UNIVERSIDADE DO SUL DE SANTA CATARINA
PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS AMBIENTAIS

ANA PAULA PROVIN

UTILIZAÇÃO DE CELULOSE BACTERIANA PROVENIENTE DA BEBIDA KOMBUCHÁ PARA FABRICAÇÃO DE BIOTÊXTEIS

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Dissertação apresentada ao Programa de Pós-Graduação em Ciências Ambientais, como quesito parcial à obtenção do título de Mestre em Ciências Ambientais.

Orientador: Dra. Anelise Leal Vieira Cubas
Coorientador: Dra. Ana Regina de Aguiar Dutra

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Aos quinze dias do mês de julho do ano de dois mil e vinte e um, às catorze horas, na sala online da plataforma digital *Zoom*: https://zoom.us/j/95897690501, realizou-se a sessão pública de apresentação e defesa de Dissertação de Mestrado de Ana Paula Provin, como requisito para obtenção do título de Mestre em Ciências Ambientais, de acordo com o Regimento Interno do Programa de Pós-Graduação em Ciências Ambientais – PPGCA/UNISUL. Reuniu-se por videoconferência a comissão avaliadora composta pelos seguintes membros: Dra. Anelise Leal Vieira Cubas, orientadora e presidente da banca; Dra. Ana Regina de Aguiar Dutra, coorientadora e docente permanente do PPGCA; Dra. Neide Kohler Schulte, avaliadora externa da Universidade do Estado de Santa Catarina (UDESC); Dra. Elisa Helena Siegel Moecke, avaliadora interna e docente permanente do PPGCA para, sob a presidência da primeira, arguirem a mestranda **Ana Paula Provin**, sobre sua Dissertação intitulada: **UTILIZAÇÃO DE CELULOSE BACTERIANA PROVENIENTE DA BEBIDA KOMBUCHA PARA FABRICAÇÃO DE BIOTÊXTEIS",** área de concentração Tecnologia, Ambiente e Sociedade" e linha de pesquisa "Tecnologia & Sociedade".

Após a apresentação, a mestranda foi arguida pelos membros da banca, tendo sido feitos os questionamentos e ouvidas às explicações a comissão avaliadora emitiu o conceito final:

(x) Aprovado

(   ) Aprovado condicionado

(   ) Reprovado

Observações: ____

Nada mais havendo a tratar, foram encerrados os trabalhos e, tendo sido lida e achada conforme, a presente ata foi assinada pelo presidente da sessão, em nome dos avaliadores presentes por videoconferência, pela mestranda e pela secretária do PPGCA.

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Dra. Anelise Leal Vieira Cubas

Presidente da Sessão

Em nome da Comissão Avaliadora presente por videoconferência

Ana Paula Provin

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Ana Paula Provin

Mestranda do Programa de Pós-Graduação em Ciências Ambientais

Caroline Corrêa da Cruz

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Caroline Corrêa da Cruz

Secretária do Programa de Pós-Graduação em Ciências Ambientais

Em 2015, os Objetivos de Desenvolvimento Sustentável (ODS) da Agenda 2030 foram elaborados pela Organização das Nações Unidas (ONU). Ao todo, são 17 objetivos compostos por 169 metas que visam contribuir com o presente e com um futuro mais sustentável. O conteúdo desta dissertação pode ser relacionado, de forma direta e indireta, com diversos ODS. No entanto, o presente trabalho está inserido principalmente no ODS 12 "Consumo e Produção Responsáveis", o qual objetiva assegurar os padrões de produção e de consumo sustentáveis.

A dissertação contribui, sobretudo, com as Metas:

a) *"12.5, reduzir substancialmente a geração de resíduos por meio da prevenção, redução, reciclagem e reaproveitamento"* (UNDP, 2015). Neste tópico, a presente dissertação colabora com as discussões acerca da geração de resíduos da Indústria Têxtil e da Moda, introduz a temática da produção de novos materiais como os biotecidos e, consequentemente, sugere-se a diminuição de resíduos e até mesmo a possibilidade de projetos de *"Zero waste"* devido à propriedade de moldabilidade, crescimento e biodegradabilidade da celulose bacteriana;

b) *"12.6, incentivar as empresas, especialmente as empresas grandes e transnacionais, a adotar práticas sustentáveis e a integrar informações de sustentabilidade em seu ciclo de relatórios"* (UNDP, 2015). Neste tópico, aborda-se a importância de investimento de pesquisas futuras e a inclusão de tecnologias mais limpas como produtos oriundos da biotecnologia e da biofabricação, tanto em âmbito acadêmico quanto em contexto empresarial;

c) *"12.a, apoiar países em desenvolvimento para que fortaleçam suas capacidades científicas e tecnológicas em rumo a padrões mais sustentáveis de produção e consumo"* (UNDP, 2015). Neste item, a presente dissertação visou contribuir com a divulgação destas tecnologias mais limpas e que estas possam ser implementadas em países em desenvolvimento, pensando em novas fontes de renda para a sociedade e repensando as formas de produção e consumo que podem ser cada vez mais sustentáveis;

d) *"12.c, racionalizar subsídios ineficientes aos combustíveis fósseis, que encorajam o consumo exagerado, eliminando as distorções de mercado, de acordo com as circunstâncias nacionais, inclusive por meio da reestruturação fiscal e a eliminação gradual desses subsídios prejudiciais, caso existam, para refletir os seus impactos ambientais, tendo plenamente em conta as necessidades específicas e condições dos países em desenvolvimento e minimizando os possíveis impactos adversos sobre o seu desenvolvimento de maneira que proteja os pobres e as comunidades afetadas"* (UNDP, 2015)[1]. Por fim, pretende-se com este trabalho mostrar a existência de possibilidades para além do uso de produtos oriundos de combustíveis fosséis como o petróleo,

[1] UNDP (2015). Transformando nosso mundo: a agenda 2030 para o desenvolvimento sustentável. A/Res/70/1, 1–49. Retrieved from http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E.

repensando também, o nosso modelo tradicional de Economia Linear e a transição para uma Economia Circular.

Fonte: https://www.ods.pt/objectivos/12-producao-e-consumo-sustentaveis/

“Se, na verdade, não estou no mundo para simplesmente a ele me adaptar, mas para transformá-lo; se não é possível mudá-lo sem um certo sonho ou projeto de mundo, devo usar toda possibilidade que tenho para não apenas falar de minha utopia, mas participar de práticas com ela coerentes”.

