xylinum* sju-1. Superabsorbent bacterial cellulose spheres were produced from grape pomace, a winery byproduct, using the bacterial strain ID13488 of *Komagataeibacter medellinensis*. This strain is known for its capacity to generate large amounts of BC from inexpensive carbon sources and acidic culture media.[36]

Shyan *et al*. investigated the process of biogas production from food waste and the cafeteria collected food waste was subjected to pre-fermentation under aerobic conditions to expedite the breakdown of food waste by yeast in SCOBY. This yeast converts organic matter into neutral ethanol during the acidogenesis phase, preventing a significant decrease in pH. Additionally, other bacteria, such as *Acetobacter* sp. and *Lactobacillus* sp., contribute to the decomposition process. The experiment was conducted in a semi-continuous mono-digestion system utilizing a SCOBY bio-starter composed of lactic acid bacteria, acetic acid bacteria and yeast. Studies have shown that utilizing a mixture of SCOBY and kombucha inoculum for the conversion of food waste into biogas yields a maximum methane output. In addition, when SCOBY infusions derived from wax mallow or green tea plants were administered to *Galleria mellonella* larvae, no harmful effects were observed in the larvae during *in vivo* model testing.[37]

Barakat *et al*. extensively explored the creation of new beverage and healthcare product formulations using unconventional ingredients such as sugary and underutilized fruits, coffee wastes, food wastes, vegetables, soymilk, dairy substrates, plants, herbal infusions, and fermentation with SCOBY.[38] The study conducted by Muzaifa *et al.* utilized exfoliated coffee cherry husk/pulp, also known as peel waste, which is a by-product of Indonesian coffee processing businesses. This waste was used to produce an extract that resembled black tea extract by employing fermentative SCOBY bacteria. This extract is referred to as "Kombucha cascara". During the fermenting process, the tannin present in cascara underwent decomposition and conversion into polyphenols, resulting in elevated quantities of antioxidants.[39,40]

Jarrell *et al*. proved the antimicrobial properties of fermented kombucha tea against *Escherichia coli* and *Staphylococcus epidermidis*. The antibacterial activities of concentrated fermented teas and vinegar were found to be equivalent to 1 mmol of ampicillin against *Escherichia coli* or 0.01 mmol of penicillin against *Staphylococcus epidermidis*.[41]

Symbiotic Culture of Bacteria and Yeast (SCOBY) in alternative substrates

There have been numerous studies and discussed by great number of authors pertaining to the investigation of alternative substrates for fermenting kombucha other than black tea extract used in routine SCOBY preparations.[42] Different fruits and juices such as apple, citrus, dragon fruit, grapes, guava, pear, snake fruit, strawberry were used as sugary rich substrate for the fermentation of probiotic kombucha SCOBY that was rich in total phenols and possessing antioxidant activity.[43] The experiments on production of SCOBY even from the agro-wastes such as banana peel wastes, sugarcane and sugarbeet molasses,[44] maize silk wastes,[45] Pine apple peel and core wastes[46] have been reported. Su *et al*. extensively studied and reviewed on the use of various herbal and tea extracts, leaves, fruits and juices, dairy wastes, pollens[47] and roselle calyx[48] and also from variety of other alternative substrates to produce

