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Useful Byproducts from Cellulosic Wastes of Agriculture and Food Industry—A Critical Appraisal

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Cellulose, an important cell wall polysaccharide, which is replenished constantly in nature by photosynthesis, goes waste in a lion's share in the form of pre-harvest and post-harvest agricultural losses and wastes of food processing industry. These cellulose wastes have an immense potential to be utilized for the production and recovery of several products and ingredients in food application. In this present study, a wide spectrum of researches in the arena of properties of cellulose, hemicellulose and lignin; their degradation; sources and composition of cellulosic and lignocellulosic wastes of agriculture and food industry; present status of converting them into value-added products of food applications; constraints in their conversions and future prospects therein has been reviewed in details. The study has encompassed production of biomass for various utilization and production and recovery of protein and amino acids, carbohydrates, lipids, organic acids, foods & feeds and other miscellaneous products.

Keywords cellulose wastes, value-added products, food application

1. *INTRODUCTION*

Cellulose is the most abundant material in the universe and makes up more than 50% of the total organic carbon in the biosphere[1] and one third of the vegetation. About 10^{11} tons of cellulose are synthesized annually,[2] and unlike other natural resources, it is replenishable by photosynthesis.[3] The consumption of cellulose is to the tune of 3 folds of steel consumption and almost equal to the quantity of cereal consumption per annum. Its main uses are in the form of wood for construction, furniture, papers, boards, cloths, foods, and feeds. In developing countries, like India, a major portion of the cellulose generated remains unutilized and goes for wastes, namely in the forms of waste from forest resources, wood, paper, and board after human uses, pulp, textile, agriculture, and food industries, etc. Major agriculture, and food industry wastes include straw, leaves, cobs, peels, etc., and damaged agricultural produces due to pre-harvest and post-harvest losses. For every one kg of grains harvested, 1–1.5 kg of straw, cobs, or other residues are generated.[4] India produces about 127 million tons of fruits and vegetables and 198 million tons of food grains, generating around 200 million tons of agricultural waste. The post harvest losses of fruits and vegetables in India range from a minimum of 5% to the maximum of 100%.[5] The area of fruits itself it amounts to 20–30% of the produce, with an annual loss of 3,000 crore of Indian currency.[6] Overall food wastage for grain products, fruits, and vegetables are 32%, 23%, and 25%, respectively in the USA.[7] It has been estimated that the dry weight of organic solid wastes annually produced in the USA is 940 × 10^6 tons, much of which is cellulosic.[8] The developed countries, like Japan, reuse more than 40% of their urban waste cellulose.[9] In the present study, properties of cellulose, hemicellulose, lignin and their degradation, the source of cellulosic and lignocellulosic waste of agriculture and food industries, present status and contemporary R and D activities in converting them into value-added products, constraints in their conversions, and future prospects therein have been discussed.

2. *PROPERTIES OF CELLULOSE, HEMICELLULOSE, AND LIGNIN*

In addition to cellulose, the cellulosic waste materials contain hemicellulose, lignin, extractives, and inorganic compounds.[10] The cellulosic waste from crop residues and other agricultural wastes contain 31–60% cellulose, 11–38% pentosans, and 12–28% lignin. Classically, cellulose is defined as a linear