Paulo Freire

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Por fim, e não menos importante, à minha turma de mestrado 2019/2. Uma turma formada somente por mulheres fortes, inteligentes e empoderadas. Mulheres que se tornaram amigas e companheiras de jornada: Camilla (Relações Internacionais), Michelle (Gastronomia), Patrícia (Engenharia Ambiental), Márcia (Polícia Ambiental Militar) e Ritannara (Cosmetologia).

RESUMO

A Indústria Têxtil além de fornecer bens de consumo essenciais em todo o mundo tem um dos mais altos níveis de emprego. Conforme a Associação Brasileira da Indústria Têxtil e de Confecção (ABIT), o setor têxtil no Brasil é considerado o segundo maior empregador na indústria de transformação e o segundo maior gerador do primeiro emprego. No entanto, é um dos setores mais complexos em relação à degradação ambiental, tanto no que diz respeito aos materiais utilizados a partir do petróleo e seus processos químicos, quanto durante sua fabricação e destinação final. Devido a este contexto, pesquisadores do mundo todo estão constantemente em busca de soluções e inovações que possam mitigar os impactos ambientais negativos decorrentes deste setor. Uma das opções é a utilização de microrganismos, pois o biomaterial formado é considerado biodegradável e tem potencial de uso para diversos setores, inclusive a Indústria Têxtil e da Moda. Portanto, o presente estudo visou contribuir com pesquisas teóricas e práticas acerca de novos materiais para a indústria da moda, dando maior ênfase a produção de biotextil obtido a partir da celulose bacteriana (CB) por meio da bebida probiótica Kombuchá. A Kombuchá é considerada uma bebida milenar chinesa que se propagou pelo mundo todo devido suas propriedades medicinais. No entanto, observou-se que a bactéria da família *Komagataeibacter xylinus* (conhecida anteriormente por *Acetobacter xylinum*), presente na bebida, é uma grande fonte para a produção de celulose bacteriana (CB) e tem potencial para substituir tecidos como o couro, na produção de roupas e acessórios por se mostrar um material inovador com propriedades vantajosas como a biodegradabilidade. Assim, a presente dissertação contempla os estudos direcionados à CB, desde sua produção e testes até as discussões acerca dos benefícios do biotêxtil diante da Economia Circular, Objetivos de Desenvolvimento Sustentável (ODS) e aos resíduos sólidos gerados pela Indústria Têxtil. Por fim, acredita-se que o sistema da Indústria Têxtil deve ser revisto, pois ainda é incongruente tanto em questões ambientais quanto sociais e econômicas. Portanto, pensar em novos materiais mais sustentáveis como a celulose bacteriana é uma forma de mitigação e contribui com os Objetivos de Desenvolvimento Sustentável.

Palavras-chave: Celulose bacteriana, Kombuchá, Biotêxteis, Objetivos de Desenvolvimento Sustentável, Moda sustentável.

ABSTRACT

The Textile Industry, in addition to providing essential consumer goods worldwide, has one of the highest levels of employment. According to the Brazilian Textile and Apparel Industry Association (ABIT), the textile sector in Brazil is considered the second largest employer in the manufacturing industry and the second largest generator of the first job. However, it is one of the most complex sectors in relation to environmental degradation, both with regard to materials used from oil and its chemical processes, as well as during its manufacture and final destination. Due to this context, researchers around the world are constantly looking for solutions and innovations that can mitigate the negative environmental impacts resulting from this sector. One of the options is the use of microorganisms, as the biomaterial formed is considered biodegradable and has potential for use in various sectors, including the Textile and Fashion Industry. Therefore, this study aimed to contribute to theoretical and practical research on new materials for the fashion industry, giving greater emphasis to the production of biotextil obtained from bacterial cellulose (CB) through the probiotic drink Kombuchá. Kombuchá is considered an ancient Chinese drink that has spread throughout the world due to its medicinal properties. However, it was observed that the bacterium of the *Komagataeibacter xylinus* family (formerly known as *Acetobacter xylinum*), present in the beverage, is a great source for the production of bacterial cellulose (CB) and has the potential to replace fabrics such as leather in production of clothing and accessories for being an innovative material with advantageous properties such as biodegradability. Thus, this dissertation includes the studies directed to BC, from its production and tests to discussions about the benefits of biotextiles in the face of the Circular Economy, Sustainable Development Goals (SDGs) and solid waste generated by the Textile Industry. Finally, it is believed that the Textile Industry system should be revised, as it is still incongruous in environmental, social and economic issues. Therefore, thinking about new, more sustainable materials such as bacterial cellulose is a form of mitigation and contributes to the Sustainable Development Goals.

Keywords: Bacterial cellulose, Kombuchá, Biotextiles, Sustainable Development Goals, Sustainable fashion.

SUMÁRIO

INTRODUÇÃO

Os têxteis possuem um papel de extrema importância em nossa sociedade, tanto pelo seu viés econômico quanto pelo seu contexto social. Através deles, possibilita-se contar e compreender parte da história da humanidade, sendo possível contextualizar o surgimento das primeiras vestimentas (fibras naturais: animais e vegetais), tanto para a proteção de nossos ancentrais quanto para compreender as distições das classes sociais. Posteriormente, com o desenvolvimento de tecnologias, outros têxteis foram surgindo como as fibras artificiais e sintéticas.

Atualmente, a Indústria Têxtil e de Confeccção representa uma parte significativa nos lucros e na empregabilidade mundial. Emprega-se mais de 300 milhões de pessoas ao longo da cadeia de valor no mundo (EMF, 2017)[2] e seu faturamento foi aproximadamentde de 3.000 bilhões de dólares no último ano (Shirvanimoghaddam et al., 2020)[3]. Tratando-se de Brasil, o país é o quinto maior produtor têxtil do mundo, em 2020 obteve um faturamento de R$185,7 bilhões, é a 2ª maior empregadora da indústria de transformação e a 2ª maior geradora do primeiro emprego (ABIT, 2020)[4]. No entanto, apesar de seus rendimentos, é considerada uma das indústrias mais poluidoras do planeta, estando associada ao elevado uso de água, energia, geração de resíduos sólidos e químicos e, em âmbito social, possui ligação com trabalhos precários, injustos, insalubres e até mesmo análogos à escravidão.

Sendo assim, é necessário realizar pesquisas que visem o alcance da sustentabilidade na cadeia produtiva têxtil e da moda. Uma das formas de melhorar as práticas na Indústria Têxtil para mitigar seus impactos negativos e alinhar essa atividade com os Objetivos de Desenvolvimento Sustentável (ODS) da Agenda 2030 é o desenvolvimento de novos materiais e, consequentemente, repensar os materiais existentes (Neto et al., 2019)[5]. Consequentemente, pesquisadores que atuam nas áreas de biotecnologia e biofabricação têm explorado alternativas de produção inovadoras, como o uso de celulose bacteriana para a fabricação de têxteis (Fernandes et al., 2019)[6].