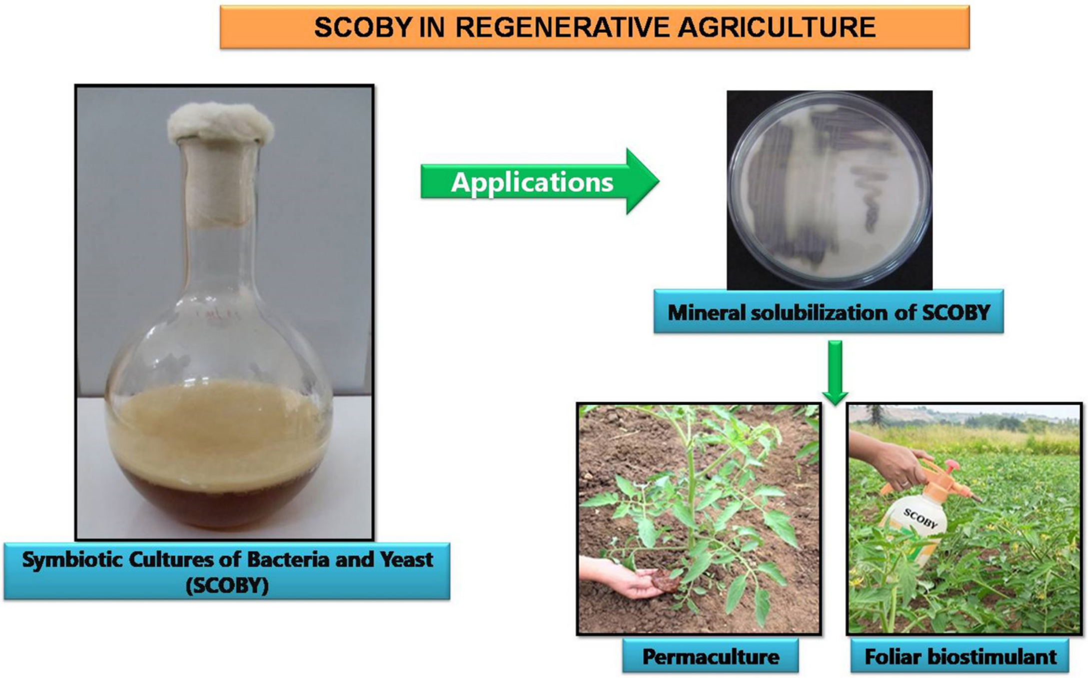

Figure 3. SCOBY in regenerative agriculture

SCOBY with varying antibacterial and antioxidant properties. Even the use of sea weeds and algae has been reported in Brown algae (*Fucus vesiculosus*) and Lichens (*Cetraria islandica*) Golovkina *et al*.[49] Red seaweed/Laver (*Porphyra dentata*) Aung and Eun,[50] Brown seaweeds (*Alaria esculenta*) and (*Saccharina latissimi)* Healy *et al*.[51]

SCOBY bioformulations for plant and animal disease management

In this closed-loop agricultural method, waste generated from one operation is transformed into an organic resource. This resource is then utilized to manage pests and diseases, as well as to enhance foliar development. Immersing harvested pear fruits in kombucha liquor for 15 minutes effectively controls pear rot and preserves the quality of the fruit during storage. This method can keep the pear fruit fresh for up to 18 days at room temperature. It highlights the significant contribution of SCOBY in managing and preventing post-harvest fruit diseases. The beneficial yeasts and bacteria present in the SCOBY suppressed the generation of reactive oxygen species, membrane lipid peroxidation, and malondialdehyde. These compounds have the potential to modify the structure of amino acids in fruits protein and compromise the integrity of cell membranes. Junping *et al*. suggest that feasible to decrease the rate of weight loss in pear fruits during storage, hence extending the duration of storage. Spent tea leaves and other food or fruit waste can be utilized in a closed loop system with minimal processing.[52] In their study, Betlej *et al*. provided evidence of the fungicidal properties of scotch pine wood and its capacity to safeguard against *Coniophora puteana*, a decay causing fungus. The wood-degrading fungi are inhibited from disintegrating by the SCOBY's biocidal effect, which is a result of the metabolites produced during the fermentation of tea substrates in the post-culture liquid.[53]

Fungi and bacteria are responsible for post-harvest illnesses in fruits and grapes, resulting in higher levels of loss. Alternative methods, such as the use of acetic acid, have been suggested for the management of fungal deterioration. Experiments have specifically concentrated on investigating the suppressive impact of kombucha crude extracts derived from tea on prevalent grape mould. Kombucha, a mixture of acetic and lactic bacteria together with yeast, has been discovered to possess inhibitory effects against *Botrytis cinerea* and *Penicillium expansum*, as well as *Aspergillus flavus* and *A. carbonarius*. The acetic acid concentration in kombucha suspensions typically varies between 8.5 and 17 g/l, as reported by Matei *et al*.[54] Ismaiel *et al*. discovered the detoxifying effect of heat-treated kombucha SCOBY mat that had the highest ability to remove poisonous secondary metabolite namely patulin secreted by *Penicillium expansum, Talaromyces purpureogenus,* and *Acremonium implicatum* causing necrotic lesions in apples.[55]