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polymer of anhydroglucose units linked at C_1 and C_4 atoms by a β-glucoside bond. The degree of polymerisation in cellulose molecule is found to be a considerably varying one.[11–13] Various models of cellulose structure have been proposed by Chang[14] and other authors. Lignin is a complex of 3-D polymer of phenolic and enolic origin, whereas hemicelluloses comprise of cellulosans and polyuronide hemicellulose.[15,16] Overall, lignins are rather heterogeneous and are branched polymers of indefinite structure and size.[17] Cellulose is insoluble in water, but soluble in a number of solvents, including concentrated acids and inorganic solvent solutions. Constrains in cellulose degradation have been reviewed by several authors.[18,19] Cellulose itself is among the least degradable natural polymers due to its high molecular weight, high degree of structural order, insolubility, and low surface area. Its association with lignin and hemicellulose makes the plant materials more stable to chemicals and enzymes. Hence, extensive pretreatment is often required to encourage degradability of the natural cellulose.[20–24] Four types of degradation have been characterized, namely hydrolytic, oxidative, microbial, and mechanical degradation.[25] The addition of NaOH prior to thermal pretreatment often enhances the degradability of wastes by disrupting lignin and lignocellulose structures, which might physically restrict the extracellular hydrolyzing enzymes of microorganisms.[26,27] Pretreatment of cellulosics is done to increase the rate and the extent of microbial digestion.[28–34] Also, enzyme action on cellulose releases chemically bound lignin. A synergistic effect of various cellulolytic microorganisms[35–39] and that of the combination of the purified enzymes from culture filtrate of *Trichoderma viride* on the hydrolysis of cellulose[40] are reported. Alkali or petrochemical treatment, electron irradiation, and ball milling to a fine particle size (70–100 μ), etc., increase the enzyme activity and biodegradability of cellulose by various fungi. Cellulose can be pretreated and swollen by some strongly electrolytic solvents, acids, etc.[41] According to Desai and Betrabet,[42] cellulose degradation is caused by cellulase secreting fungi, bacteria, and actinomycetes. The cellulase is a complex enzyme, which consists of β-1,4-endoglucanase and β-1,4-exoglucanase. A third enzyme β-glucosidase (Cellobiase) is always associated with the two glucanases and is essential for the complete hydrolysis of cellulose to glucose.[43] The cellulolytic bacteria most studied are *Cellvibrio (Pseudomonas) fulvus* and *Pseudomonas fluorescence* strain.[44,45] Few other cellulolytic organisms studied are *Coniophora cerebella* and *Sporotrichium pulverulentum* under Basidiomycetes; *Trichoderma. viride*,[46] *T. koningii*,[36,47–52] *Penicillium funiculosum*[53,54] *and Fusarium solani*[37,55,56] under Ascomycetes and Deuteromycetes; thermophilic fungi: *Chaetomium thermophile var. dissitum*, etc.

Table 1 Cellulose content and composition (g/100 g of dry matter)

Cellulosic wastes	Cellulose	Lignin	Hemicelluloses
1. Agricultural residues			
Barley straw[57]	44	7	27
Oat Straw[57]	41	11	16
Oat Straw[58]	42.8	—	—
Rice Straw[57]	33	7	26
Rice Straw[10]	32.1	—	—
Wheat Straw[57]	39	10	36
Wheat Straw[10]	30.5	—	—
Sorghum Straw[57]	31	11	30
Cottonseed Hulls[57]	59	13	15
Sugarcane Bagasse[57]	40	13	29
Entire Bagasse[30]	46	—	—
Fibre Bagasse[30]	56.6	—	—
Pith Bagasse[30]	55.4	—	—
2. Fruits & Vegetables[59]			
Apples	2.9	Trace	5.8
Banana	1.3	0.93	3.83
Lemons	—	35	—
Oranges	—	14	—
Pineapples	—	7.64	—
Strawberries	3.6	8.4	10
Potato	1.2	Trace	9.2
Carrot	12.9	Trace	19
Cauliflower	13.4	Trace	13
Cabbage	8.9	4.3	26
Tomato	9.1	5.3	11
Peas	14	2	36
3. Seeds[60]			
Barley	5.3	—	—
Corn	2.4	—	—
Wheat	2.1	—	—
Oat	11.9	—	—
Grain Sorghum	2.7	—	2.5
Peanuts	2.8	—	2.5

3. SOURCES

From the agricultural firms, plantations, and orchards, the cellulosic residues generated in the form of stalks, straws, stems, leaves, cobs, chaffs, bunches, stumps, and stubbles, damaged grains, fruits, vegetables, etc. The major cellulosic wastes from food industries include damaged fruits, vegetables and grains, and post-processing residues, like skins, peels, seeds, leaves, bunches, husks, bagasse, vinasse, pomace, etc. These vary in cellulose content and composition as described in Table 1.

4. CONVERSIONS OF CELLULOSICS AND R AND D ACTIVITIES

Cellulose is a great reservoir of energy in the world. Cellulosics generated from agriculture and food processing industries have been given great attention by various workers because they add value to products. Some of these are biomass production, production and recovery of protein, amino acids, etc., carbohydrates production, acid production, lipid production, production of foods and feeds, and others.