Uma forma de se produzir a celulose bacteriana é através da Kombuchá, considerada uma bebida milenar chinesa que se propagou pelo mundo todo devido suas propriedades medicinais. No

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[2] EMF. (2017). A New Textiles Economy: Redesigning Fashion'S Future. Ellen Macarthur Foundation, p. 150. Retrieved from https://www.ellenmacarthurfoundation.org/publications/A-New-Textiles-Economy_Full-Report_Updated_1-12-17.pdf%0Ahttps://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report_Updated_1-12-17.pdf.

[3] Shirvanimoghaddam, K., Motamed, B., Ramakrishna, S., & Naebe, M. (2020). Death by waste: Fashion and textile circular economy case. Science of the Total Environment, 718, 137317. https://doi.org/10.1016/j.scitotenv.2020.137317.

[4] ABIT. (2020). Abit - Associação Brasileira da Indústria Têxtil e de Confecção. Retrieved August 1, 2020, from Associação Brasileira da Indústria Têxtil e de Confecção website: https://www.abit.org.br/cont/perfil-do-setor#sthash.Dqb2QtO9.dpuf.

[5] Neto, G. C. de O., Ferreira Correia, J. M., Silva, P. C., de Oliveira Sanches, A. G., & Lucato, W. C. (2019). Cleaner Production in the textile industry and its relationship to sustainable development goals. Journal of Cleaner Production, 228, 1514–1525. https://doi.org/10.1016/j.jclepro.2019.04.334.

[6] Fernandes, M., Gama, M., Dourado, F., & Souto, A. P. (2019). Development of novel bacterial cellulose composites for the textile and shoe industry. Microbial Biotechnology, 12(4), 650–661. https://doi.org/10.1111/1751-7915.13387.

entanto, observou-se que a bactéria da família *Komagataeibacter xylinus* (conhecida anteriormente por *Acetobacter xylinum*), presente na bebida, é uma grande fonte para a produção de celulose bacteriana (CB) e tem potencial para substituir tecidos na produção de roupas e acessórios por se mostrar um material inovador com propriedades vantajosas como a biodegradabilidade (Domskiene et al., 2019)[7].

Assim, o presente estudo visou contribuir com pesquisas teóricas e práticas acerca da produção de celulose bacteriana (CB) através da bebida probiótica Kombuchá para a produção de biotêxteis. Bem como, discutir formas viáveis de produção da CB, suas propriedades, as vantagens e desvantagens do biotecido e sua relação com a Economia Circular.

Como resultado desta vasta pesquisa acerca da contextualização da Indústria Têxtil, materiais promissores e mais sustentáveis, o uso de celulose bacteriana para produção de biotecidos, Economia Circular e os Objetivos de Desenvolvimento Sustentável (ODS), foram obtidos seis artigos e organizados por capítulos:

I. CAPÍTULO 1 - "Alternativas de materiais e processos mais sustentáveis para a indústria têxtil atual – Uma revisão". Artigo de revisão que buscou compilar estudos acerca do contexto da Indústria Têxtil atual, abordando suas complexidades relacionadas ao meio ambiente. Foram temas do primeiro artigo as possibilidades de materiais e processos mais sustentáveis. Artigo publicado na Revista ModaPalavra (A3);
II. CAPÍTULO 2 - "New materials for clothing: rethinking possibilities through a sustainability approach - a review". Artigo de revisão que buscou compilar estudos acerca do contexto da Indústria Têxtil atual, abordando suas complexidades relacionadas ao meio ambiente. Foram temas do segundo artigo, pesquisas acerca dos novos materiais como materiais provenientes da técnica de upcycling, têxteis inteligentes e materiais de microrganismos. Incluiu-se também uma profunda discussão relacionando os materiais abordados com os ODS. Artigo publicado no periódico Journal of Cleaner Production (A1);
III. CAPÍTULO 3 - "Circular economy for fashion industry: use of waste from the food industry for the production of biotextiles". Artigo de revisão que buscou compilar estudos acerca do contexto da Economia Circular, abordando suas complexidades relacionadas às possibilidades de modelos de negócios mais sustentáveis, principalmente através da interdisciplinaridade entre setores. Foram temas do presente artigo pesquisas acerca da Economia Circular, Economia Circular na Indústria Alimentícia, Economia Circular na Indústria Têxtil, o uso de resíduos alimentares para a produção de novos têxteis como a celulose bacteriana através da bebida Kombuchá. Por fim,

[7] Domskiene, J., Sederaviciute, F., & Simonaityte, J. (2019). Kombucha bacterial cellulose for sustainable fashion. International Journal of Clothing Science and Technology, 31(5), 644–652. https://doi.org/10.1108/IJCST-02-2019-0010.

incluiu-se também uma profunda discussão relacionando a Economia Circular com os ODS. Artigo publicado no periódico Technological Forecasting and Social Change (A1);

IV. CAPÍTULO 4 - “Textile Industry and Environment: Can the use of bacterial cellulose in the manufacture of biotextiles contribute to the sector?”. Artigo de revisão que buscou compilar estudos acerca do contexto da produção de celulose bacteriana através da bebida probiótica Kombuchá. Foram temas do presente artigo pesquisas acerca da produção biotexteis a partir da celulose bacteriana, os benefícios do biotecido como sua biodegradabilidade em relação ao contexto dos resíduos gerados pela Indústria Têxtil. Por fim, incluiu-se também uma profunda discussão relacionando o biotecido com os ODS. Artigo submetido no periódico Clean Technologies and Environmental Policy (A2);

V. CAPÍTULO 5 - “Use of bacterial cellulose in the textile industry and the wettability challenge - a review”. Artigo de revisão que buscou compilar estudos acerca do contexto de uma das propriedades da celulose bacteriana, sua molhabilidade. Foram temas do presente artigo pesquisas acerca da molhabilidade da celulose bacteriana, sua propriedade natural hidrofílica e os métodos para tornar o biomaterial mais hidrofóbico pensando na indústria têxtil. Artigo aceito para publicação no periódico Cellulose (A1);

VI. CAPÍTULO 6 - “Use of bacterial cellulose produced by Kombuchá drink for the manufacture of biotextiles for the benefit of sustainability”. Artigo de pesquisa que buscou compilar estudos acerca da produção de celulose bacteriana através da bebida Kombuchá, demonstrando alguns testes realizados no Laboratório de Plasma da UNISUL e na Central de Análises (EQA) da UFSC, como a Microscopia Eletrônica de varredura e a purificação através do uso da tecnologia do Plasma não-térmico (PNT) comparada ao método tradicional usando NaOH. Artigo aceito para publicação no 17º International Conference on Environmental Science & Technology (CEST2021).