Fu *et al*. found that using Chinese herbal extracts, specifically green tea, chrysanthemum, liquorice, and Grosvenor momordica, combined with *Saccharomyces pastorianus* and *Acetobacter xylinum*, can be an effective non-vaccination approach to prevent outbreaks of Foot and Mouth Disease (FMD) and minimize the necessity of culling animals in countries that are free from FMD. By combining kombucha spraying with slaughter and vaccination, it is possible to create large FMD-free areas worldwide, significantly improving global food security.[56]

SCOBY as an organic biofertilizer for crops

According to Quiroz and Cespedes,[57] the fermented SCOBY provides opportunities for applying regenerative principles in agriculture and horticulture. Sustainable and regenerative farming prioritizes the long-term enhancement of soil health, biodiversity, and ecosystem well-being. One crucial idea in this context is permaculture, which involves the use of locally and sustainably sourced resources, while minimizing the use of synthetic pesticides and fertilizers (Figure 3). In the case of kombucha production, SCOBY can be utilized to collect tea leaves and other alternative substrates, as well as the components used to flavor it. Bokashi tea is a fermented preparation that has been used for centuries in Japanese organic farming and Korean natural farming systems. It is made by fermenting food waste items, resulting in a highly concentrated inoculant that improves soil and plant root rhizosphere, provides foliar nutrition, and enriches compost piles. It is crucial to differentiate between kombucha tea and bokashi tea. Kombucha tea is created by introducing specific *Lactobacilli* bacteria to selected substrates, such as rice, cow milk, or organic matter. These bacteria thrive in settings without oxygen and generate intricate byproducts through fermentation.

In a study conducted by Durmus,[58] a pot culture experiment was carried out using sandy loam soils with alkaline conditions. The research focused on the effects of applying comboutea liquid inoculum and lyophilized comboutea culture waste on various biological parameters, including *in situ* CO_2 production, soil basal respiration rate, and microbial biomass carbon. The results showed that these applications led to an increase in these parameters. Comboutea products, including both liquid cultures and lyophilized waste, clearly have a positive impact on soil vitality and microbial activity.

By prioritizing waste reduction, the SCOBY can be regarded as a valuable asset. Surplus SCOBYs can be distributed among others, utilized in culinary preparations, or incorporated into compost, so contributing to an eco-friendly waste management system. By amalgamating these ideas, one can foster a more sustainable and integrated approach to the production and use of food. SCOBY, a fermentation culture, can be further enhanced in terms of sustainability and distinctiveness by incorporating home gardening activities into the kombucha-making process. This potential allows for the connection with the source of ingredients, the reduction of environmental effect, and the creation of a beverage that is more personalized and produced locally. Cultivating fermented foods and using permaculture principles both foster community engagement. SCOBY, being composed of 100% cellulose, may be easily decomposed by rhizosphere microorganisms. By adding SCOBY to compost, one can bring helpful and efficient microbes to the composting process, so enriching the soil with organic matter. The nutrient-dense leftovers of SCOBY fermentation can be diluted and used as liquid biofertilizers to efficiently recycle resources and enhance overall plant growth.[59] *Gluconacetobacter xylinum* undergoes fermentation of coconut water, resulting in the production of *nata-de-coco*. The cellulose can be utilized for the production of carboxy methyl cellulose, which is beneficial in the creation of various water-loving polymeric substances. Specifically, it can serve as a desiccant in arid farming due to its high water absorption capacity and ability to contract and expand.[60] According to Saddam *et al.*[61] the application of a 5% liquid organic fertilizer derived from Clitoria (*telang*) flower kombucha fermentation waste resulted in increased tomato leaf count, plant height, and overall growth and yield parameters. This is attributed to the nitrogen present in the *telang* SCOBY, which stimulates apical meristem growth, leading to longer growth compared to other treatments. Similarly, the application of a liquid organic fertilizer including waste from the fermentation of Clitoria flower kombucha, which is fermented using *Saccharomyces* and *Acetobacter*, resulted in improved plant biomass, plant growth parameters, and fruit yield in green chilli (*Capsicum frutescens*).[62]

Naturally occurring liquid organic fertilizer includes nutrients that can enhance plant development and improve the biological, physical, and other properties of soil. The objective of this study was to evaluate the impact of a liquid fertilizer derived from the waste of telang kombucha fermentation on the growth of mustard plants. The study focused on the following plant characteristics: height, leaf count, fresh weight, and dry weight. The study results indicate that the application of liquid organic fertilizer, containing the fermentation waste of butterfly pea blossoms for kombucha, has an impact on many parameters associated with the growth of mustard plants. According to the study conducted by Hariadi *et al*.[63] the use of a liquid organic fertilizer prepared from fermented kombucha flower butterfly pea leftovers, enhances the wet and dry weight, height, and leaf count of mustard plants.