4.A. Biomass Production

Microorganisms are grown on cellulosic substrates for their biomass production in view of their use as or in foods, feeds, the production of enzymes, single cell protein (SCP), amino acids, lipid, carbohydrates, and organic acids. A large number of fungi have been screened for their ability to grow on cellulose.[61]

Lignocellulosic and other food and agricultural wastes have been utilized for the production of mushrooms.[62] Sugarcane leaf and bagasse are obtained in huge mass from sugarcane field and sugar industry. Sugarcane bagasse and bagasse pith both pre-treated with NaOH solution have been used separately for the growth of *Cellulomonas spp.*[63,64] A biomass production by growing a defined mixed culture of *Trichoderma viride* and *C. utilis* on pretreated bagasse has been attempted.[65] Sugarcane (*Saccharum sinensis*) bagasse or tobacco (*Nicotiana tabacum*) stalks, when fortified with $(NH_4)_2SO_4$ and KH_2PO_4, produces a fresh mushroom, *Pleurotus sajor-caju.*[66] Some were able to produce bacterial biomass of *Cellulomonas* sp. and *Thermomonospora fusca* on physically and chemically pretreated cellulosic wastes, like bagasse and straw.[67,68] Cellulosic wastes from citrus processing[69] and tea production unit[70] have been found to support the biomass production of edible fungi basidiomycetes. A good production of edible mushroom, such as *Agaricus bisporus* and *Morchella crassipes*, has been noticed on lime waste.[71] In another study, successful utilization of date wastes, such as substrates has been indicated for the production of yeast (*Saccharomyces cerevisiae*) biomass.[72] Sturion and Oetterer[73] have conducted studies on waste banana leaf and prescribed it as a more efficient substrate than wheat straw for the cultivation of edible fungi, such as *Pleurotus sp. subsp. florida, Pl. obstreatoreseus* and *Pl. sajor-caju*. Soybean wastes from the processing of soy-milk and tofu have been utilized for the growth of various edible fungi, namely *Coriolus versicolor, Tricholoma lobayense T-2, Lycophyllum shimeji M-46 Morchella elata M-26, Pl. sajor caju. Pl-27*, and *Volvariella volvacea V.34.*[74] These are all potential producers of high value metabolites, including nutraceuticals. Cellulolytic *Aspergillus* sp. strains VK PMF 559 isolated from a water treatment plant can convert 80% of cellulose in corn cobs into its biomass.[75] *Penicillium expansum* is able to yield a biomass in a mineral medium containing acid-treated rice husk.[76] An early rapid proliferation of yeast in food waste containing rice and vegetable residues has been observed,[77] but has been described as an insignificant activity by Nakasaki and colleagues.[78,79] The cellulose rich hulls, when treated with NaOH and heat, have produced a black liquor, which has been used as a substrate for the growth of 5 species of *Aspergillus*, 3 spp. of *Paecilomyces*, 2 spp. of *Penicillium*, 1 spp. each of *Alternaria, Trichoderma, Chaetomium*, and *Actonopolyspora.*[80]

4.B. Recovery and Production of Protein and Amino Acids

Single cell protein (SCP) production from cellulose has been preliminarily evaluated, suggested, or reviewed by several authors.[67,81,82] Some agricultural by-products, such as cereal straws are in use for microbial protein production, but still more can be used (especially if alkali treated) without any harm to the live weight gain of the animal fed with this.[83,84] A method for the production of nutritive protein by growing a cellulase producing microorganism and *Alcaligene faecalis* on delignified cellulosic materials, like bagasse, rice straw, Johnson grass, Prairie grass, oat straw, wheat straw, sorghum bagasse, corncobs, and cottonseed hulls has been described.[85] Barley straw has been converted by *Trichoderma viride* alone or a mixed culture of *Trichoderma viride* and *C. utilis* into a product containing 21–26% protein. Other cellulosic wastes can also be utilized.[86] The interest of the bioconversion of lignocellulosic material for protein enrichment of animal feeds using SSF has been highlighted.[87] A dilute acid hydrolysis without separation of the products (SCP) as they are formed is commonly used when straw is the substrate. An alternative way to produce SCP from cellulose materials after their enzymatic and microbial degradation to glucose has been proposed by Brown and Fitzpatrick[88] and supported by Kamikubo and colleagues.[89] Enzymatic hydrolysate of cellulosic wastes of tea concentrate has also been used to produce SCP.[90] Sorghum husk, millet husk, and banana stem digested with 0.6N H_2SO_4, have been used in a culture medium to grow *Penicillium expansum*, in order to produce a considerable quantity of histidine and lysine amino acids.[91] This organism has also produced SCP (37–62%) on a medium containing similarly treated rice husk.[76] The cells of a photosynthetic bacterium, *Rhodopseudomonas gelatinosa*, grown on wheat bran infusion, contain significant quantities of protein and vitamins. Moo-Young[92] has proposed several fermentation processes for the production of SCP. A novel multistage fermentation process has been proposed for the production of SCP (*Chaetomium cellulolyticum*) to be used as an animal feed supplement. The mycelial mass is found to be nutritious, digestible, and non-toxic. This SCP resembles highly with fodder yeast and soy meal in terms of essential amino acid composition, but, as per FAO reference, this is deficient in sulfur containing amino acids.[93] The stillage residues from the ground high lysine corn used for alcohol fermentation can be fractionated into distiller's grain, centrifuged solids, and stillage soluble. The centrifuged solids have the highest protein content (37–49%), followed by distiller's grain (31–35%). The latter has potential for use in human food and non-ruminant feed. On the other hand, the stillage soluble is found to have a high lysine content.[94] A process has been developed for SCP production, upto 60% crude protein by *Cellulomonas spp.* grown on sugarcane bagasse.[95] The treatment of bagasse with 1% NaOH yields a maximum protein production with a mixed culture of *Cellulomonas spp.-Bacillus subtilis.*[96] A remarkable work has been carried out on pretreated Egyptian sugarcane bagasse.[65] The bagasse pretreated with alkali plus γ-irradiation, acid plus γ-irradiation, and $NaClO_3$ enables a mixed culture of *Trichoderma viride* and *Candida utilis* to produce a biomass containing 35.5% protein and all the essential and non-essential amino acids in accordance with FAO reference. A growth of *Aspergillus spp.* strain VK PMF 559 on corn cobs[75] and Basidiomycetes on citrus wastes[69] or higher Basidiomycetes (*Cerrena unicolor, Coriolus hirsutus, Pleurotus ostreatus* IBK-191) on tea waste[70] has produced a biomass containing a varied quantity of protein. Lee and Kim[97] have extracted proteins from soymilk residue using enzymes from *Asp. oryzae*. Various fruit and vegetable waste from the aubergene, tomato, grape, apple, cabbage, carrot, beet root, and watermelon are the substrates for lysine production by