OBJETIVO GERAL

Contribuir com pesquisas teóricas e práticas acerca de novos materiais para a indústria da moda, dando maior ênfase a produção de biotecido obtido a partir da celulose bacteriana (CB) por meio da bebida probiótica Kombuchá.

OBJETIVOS ESPECÍFICOS

- Investigar o contexto atual da Indústria Têxtil e da Moda em relação ao meio ambiente;
- Identificar as possibilidades de novos materiais têxteis por meio da literatura científica;

- Apresentar o estado da arte de pesquisas sobre celulose bacteriana e as fontes de produção como a Kombuchá;
- Produzir amostras de celulose bacteriana provenientes da bebida Kombuchá;
- Analisar as vantagens e desvantagens do uso da celulose bacteriana para a fabricação de biotêxteis por meio da literatura científica;
- Contribuir com a pesquisa científica através de estudos e análises sobre os biotêxteis e a sua potencial relação com a Economia Circular e os Objetivos de Desenvolvimento Sustentável.

CAPÍTULO 1

Alternativas de materiais e processos mais sustentáveis para a indústria têxtil atual – uma revisão

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Resumo: Inúmeros estudos são realizados todos os anos no intuito de descobrir formas inovadoras de elaborar têxteis para o conforto, segurança e, muitas vezes, que representam as ideologias do consumidor. No entanto, devido à problemática da indústria têxtil relacionada à degradação ambiental, pesquisadores têm realizado estudos acerca de materiais e processos que sejam mais sustentáveis. Portanto, o presente artigo propõe uma revisão bibliográfica de caráter analítico, em três bases de dados, a *Scopus*, *ScienceDirect* e *ProQuest*, sobre materiais e processos mais sustentáveis utilizados no setor de têxteis entre os períodos de 2015 e 2020. Os resultados mostram 38 artigos sobre alternativas sustentáveis de materiais e processos para o mercado atual, bem como sobre pesquisas em andamento sobre novas possibilidades de têxteis nos campos da engenharia, biotecnologia, design, entre outros.

Palavras-chave: Vestuário. Materiais têxteis. Sustentabilidade.

1. INTRODUÇÃO

As roupas além de serem úteis para vestir os seres humanos e protegê-los de eventuais intempéries, também são elementos fundamentais para o conforto e funcionalidade, assim sendo, com o desenvolvimento da sociedade, novas exigências vão surgindo através dos indivíduos que a compõem e, consequentemente, este movimento acarreta em adaptações do próprio mercado (Lurie, 1997). Da mesma forma, o avanço e as melhorias dos padrões de vida materiais e culturais, fazem com que ocorram mudanças nos níveis de consumo de roupas, buscando opções que lhes ofereçam mais conforto, segurança e que expressem suas ideologias e pensamentos (Jiang, 2013; Sarier *and* Onder, 2012).

No entanto, a indústria da moda possui uma dinâmica competitiva no mercado, principalmente pelo rápido movimento das tendências e a grande oferta de opções por parte dos empreendedores (*Fast Fashion*) (Haslinger *et al., 2019*; Yasin *and* Sun, 2019). Consequentemente, os produtos possuem um ciclo de vida curto, um descarte inadequado, processos de fabricação tóxicos e essas questões desafiam os aspectos de sustentabilidade da indústria da moda (Hu *et al*, 2018; Moretto *et al.*, 2018).

Pode-se dizer que nos últimos anos, algumas questões referentes ao desenvolvimento sustentável atraíram muita atenção em relação ao cotidiano de inúmeras pessoas, tornando-se um estilo de vida em vários aspectos como a alimentação, tecnologias e o vestuário (Ng *et al*., 2013). A indústria têxtil e da moda são um dos setores que mais enfrentam problemas com questões ambientais e sustentáveis, não somente pela utilização de produtos químicos e o descarte de resíduos, mas pela postura do próprio consumidor ao fazer parte dessa cadeia e não repensar nas atitudes em relação ao consumo e os materiais utilizados nos produtos (Eifler *and* Diekamp, 2013).

Em muitos casos, as pessoas possuem a consciência de que existem produtos não nocivos ao meio ambiente, no entanto, devido ao seu estilo de vida e preferências, acabam optando por tecidos considerados esteticamente bonitos e mais confortáveis (Lurie, 1997). Entretanto, com o avanço de pesquisas na área, uma das soluções encontradas foi repensar a matéria-prima e encontrar possibilidades que atinjam o conforto e beleza exigidos pelo cliente através de tecidos sustentáveis, naturais e que não agridam o meio ambiente (Ng *et al.*, 2013). Salienta-se que, os meios de seleção de materiais estão progredindo, pois existem bibliotecas de materiais físicos, bancos de dados, software e ferramentas que conectam estes materiais com designers (Prendeville *et al., 2014)*.

Sendo assim, o mercado de roupas que visa o protecionismo ambiental está crescendo, por isso, deve-se prestar atenção suficiente às questões sustentáveis (Ng *et al.,* 2013). A urgência para desenvolver e fabricar roupas com esse viés vai além de aumentar a consciência ambiental de designers, consumidores e empresas de vestuário, necessita-se de esforços para projetar, pesquisar e desenvolver roupas ecologicamente corretas através de novos materiais (Zhao, 2011).

Materiais provenientes de recursos renováveis, reciclados e reaproveitados estão cada vez mais em voga como alternativas de produção, juntamente com as áreas da biotecnologia e da biofabricação (Camere *and* Karana, 2018). Além das possibilidades com micro-organismos e modificações de tecidos já existentes, dentro do que podem ser consideradas alternativas sustentáveis, materiais naturais como fibras de cânhamo e bambu surgem, também, como novas alternativas de estudo para a adequação em vestuários (Nayak *and* Mishra, 2016).

Outras áreas também surgem com o intuito de fomentar pesquisas para o desenvolvimento tecnológico de tecidos, um exemplo disso são as novas descobertas com fibras têxteis "inteligentes", nanotêxteis e microfibras produzidas via eletrofiação coaxial (Rossi *et al.*, 2011; Lagerwall, 2012). Estudos já comprovaram que, à medida que a indústria do vestuário e as pesquisas acadêmicas vêm realizando grandes avanços na integração de variados elementos para o desenvolvimento de tecidos e processos, os desafios surgem paralelamente, exigindo novas soluções (Sarier *and* Onder, 2012).