SCOBY in resource recycling and waste management

Laurenson *et al*. conducted a study to ascertain the potential of utilizing kombucha SCOBY liquor for agricultural purposes and treating dairy shed wastewater effluent from New Zealand's dairy farms. When exposed to SCOBY, a readily accessible source of carbon and nutrients in the form of sugar and tea, *Escherichia coli* experienced effective treatment and a decrease in population. This led to improvements in bio-economic availability, resource recycling, and utilization, potentially resulting in enhanced water quality.[64]

The adsorption isotherm behavior of Pb (II) removal in waste water by SCOBY adsorbents was examined by the utilization of Langmuir and Freundlich models. According to Mousavi *et al*.[65] the findings indicated that Kombucha SCOBY was both cheaper and more efficient than graphene oxide/Fe_3O_4 nanoparticles in removing lead from wastewater. An experimental study was conducted using a batch reactor to assess the efficacy of Kombucha SCOBY in the separation and extraction of Ni (II) from an aqueous waste water solution. The SCOBY, or "tea fungus," produces a zoogleal mat functions as an adsorption/separation membrane within a four chamber physical barrier bioreactor. In addition, the cellulose membrane produced by SCOBY after 21 days of fermentation plays a role in the development of a method for effectively eliminating arsenates and Ni (II) from wastewater.[66] Pathy *et al*. conducted research in Rourkela, India, to produce composite biochar by combining kombucha SCOBY with microalgal biomass (*Chlorella* sp*., Scenedesmus* sp*., Synechocystis* sp*.,* and *Spirulina* sp.). The objective was to eliminate malachite green from freshwater that had been polluted with the dye. The results demonstrated that the inclusion of SCOBY increased the surface area of the algal biomass, while maintaining the integrity of the surface functional groups of the algae. Phytoremediation, chemisorption, and diffusion processes have the potential to eradicate up to 98% of the dyes responsible for contaminating fresh water environments.[67]

While crossing over the review of literatures available, there is fruitful evidence to show the therapeutic and biomaterial management aspects of bacterial cellulose or the kombucha SCOBY. But the subject of SCOBY in agriculture with special relevance to foliar application on phyllosphere or as plant growth promoter has received minimal attention by most of the researchers. The greatest research effort on this novel product in circular regenerative agriculture is very meager and only little theoretical attention have been implicated in the area of SCOBY.

CONCLUSION

Experimenting with various substrates for the production of cellulosic kombucha SCOBY is becoming increasingly popular worldwide. The antioxidant capacity of kombucha was evaluated and documented in nearly all of the previously stated studies. Furthermore, kombucha has proven to be effective in unconventional uses, such as its utilisation as a cooking component, a preservative for fruits and vegetables, and a source of cellulose for certain sectors. The utilisation of by-products as substrates for kombucha fermentation has been thoroughly investigated. This review paper envisages using SCOBY as a newer generation plant growth promoting symbiotic phyllosphere bacterial bioformulations instead of synthetic fertilisers. The inherent ability of SCOBY to enhance agricultural output both directly and indirectly, soil bioremediation, regenerative agriculture are highly critical and need of the hour. Currently, there is a lack of study on the utilisation of Symbiotic cultures of bacteria and yeast as a crop biostimulant based extensive research through performance in field studies, permaculture, precision farming and thorough exploration in a specific field to enhance productivity is very meagre. Hence, this review paper thrusts on the various plausible approaches for the use of bacterial cellulose based SCOBY in various dimensions and finds out strategies for developing frontiers in microbial bioformulations.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTION

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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DATA AVAILABILITY

All datasets generated or analyzed during this study are included in the manuscript.

ETHICS STATEMENT

Not applicable.

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