Brevibacterium spp.[98] A protein enrichment has been obtained by growing *Aspergillus niger* on mango peel, orange peel, green and over-ripe banana, and carrot waste in SSF.[99–101] The protein content of apple pomace to be used as an animal feed has been enriched by SSF and submerged fermentation by various co-culture of cellulolytic fungi and yeasts, out of which a coculture of *Candida utilis* and *Asp. niger*, was the best performer in increasing the protein content of dried pomace and pectin extracted apple pomace to 20% and 17% respectively under SSF.[102] Similarly native and mutant strains of *Trichoderma aureoviride* have been used in a solid state column fermentation of leached sugar beet pulp waste for protein enrichment upto 40% of total dry weight.[103] Edible fungi basidiomycetes grown on citrus waste can produce biomass with high protein content of about 18–19%.[69] *Aspergillus niger* TMF-15 is able to convert 90–92% of cellulose in a mixed substrate of extracted grape waste and pressed apple pulp into a product having a higher protein content (35%) than those obtained from *Penicillium funiculosum* 515 and *Myrothecium verrucaria* 9095.[104] An enrichment of protein upto 32–34% has been observed by growing *Chaetomium globosum* and *Sporotrichium pulverulentum* on kinnow—mandarin wastes of peel, pulp, and seeds.[105] SCP is produced from banana wastes, employing *Pichia spartinae* and date wastes by a mixed culture of *Saccharomyces cerevisiae*, *Candida utilis*, and *Saccharomyces rouxii*. A five-fold improvement in the protein content of cassava meal has been reported.[106] Sun dried tapioca fibrous residue[107] and soybean waste residue[108] can also be used for SCP generation. Various fungi have been investigated for their growth on coffee processing waste in ICAITI, Guatemala.[109,110] *Trichoderma harzianum* produces dry solids containing about 56% protein from coffee processing wastes. A trial experiment has been conducted by growing ten strains of yeasts on Egyptian vinasse with the possibility of successful recycling of the waste for microbial protein production.[111] Various substrates are used by various researchers for the production of biomass having enriched protein content (Table 2). Cabbage can be utilized economically by enriching its protein content by native commensal microflora.[112] Cocultures of cellulolytic and non-cellulolytic microbes have demonstrated higher yield and productivity than the monocultures.[122] It is because cellulases from cellulolytic species catalyze cellulose to glucose, which is, in turn, fermented by non-cellulolytic microorganism. A wide range of cellulases obtained from *Trichoderma spp.* has been well-characterized.[123] The SCP produced by *C. utilis* grown on acid and enzymatic hydrolysates of waste rice straw should be used as protein supplement and not as a major diet component from a nutritional safety point of view.[124] The fungal mass grown on various crop residues is found as a safe and acceptable food product, as implied by toxicity trials and food textural studies.[121]