Portanto, pesquisas relacionadas à área têxtil, juntamente com laboratórios de engenharias, química, entre outros, possibilitaram investimentos nas descobertas de materiais alternativos e processos têxteis que influenciarão não somente áreas profissionais, mas outros setores da atividade humana, como o próprio consumido (Jiang, 2013). Diante desse contexto, tem-se por objetivo mostrar uma revisão sobre alternativas de materiais e processos mais sustentáveis para a indústria têxtil atual, suas formas de produção e tecnologias através de uma compilação de artigos científicos nacionais e internacionais publicados entre o período de 2015 a 2020.

2. METODOLOGIA

A pesquisa constitui-se em uma revisão bibliográfica de caráter analítico, com relevância nas bases de dados acadêmicas acessadas via Portal Periódico Capes (CAPES, 2019). Para operacionalizar tal pesquisa, utilizou-se a bibliometria que tem como função, a partir de métodos estatísticos, mapear informações de registros bibliográficos de documentos armazenados em bancos de dados (Campbell *et al*., 2010).

Posteriormente a escolha dos artigos, a etapa a seguir é a análise esmiuçada do conteúdo, que tem como finalidade congregar e sintetizar resultados de pesquisas sobre um determinado assunto, contribuindo para o aprofundamento do conhecimento do tema investigado.

2.1 Análise Bibliométrica

Para o enriquecimento dessa análise foram selecionadas as palavras-chave: *clothing* AND *"textile materials"* AND *sustainability*. Posteriormente, foi elaborada a indagação norteadora da pesquisa, que se baseia nas alternativas de fibras e processos têxteis que sejam mais sustentáveis no mercado atual da moda. Por conseguinte, o procedimento utilizado para realizar a pesquisa bibliográfica foi constituído por três etapas: coleta de dados, análise de dados e síntese dos resultados.

2.1.1 Coleta de dados

As bases de dados escolhidas para a escrita do presente artigo foram: a) *Scopus:* possui um vasto banco de dados de resumos e citações da literatura revisada por pares, periódicos científicos, livros e anais de congressos; b) *ProQuest:* o banco de dados de Ciência e Engenharia de Materiais inclui os renomados bancos de dados da *Metadex*, *Copper* and *Polymer Library*, fornecendo títulos de textos completos de todo o mundo; c) *ScienceDirect:* é considerada uma das mais importantes plataformas de pesquisa acadêmica pela *Elsevier*. Suas coleções possibilitam pesquisas na área de bioquímica, genética e biologia molecular, química, medicina clínica, engenharia e medicina veterinária.

2.1.2 Análise de dados

Para a realização da análise de dados, os artigos selecionados continham um título, resumo ou a presença de palavras-chave referindo-se aos termos no corpo do texto, como *clothing* AND *"textile materials"* AND *sustainability*. Sendo assim, foram empregados os critérios de inclusão e exclusão conforme as leituras fossem compatíveis com a proposta da pesquisa.

2.1.3 Síntese dos resultados

Esta última etapa, abrangeu a leitura de todos os artigos na íntegra, permitindo mais uma seleção com o intuito de excluir os que não demonstraram anuência à temática investigada. Por conseguinte, eliminando alguns documentos que foram indicados na fase anterior por possuir algum termo na palavra-chave, no título ou no resumo que não remetesse a proposta pesquisada.

3. RESULTADOS

Foram encontrados 131 artigos na base de dados *ScienceDirect*, 72 artigos na base de dados *Scopus* e 62 artigos na base de dados da *ProQuest*, utilizando os termos *clothing* AND *"textile materials"* AND *sustainability*, seguindo respectivamente os mesmo filtros como artigos acadêmicos, no período de tempo entre 2015 e 2020, totalizando assim 265 artigos. Posteriormente, foram excluídos os artigos repetidos entre as bases de dados, 4 artigos repetidos entre as bases *ScienceDirect* e *Scopus* e 2 repetidos entre as bases *Scopus* e *ProQuest*, totalizando 259 artigos.

Na fase de leitura dos títulos, resumos (abstract) e palavras-chaves de cada artigo, foram escolhidos aqueles que estavam alinhados com o tema da busca. Sendo assim, foram excluídos 82 artigos da base de dados da *ScienceDirect*, 51 artigos da base de dados da *Scopus* e 49 artigos da base de dados da *ProQuest*. Por conseguinte, com a leitura dos artigos na íntegra e para a realização da feitura do presente artigo de revisão, ainda no processo de exclusão dos artigos que não condiziam com a temática abordada, foram subtraídos 26 artigos da base *ScienceDirect*, 12 artigos da base *Scopus* e 7 artigos da base *ProQuest*, totalizando 38 artigos.

A **Figura 1** exemplifica o processo utilizado para a análise bibliométrica.

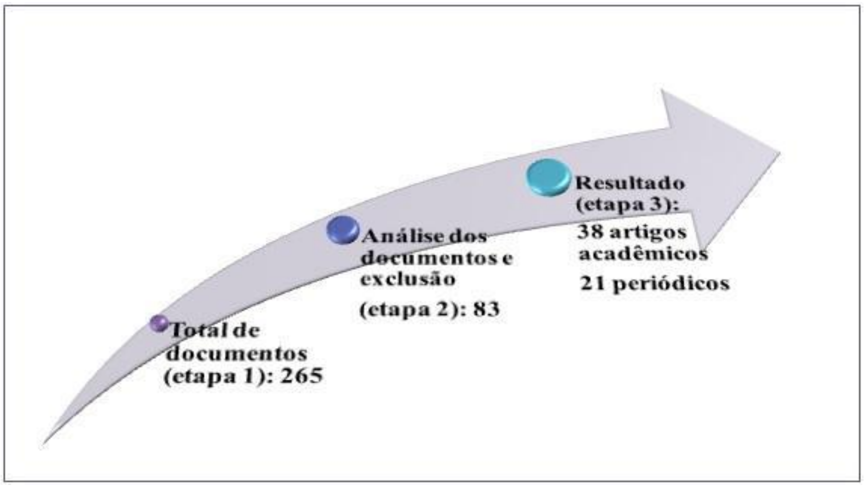

Fig. 1. Etapas da análise bibliométrica. **Fonte:** Autores.

A **Tabela 1** a seguir**,** explicita os dados referentes ao fator de impacto (F.I), a qualificação pela CAPES dos periódicos em que os artigos foram publicados e a quantidade de artigos encontrados em cada revista. A apresentação das revistas segue em ordem decrescente referente ao número de publicações.

Tabela 1. Avaliação CAPES e fator de impacto dos periódicos.