4.C. Production of Carbohydrates

Pretreatments of the cellulolytic waste from crop residues and other agriculture wastes with acids,[125] alkali,[126] or enzymes[127] are effective to release a variety of fermentable sugars. The sun dried tapioca fibrous waste residue can be utilized for the production of glucose syrup, high fructose syrup, and confectioner's syrup.[107] It has been strongly supported by a study on the conversion of cellulose slurries to glucose syrup.[128] Cellulosic cassava waste saccharified with a culture filtrate from *Trichoderma viride* and a soil Basidiomycetes, together with commercial amylases, enables an enhanced sugar formation. A syrup containing a high concentration of xylose and other sugars can be produced by a two phase acid hydrolysis of hemicellulose-rich plant materials, viz., are leaves and stems of sorghum, maize, or wheat.[129] A xylose syrup has been generated from acid-hydrolysed xylan-rich cottonseed hulls.[130] A large-scale enzymatic depolymerization of xylan extracted from corncob meals has yielded various sugars, like xylobiose, xylotriose, and arabinose oxylo-oligosaccharides.[131] The enzyme used is endo-1, 4-β-xylanase, obtained from *Clostridium thermolacticum* DSM 291. A medium containing straw, microcrystalline cellulose and xylose, has been utilized to produce endoglucanases and xylanases (by *Allesheria terrestris*), which have been employed to hydrolyze cellulose and hemicellulose present in fruit cannery wastes to yield monosaccharides predominantly glucose.[132] Toyama and Ogawa[133] have been able to produce 10% sugar syrup from a substrate made up of rice straw and bagasse delignified by boiling with 1% NaOH and saccharified by a commercial cellulase preparation (1% Meicelase) from *Trichoderma viride* at 25% substrate concentration. Conversion of ignocellulosic residue of corn-cobs or alkali- and heat-treated hulls into pentoses have been studied separately.[80,134] Fungal enzymes cellulases and hemicellulases have been used to saccharify agro-waste.[135] Enzymes from *Aureobasidium* spp. strain NRRL Y-2311-1 to saccharify corn fibres[136] and other enzymes[137] have been used to saccharify coffee bean solid waste. In India, efforts have been directed to utilize mango-processing waste for the recovery of starch.[138] The microbial production of polysaccharides from agricultural wastes or a mixture of pure chemical and agricultural wastes has been studied.[139] Grape skin pulp extract[140] and carob pod[141] are used as substrates for the production of pullulan by *Aureobasidium pullulan* NRRL-Y 6220. Xanthan gum has been produced by *Xanthomonas campestris* ATCC 13951 from four types of citrus waste fractions viz., whole citrus waste from oranges, lemons and grape fruits, pectic extracts, hemicellulosic extracts, and cellulosic extracts. The biodegradability of hemicellulosic and cellulosic wastes is found to be lower than that of the other two fractions.[142,143] An alkaline extraction of xyloglucan from depectinized apple pomace[144] and production of cyclodextrin from rice bran[145] have also been reported. Applications of microbial polysaccharides[146] and xanthan gum in foods[147] have been summarized.

4.D. Production of Lipid

Fat production by yeast and other microorganisms has been adequately highlighted.[148,149] A correlation has been established between the possession of the enzyme, ATP-citrate lyase, and

Table 2 Protein content of biomass

Microbial biomass	Substrates	Composition (g/100 g dry wt.)		
		N_2	Protein	Fat
A. Bacterial biomass				
Cellulomonas sp.[63]	Bagasse	9.3	58	—
Cellulomonas sp. & Alcaligene sp.[29]	Bagasse	14	87	8
Cellulomonas sp.& Alcaligene faecalis	Alkali treated rye grass	—	6.8	—
	NH_3 treated rye grass	—	9.5	—
Cellulomonas sp. & Candida utilis[113]	Barley straw	9.3	10.6	58–66
Bacillus sp.[114]	Rice hulls	4.5	28	—
Pseudomonas sp. & Chaetomium cellulolyticum[115]	4% NaOH treated rice straw	—	19	—
	4% NaOH treated corn stover	—	20–24	—
	3% NH_3 treated corn stover	—	17	—
B. Filamentous fungi				
Aspergillus fumigatus I 21[116,117]	Cassava extract	40	31.5	12.2
	Cassava	37	27	—
Chaetomium cellulolyticum[118]	Crop residues	45	—	10
Fusarium moniliforme[119]	Carob extract	43	30	5
Rhizopus chinensis[120]	Cassava extract	49	37	....
Sporotrichum album[116]	Cassava extract	64	54	6–12
Aurobasidium pullulans[121]	Acid—treated and NH_3-neutralized straw	—	14	—
Candida utilis[121]		—	12.4	—
Trichoderma viride[121]		—	10.9	—
Fusarium semitectum[122]	Oat husk	—	11	—
	Sugarcane bagasse	—	5.6	—
	Cocoa shell	—	5.9	—
	Spent hops	—	5.9	—