REVISTA	FATOR DE IMPACTO	AVALIAÇÃO CAPES	QUANTIDADE
Journal of Cleaner Production	6.395	A1	8
Cellulose	3.917	A1	3
Industrial Crops & Products	4.191	A1	3
Journal of Natural Fibers	1.252	A3	3
Geoforum	2.926	A1	2
International Journal of Biological Macromolecules	4.784	A1	2
Materials and Design	5.770	A1	2
Fibers and Polymers	1.439	A2	2
Materials Review	3.532	A2	1
Textile Research Journal	1,54	A2	1
Environmental Development	2,5	A1	1
Nano Research	8.515	A1	1
International Journal of Clothing Science and Technology	0,796	A4	1
Fashion and Textiles	0,85	A2	1
Arabian Journal of Chemistry	3.298	A2	1
Scientific Reports	1,41	A2	1
Process Biochemistry	2.883	A4	1
Nano energy	15.548	A1	1
Optik	1.914	A4	1
Sustainable Chemistry and Pharmacy	2.404	A3	1
Dyes and Pigments	4.018	A1	1

Fonte: Autores

Através da **Tabela 1** é possível observar que os periódicos ficaram qualificados pela CAPES entre A1 e A4 e com a grande maioria com o fator de impacto > 1, demonstrando assim, autenticidade e segurança nos conteúdos apresentados pelos artigos. Destaca-se também que o maior número de artigos foi encontrado no "*Journal of Cleaner Production*", uma revista interdisciplinar com o escopo voltado para as questões de sustentabilidade em diversos setores.

A F**igura 2** demonstra o número de artigos publicados de cada continente e as parcerias realizadas entre continentes.

Fig. 2. Publicação de artigos por continente e suas parcerias. **Fonte:** autores.

Através da **Figura 2** é possível observar que os continentes com o maior número de publicações acerca de materiais e processos sustentáveis foram a Europa (14 artigos) e a Ásia (9 artigos), destacando a China como o país com o maior número de publicações (6 artigos). Segundo Zhao *and* Lin (2019) e Baiardi *and* Bianchi (2019), a indústria têxtil é considerada uma tradição chinesa e valorizada como um de seus pilares econômicos, mantendo-se líder principalmente nas exportações, no entanto, apresentam diversas problemáticas relacionadas à sua forma de produção e questões ambientais e sociais.

3.1 Alternativas de materiais mais sustentáveis

Estudos comprovam que os compósitos de biopolímero de tecido de fibra natural são biodegradáveis, renováveis e recicláveis, podendo ainda substituir ou reduzir o uso de fibras sintéticas em várias aplicações têxteis (Fazita *et al.*, 2016). Assim sendo, celulose e materiais lignocelulósicos estão sendo utilizadas por muitos fins tradicionais e inovadores (Judit et al., 2016).

Fibras naturais de celulose são reconhecíveis como parte de uma planta original, sendo possível a utilização das sementes (algodão, kapok), hastes (linho, cânhamo, juta, kenaf, rami), folhas (sisal, abaca), frutas (coco, abacaxi) e de plantas em decomposição, como fibras à base de turfa (Mikucioniene *et al.*, 2018). Para além da utilização dos recursos naturais das celuloses vegetais, áreas como a biotecnologia e a biofabricação, exploram alternativas como a utilização de microrganismos para a fabricação de têxteis, tanto para roupas quanto para a indústria calçadista (Camere *and* Karana, 2018; Saraç *et al.*, 2015; Scarlat *et al.*, 2019).

Por conseguinte, salienta-se que os têxteis eletrônicos, denominados tecidos inteligentes, vêm em uma crescente de pesquisas nos últimos anos (Saraç *et al.*, 2019). Segundo Busi *et al.* (2016) e Li *et al.* (2018), a nanotecnologia tem um altivo potencial tecnológico para o setor têxtil, pois tem se percebido uma tendência com o desenvolvimento de têxteis eletrônicos vestíveis inteligentes, que apresentam novas possibilidades para o vestuário funcional e para o monitoramento da saúde pessoal, por exemplo. Portanto, com base em pesquisas nacionais e internacionais, o artigo explanará sobre diversos materiais naturais oriundos de plantas, microrganismos e os chamados têxteis "inteligentes".

3.1.1 Algodão

Entre os diferentes materiais, o algodão é uma das que mais contribuem para a destruição do ecossistema de água doce em âmbito global, embora a fibra de algodão venha de uma fonte sustentável. Contudo, para o plantio do algodão são utilizados inseticidas, pesticidas e, salienta-se, para produzir 1 kg de fibra de algodão pode-se exigir mais de 20.000 L de água (Tausif *et al.*, 2015). Compreende-se que o desempenho, a relação custo-benefício e a estética dos tecidos podem ser aprimorados pela mistura de diferentes tipos de fibras, por isso, a mistura de poliéster e algodão (PC) é uma das mais praticadas na indústria têxtil, gerando assim, maiores complexidades nas questões de sustentabilidade (Domskiene *et al.*, 2018).

Na Etiópia, por exemplo, existem planos para o país se tornar o quinto maior produtor do mundo em algodão, no entanto, voluntários dos programas de certificação prometem garantir a sustentabilidade desse desenvolvimento e convocam consumidores a "aderir à revolução da moda" comprando roupas certificadas (Partzsch *and* Kemper, 2019). Segundo Partzsch e Kemper (2019), já existem alguns programas de certificação que evoluíram a partir de movimentos ativistas em oposição ao sistema convencional, citando como exemplo o Global Organic Textile Standard (GOTS), fazendo com que as pessoas fiquem a par das informações específicas como salário mínimo e a proibição de produtos tóxicos como pesticidas e fertilizantes.

3.1.2 Bambu

Pode-se afirmar que, o bambu é uma planta que possui grande destaque no que se refere ao desenvolvimento socioeconômico, pois se encontra em abundância no meio ambiente, crescem rapidamente e em sua maior parte é cultivada organicamente, sem uso de pesticidas e fertilizantes (Nayak *and* Mishra, 2016). Considera-se o bambu uma fibra lignocelulosica natural obtida do colmo de bambu, tendo sua composição química, estrutura e propriedades frequentemente comparadas com outras fibras liberianas como o linho e a juta (Mishra *et al.*, 2012).

Atualmente, algumas empresas estão interessadas em fibras de bambu regeneradas, supostamente devido a algumas características especiais como propriedades antibacterianas, absorventes, anti-UV e antiestática (Mishra *et al.*, 2012; Nayak *and* Mishra, 2016). Conforme Tausif *et al.* (2015), a fibra de viscose de bambu foi estudada como uma alternativa ecológica à fibra de algodão em misturas poliéster-celulósica. Assim, é crucial reconhecer as propriedades funcionais necessárias para o biopolímero de tecido de fibra natural e seus compósitos para serem utilizados não somente pela indústria têxtil, mas também como outras opções de mercado como, por exemplo, material para embalagens (Fazita *et al.*, 2016).