the ability of yeast to accumulate more than 20% of its biomass as a lipid.[150] Fat production by red yeast, *Rhodotorula gracilis*, seems very promising. The only bacterium, which has been reported as a producer of significant amount of triacylglycerol, is *Arthrobacter* AK 19.[151,152] Date extract and rice hull hydrolysates have been considered as a substrate for the production of microbial oils by *Penicillium soppi* and *Lipomyces* spp., respectively. A few specialized cellulolytic fungi appear to be non-oleaginous, but cellulose, after its hydrolysis, can be a suitable form of fermentable carbohydrate for them. The estimated cost per ton of generated fermentable carbohydrate is not too high to use cellulose as a substrate for microbial oil production. Some yeasts grow on hydrolysates and oxidates of cellulosic peat for production of both protein and oil.[153,154] One strain each of *R. gracilis* and *Trichoderma cutaneum* is found to be oleaginous with the lipid content of the culture being 21.9% and 26.1% on yeast dry matter, respectively. When grown on a synthetic medium and a carrot juice containing medium, *R. gracilis* has produced cells containing 25% and 17–20% lipid and *T. cutaneum* with 35.5% and 21–25% lipid.[155,156] An extraction of oil from olive pomace, apple pips, and mango processing wastes has been reported.[157,158]

4.E. Production of Organic Acids

Cellulosic wastes of agriculture and food processing can also be made use of for the production of various acids having a potential use in the food and chemical industries. Vinegar can be prepared from citrus peel or molasses,[159] mango processing waste,[138] fermentation of cellulosic waste of potato starch industry by *Fusarium oxysporum* 841,[160] and waste from pineapple juice.[161,162] An interesting conversion of cellulose to acetic acid by a new sewage isolate of *Aceto-vibrio spp* has been proposed.[163] *Asp. niger* has been employed by a few researchers for citric acid production from a variety of cellulosic substrates.[164,165] The pineapple peel, apple pomace, wheat bran, and rice bran are utilized as substrates for the production of citric acid in SSF by *Aspergillus foetidus* ACM 3996. Pineapple peel is found to be a better substrate than others, producing the highest yield at 16.1 g citric acid/100 g dry peel.[166] Hang and Woodams[167–170] have been able to produce citric acid successfully from apple pomace, grape pomace, kiwi fruit, and pineapple peel in a SSF. Waste from the preparation of guava jelly has enough cellulosic material to be used for citric acid production by microorganisms.[171] Citric acid has been generated from dewatering of orange peel by using 3 strains of *Aspergillus niger*. The greatest yield of 30 g citric acid per kg press liquor is produced by strain NRRL-599.[172] By cultivating *Asp. niger* CFTRI 30 on dry coffee husk, potentiality of production of citric acid has been commercially demonstrated.[173] *Asp. niger* NRRL 2270 and *Rhizopus oryzae* NRRL-395 are found to generate citric acid and lactic acid with 36% and 58% yield, respectively.[174] Cocoa juice, a waste from cocoa bean fermentation, has supported the growth of *Candida lipolytica* ATCC 8661 and *Asp. niger* ATCC 10581 to produce citric acid.[175] Sugarcane press mud is a novel and inexpensive substrate for citric acid production in SSF by *Lactobacillus casei subsp. casei* CFTRI 2022, *Lb. velveticus* CFTRI 2026, and *Streptococcus thermophilus* CFTRI 2034.[176] Cellulosic materials, such as corncobs, corn stalks, cottonseed hulls, and straw can also be used for the production of lactic acid.[177] In a lactic acid fermentation of the cellulosic materials, the recovery of lactic acid from the crude broths and presence of lignin pose additional problems for their further conversion.[178] The manufacture of tartaric acid from grape pomace[179] and oxalic acid from apple pomace[158] has been reported. Cassava bagasse, a starch-rich lignocellulosic residue, has been estasblished as a sole carbon source to produce fumaric acid by several *Rhizopus* strains in submerged fermentation. The strain, *Rhizopus formosa* MUCL 28422, has been reported as the best producer.[180] Fumaric acid, due to its non-toxic and non-hygroscopic properties, is used as an acidulant in food and beverages. Propionibacterium or mixed bacterial culture is able to ferment lignocelluloses to produce propionic and or acetic acid.[181,182] Dynatech workers have successfully fermented aquatic weed to produce organic acids in a high yield with 43–45% conversion of algal species and with the production of acetic acid up to 40–60% of total acids.[183]