3.1.3 Cânhamo e linho

Cânhamo industrial e linho são fontes muito prósperas de celulose, fornecendo importantes substâncias celulósicas e não celulósicas com baixo investimento agrícola e pode ter diversos usos roupas, isolamento, agricultura, filtração, compósitos, adsorção de alguns contaminantes e biocombustíveis (Borsa *et al.*, 2016). Atualmente, há um interesse crescente em métodos especiais de cultivo e os destinos de uso final devido à sua pegada de carbono relativamente pequena, eles têm um papel crescente no mercado de biocompósitos, principalmente para o setor automotivo e de isolamento materiais (Borsa *et al.*, 2016).

Nas últimas décadas, a mídia destacou o esgotamento do ozônio como o maior problema ambiental resultando em um aumento da radiação ultravioleta (UVR), atingindo a superfície da Terra e essa radiação é capaz de causar danos à população humana, sendo assim, a proteção UV fornecida pelas roupas torna-se um assunto de interesse significativo dos produtores e consumidores de tecidos (Kocic *et al.*, 2019; Zhou *et al.*, 2020). Apesar de muitas fibras terem pouca capacidade de proteção UV, destaca-se o potencial da fibra de cânhamo no desenvolvimento de produtos têxteis funcionalizados como protetores contra UV, mais sustentáveis e saudáveis (Kocic *et al.*, 2019).

3.1.4 Celulose bacteriana

A inclusão de sistemas biológicos vivos no campo da nanotecnologia e ciências de materiais, por meio de extensivas pesquisas, faz com que sejam criadas estratégias e soluções de novos materiais sustentáveis que não serão uma fonte de poluição para o nosso planeta (Camere *and* Karana, 2018). Salienta-se que esta necessidade surge através do entendimento de inúmeros estudiosos que se preocupam com o desenvolvimento de novos materiais sustentáveis que não serão uma fonte de poluição para o nosso planeta (Haneef *et al.*, 2017).

O uso de biomateriais nos negócios da moda pode ser promissor, pois o material pode se desenvolver no tamanho necessário para a sua utilização e possui propriedades biodegradáveis (Domskiene *et al.*, 2018). Para a produção de materiais a partir de bactérias, por exemplo, observam-se os processos de fermentação para gerar um material que pode ser confeccionado e desenvolvido como material fino e flexível, e com grande potencial para substituir o couro de animais (Yim *et al.,* 2017*).*

A produção de celulose bacteriana, biomaterial produzido a partir de bactérias, se efetiva através da fermentação de uma cultura simbiótica de bactérias com leveduras (*SCOBY*) em meio nutriente ácido, contendo monossacarídeos como glicose, frutose ou glicerol e quando fornecidos com os nutrientes corretos as bactérias produzem uma camada de 100% de celulose pura (Domskiene *et al.,* 2018). Percebe-se na produção de celulose bacteriana a baixa utilização de energia e de água, salientando assim, as vantagens sustentáveis de desenvolvimento comparados a outros materiais comuns do nosso cotidiano (Camere *and* Karana, 2018; Costa *et al*., 2019).

Pesquisas demonstraram algumas viabilidades para a modelagem através do cultivo da celulose bacteriana chamada também de Self-grown Fashion, demonstrando dois métodos principais: a) Formato 2D: forma folhas 2D usando bactérias de cultivo estáticas em caldo e, através desse método, o material pode ser cortado e costurado como uma peça de roupa semelhante ao tecido convencional; e b) Formato 3D: modela diretamente em uma forma 3D como um manequim, sendo moldado em 3D e seco sem a necessidade de corte e costura, economizando tempo e custos do corte tradicional (Domskiene *et al*., 2018).

3.1.5 Têxteis inteligentes

Fontes de energia vestíveis com alto desempenho estão atraindo atenção intensiva, devido ao seu grande potencial em eletrônicos vestíveis de nova geração (Bai *et al*., 2019). Assim, há uma comunidade crescente de têxteis inteligentes, na qual os designers utilizam materiais de engenharia e tecnologias avançadas de fabricação para criar produtos comercializáveis (Velden *et al*., 2015).

Além da função de captação de energia, esses tecidos inteligentes também podem ser integrados a roupas de uso diário e sentir a amplitude dos movimentos humanos, servindo como um sensor altamente sensível dos movimentos e posturas humanas (Qiu *et al.*, 2019). Segundo Busi *et al.* (2016), a nanotecnologia possui alto potencial tecnológico para a indústria têxtil, citando como exemplo os "têxteis autolimpantes", que podem ser facilmente lavados e mantidos, capazes de melhorar o desempenho do processo em termos de energia e recursos de consumo de água. No entanto, pesquisadores recomendam uma expansão nos estudos sobre tecidos autolimpantes para considerar o custo e o benefício da fase de produção agregando todos os pilares da sustentabilidade (Yun *et al.*, 2016)

Exemplos também de desenvolvimento de nanogeradores triboelétricos (TENGs) podem ser utilizados como uma nova ideia para aliviar a grave crise energética (Yan *et al.*, 2018). Têxteis flexíveis nomeados TENG, baseados em membranas termofásticas poliméricas de nanofibras termoplásticas fabricadas pelo método de extrusão por fusão poderia ser usado para coletar a energia mecânica de baixa frequência produzida por movimentos humanos (Yan *et al.*, 2018; Qiu *et al.*, 2019).

Por fim, para implementar uma maneira ambientalmente consciente de inovação de produtos, o impacto ambiental de tais produtos precisa ser levado em conta já nos estágios iniciais do projeto (Velden *et al.*, 2015). Para Velden *et al.* (2015), uma nova perspectiva do ciclo de vida dos produtos da moda, fazem com que os designers adotem atitudes mais sustentáveis para a preservação do meio ambiente.