4.F. Production of Foods and Feeds

Ruminants retain cellulose for a long time in their alimentary canal, the micro-flora within which aid in digestion. The cereal straw has long been used as animal feed. The shortcomings of straw as a feed are its low digestibility, low protein content, poor palatability, and bulkiness. The digestibility of lignocellulosic straw is generally inversely related to the amount of lignin present.[184–187] The digestibility of waste plant materials can be improved by acid/alkali treatment,[188–190] steaming at super atmospheric pressure,[191] irradiation,[192] or microbiological treatment.[30,193–197] The physico-chemical mechanism of pretreatment for increased digestibility of lignocellulosics have been elucidated.[58,193,198] A number of oxidizing agents have been used on sugarcane bagasse for this purpose.[199] The dioxane treatment has improved the digestibility of rye grass straw and rice straw, but not that of sugarcane bagasse.[200] The method of converting sugarcane stalks and tops by Bishop,[201] sugarcane pith by Miller and Lauric,[202] and leaves, tops, and short top pieces by Worden[203] have been patented. An extrusion process of tomato pomace has been described, and the product has been evaluated for its composition.[204] *Kloceckera apiculata* and *Candida utilis* can transform apple pomace into an improved stockfeed by SSF.[205] Use of fruit pomace for the manufacture of functional drinks and sour fruit beverages has been prescribed.[206,207] An animal feed[208] and a sauce[209] from apple pomace have been produced and evaluated. The effective utilization of carrot pomace in bread, cake, dressings, and pickles has been studied in details.[210,211] A protein-rich fibrous foodstuff called germinated barley has been made from brewers' spent grain. This product contains glutamine-rich protein and the dietary fibres of cellulose, hemicellulose, and lignin.[212] Wu[94] has shown that distillers' grain, a fraction of stillage residue of alcohol fermentation of ground high lysine corn, has a potential use in human food and non-ruminant animal feed because of its high protein quality. Likewise, a food product for human beings has been developed from distillers' spent cereal grains and solubles.[213] A silage preparation technique has been evolved from barley shochu distillery by-product and juice residues of mandarin oranges and carrots.[214] Coffee pulp, a huge by-product of the coffee processing unit, can be safely used as feed, if the caffeine, tannins, and polyphenol are removed. Several caffeine degrading microorganisms belonging to genera *Aspergillus*, *Penicillium*, *Trichoderma*, *Fusarium*, and *Humicola* have been isolated. It has been found that 5 strains of *Aspergillus spp.* and 2 strains of *Penicillium spp.* can degrade 100% of the caffeine in the liquid medium.[215] Mahadevaswamy and Venkataraman[216] have enlightened an integrated approach of utilization of mango processing waste. The effluent of biogas production from mango processing waste has been utilized for the production of fresh water fishes, like major carp, rohu (*Labeo rohita*), and common carp (*Cyprinus carpio*). Cull grape fruit and Jerusalem artichokes have been examined as potential feed-stocks,[177] and the nutritional and toxicological evaluation of wild apricot pomace has been carried out.[217]

4.G. Production of Miscellaneous Products

Several other food ingredients or additives, namely pectin, edible fibre, pigment, flavouring, antioxidant, etc., which have potential application, can be generated from various cellulosic wastes. The utilization of cassava fibrous residue[218] and wastes from the processing of apple,[219,220] for value-added products, has been widely reported. The aspect of pectin production from the fruit processing wastes has been reviewed by Sudhakar and Maini.[221] Apple pomace and wastes from the processing of peas, peaches, apricots, and other fruits are found to be the good sources of pectin production.[222] The extraction and production of pectin from apple pomace,[223,224] apple wastes,[225] citrus wastes,[226] orange peel,[227] and mango wastes[228,229] have been carried out successfully. Food fibre is another ingredient studied by few researchers. The dietary fibre content of pear, kiwi,[230] and grape pomace[231] has been described. In India, the utilization of mango processing wastes for the recovery of valuable chemicals, such as pectin, pigments, tannins, and cocoa butter substitutes has been directed. A comprehensive review of Kennedy's research[158] has suggested the potential development of food additives, flavourings, anti-browning agents, etc. from kiwi fruit wastes and the manufacture of pectin, aroma compound, fibre, etc. from apple pomace. The antioxidant activity of potato peel waste or red grape pomace and peel has been reported.[232–234] Also, a red pigment has been obtained from red grape pomace.[235] An algae, *Chlamydomonas reinhardii*, is able to produce biomass and photosynthetic pigments when grown on vinasse, a waste from beet and cane fermentation.[236] The apple industry wastes can also be utilized for the production of biogenous thermoplastic materials.[237] The lignin present in cellulosic waste can also be oxidized by chemical, microbial, or enzymatic processes to produce a flavour compound, vanillin.[238] The banana processing waste of about 8.30 lakh tons generated annually in India can be utilized for the generation of furfural and pectin. The presence of waxes, including triterpenoids in dried apple pomace and its depectinised residue, has been indicated.[239]

5. CONSTRAINTS IN CELLULOSE CONVERSIONS AND PROSPECTS

Bottlenecks on the economic utilization of cellulosic wastes of agriculture and food processing are chiefly reported as a lack of rapid enzymatic hydrolysis of cellulose, lack of rapid microbial growth on celluloses, lack of cellulases with high catalytic power, high cost of pre-treatment, and presence or association of other substances with them. The problem with all cellulolytic bacteria is that the in-vitro (cell free) system has a high degree of activity on soluble cellulose derivatives, but very low activity, if any, towards native cellulose. Microbial growth and cellulase production are influenced by various factors, like medium, pH of medium, inoculum, environmental factors, etc.[240] The lignin bound to celluloses inhibits microbial attack and enzyme action on celluloses. Martinez and his colleagues[241] have been able to fractionate residual lignocellulosics from almond shells by dilute acid pre-hydrolysis and alkaline extraction. There are other approaches to the utilization of cellulosic wastes without a separate step of hydrolysis by acid or enzyme. If technically feasible, the direct use of polysaccharide is preferred.[242–244] Although the microbial degradation of lignin has been reviewed by several authors,[245–247] lignin is found to inhibit the breakdown of cellulose by enzymes, acids, or microorganisms.[248] Processes in which acids are used to catalyze cellulose hydrolysis are not commercially attractive.[249–252] This is because the cost of sugar production is high and the yields are typically low. Basically, cellulose is more chemically stable than starch, therefore, harsher acid hydrolysis conditions or more potent enzyme solutions are required for its hydrolysis.[24] In Japan, cellulases from *A. niger* and *T. viride* are produced commercially at a rate of 45 tons per year representing an economic output of 170×10^6 yen per year. Presently both the exorbitantly high cost and the limited efficiency of known cellulase preparation make many potential applications non-profitable. The cost of cellulase enzymes encompasses about 60% of total cost of saccharification,[253] therefore, the reuse of the enzyme, as well as its stability, is essentially important. To improve process efficiency, one can search for more active cellulases or develop cheap methods for pretreatment of the substrates. The attention of some workers has been paid onto hemicellulases, pentosanases, and xylanases. The manufacturing cost of SCP is very much dependent upon the cost of carbon and energy source to the producer of SCP products. The raw material cost of bagasse ranges from 17 to 26% of the total cost of SCP production. On the basis of the work of Abbott[254] and Wang,[255] protein generated by bacteria grown on cellulose is much cheaper than many other conventional proteins from beef, chicken, eggs, fish, cheese, etc. The cost associated with the collection and transportation of wastes will be excessive, if SCP production plants are far away from the waste generation site. An economic feasibility study on production of animal feed protein from lignocellulosic wastes pretreated with chemicals, enzymes, microorganisms, or a direct bioconversion into protein-enriched fermented fodder and sugar syrup has been extensively carried out in a research programme in KISR.[256] Ratledge[257] has argued that SCO could be a more valuable product than SCP, as the oil would be several times higher in value than animal protein. Any future economic utilization of cellulosics should be based on their current exploitation pattern. Economies derive from the carbohydrate substrate for fermentation from the hydrolysis of crops and forest residues, rather than from grains or other high grade food materials.[258,259] That is why cellulosics have received a great attention as possible feedstocks on the assumption that raw material costs from agriculture and lumber waste are negligible[4].

6. CONCLUSION

Cellulosics can be utilized for production or recovery of some value-added ingredients or products of various usages, providing monetary benefit to the firms. The Government Regulations on pollution and environment protection, pressure from social groups, and threat from politicians also lay emphasis on the utilization of cellulosic wastes of agriculture and food industry origin. The utilization of cellulose, a replenishable resource, can be transformed into a lucrative and profitable business, if future research in this area is aimed at overcoming or relieving successfully overcoming the constraints underneath it.

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