3.2 Processos de fabricação têxtil

À medida que a demanda global por têxteis aumenta, o mesmo ocorre com os possíveis impactos ambientais negativos decorrentes da sua produção, uso e descarte e, consequentemente, os rios costumam ser os principais receptores de resíduos gerados durante a produção de tecidos (Stone *et al.*, 2019). No entanto, observa-se que apesar dos consumidores desejarem um aumento no conforto, também existe uma conscientização crescente entre os mesmos e o meio ambiente (Tausif *et al.*, 2015)

O processo de fabricação têxtil é caracterizado pelo alto consumo de recursos como água, combustível e uma variedade de produtos químicos em um longo processo sequenciado, gerando uma carga significativa ao ambiente (Parisi *et al.*, 2015). Os processos comuns de tingimento de têxteis, por exemplo, são grandes responsáveis pelo descarte de resíduos inadequados, no entanto, o tingimento de corantes naturais tem se tornado mais popular, garantindo não somente a mitigação dos processos poluentes, mas ampliando um leque de cores e abrindo novas possibilidades para os designers têxteis (Fröse *et al.*, 2019)

A extração de corantes naturais a partir de folhas de resíduos e cascas superficiais das plantas poderia ser uma tecnologia sustentável para a utilização de resíduos de biorrecursos pelos segmentos de pequena escala, bem como pelas áreas rurais (Baliarsingh *et al.*, 2015). Conforme El *et al.* (2015), extratos coloridos de subprodutos naturais como a utilização da pimenta, exibe características positivas de tingimento e eficácia antimicrobiana contra patógenos humanos comuns como *Pseudomonas aeruginosa* e *Staphylococcus aureus.*

Pesquisadores demonstraram através de estudos outros procedimentos eficientes de pigmentação usando métodos variados e diversas espécies de plantas como a casca de grão de bico (um potencial desperdício agrícola que pode ser utilizado para a coloração e funcionalidade acabamento de têxteis) (Jose *et al.*, 2019); extrato de flor de *Tagetes erecta* para tingimento, acabamento anti-UV e antioxidante economicamente viável (Shabbir *et al.*, 2017); extrato de casca de romã (*Punica granatum l*) com propriedades antibacterianas e funcionalização antifúngica (Butola *et al.*, 2019; Zuber *et al.*, 2019) e extração assistida por ultrassom por micro-ondas de corantes naturais da casca de sorgo com diferentes solventes (Wizi *et al.*, 2018).

Inúmeras pesquisas e projetos têm sido realizados em âmbito global. O tratamento de desbotamento das cores dos produtos têxteis coloridos, por exemplo, é um tópico importante devido à sua importância comercial, entretanto, acarreta em vários problemas ambientais (Kan *et al.*, 2016). Para Kan *et al.* (2016), o tratamento com ozônio induzido por plasma é um processo ecológico que não gera efluentes químicos, e ocasiona a redução das etapas e o custo do processamento quando comparado com a cor convencional de tratamento de desbotamento. A viabilidade dessas soluções alternativas foi demonstrada também durante o projeto BISCOL da União Europeia, propondo um novo processo de tingimento como alternativa global para a conversão de matérias-primas em produtos finais competitivos e ecologicamente viáveis através da integração de síntese enzimática de corantes em escala semi-industrial, pré-tratamento têxtil com base na tecnologia de plasma (Parisi *et al.*, 2015).

Apesar dos corantes naturais serem mais ambientalmente sustentáveis em comparação aos sintéticos, seu desempenho é pior, fazendo com que mordentes tipicamente metálicos sejam aplicados para melhorar a afinidade do corante em relação aos substratos, mas essa não é uma técnica adequada em uma "história verde" (Phan *et al.,* 2020). Pesquisadores perceberam um grande potencial utilizando a quitosana que é um amino polissacarídeo versátil e renovável em potencial e pode ser utilizado no desenvolvimento de tecidos de lã coloridos e multifuncionais sem a necessidade de mordentes de sal metálico (Butola *et al.*, 2019). Os resultados além de terem sido positivos em relação à durabilidade das cores, conferiu excelente propriedade antibacteriana contra *E. coli* e *S. aureus* e, portanto, oferece novas oportunidades no domínio do tingimento natural (Tadesse *et al*., 2019; Shahid *and* Rather, 2018). Outros estudos demonstraram a efetividade em um novo tingimento livre de mordente de tecido de poliéster com curcumina, corante natural, usando processo de tingimento supercrítico de dióxido de carbono (scCO2), isento de água e eficiente em recursos naturais (Tadesse *et al*., 2019).

Por fim, além dos estudos acerca de materiais têxteis já conhecidos e plantas diversas, o surgimento de têxteis novos como biotecidos oriundos de celulose bacteriana e os processos de tingimentos também estão sendo explorados, afinal, a mitigação eficaz pode combinar avanços tecnológicos com mudanças sociais nos mecanismos de mercado (Stone *et al*., 2019). Segundo Fernanda *et al*. (2019), é possível o uso de corantes naturais à base de plantas em celulose bacteriana (BC) sem perder o valor estético às películas tingidas e mantendo as propriedades mecânicas. Pigmentos naturais de *Clitoria ternatea L.* e *Hibiscus rosa-sinensis* foram testados em relação à fixação, reidratação, resistência à tração e elasticidade nas celuloses bacterianas e foi possível comprovar que o tingimento é um processo que pode ser realizado na CB hidratada, comprovando a importância dos estudos relacionados à consciência ambiental e preocupação pública em relação ao aumento da poluição (Fernanda *et al*., 2019).

4. Conclusões

Perante a importância no desenvolvimento de pesquisas relacionadas ao assunto da indústria têxtil e suas novas descobertas, o objetivo do artigo se concentrou na reunião de referências bibliográficas para explanar as alternativas existentes no mercado atual mundial. Foram selecionados os artigos mais relevantes para a análise do tema proposto, levando em consideração as principais propostas acerca da sustentabilidade e das novas possibilidades tecnológicas.

Posteriormente, através da análise bibliométrica, foi possível averiguar a potencialidade de cada artigo, periódico e suas contribuições acadêmicas. Diante das análises dos artigos, observou-se que, com o desenvolvimento da sociedade e dos estilos de vida dos sujeitos que a compõem, novas exigências do mercado do vestuário foram surgindo. Sendo assim, percebeu-se uma movimentação tanto das indústrias têxteis e dos designers, quanto de pesquisadores acadêmicos na busca por descobertas inovadoras de materiais e processos, que sejam menos degradantes para o meio ambiente.

Portanto, mediante ao exposto, conclui-se que estudos vinculados à área têxtil, juntamente com pesquisadores das engenharias, biotecnologia, materiais, entre outros, proporcionam investimentos nas descobertas de materiais e processos mais sustentáveis e estes modificam, não somente áreas profissionais, mas outros setores da atividade humana de forma efetiva.

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CAPÍTULO 2

New materials for clothing: rethinking possibilities through a sustainability approach - a review

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Abstract: The textile industry has one of the highest levels of employment around the world, but this is considered one of the most polluting activities. Researchers are therefore constantly looking for solutions and innovations that can mitigate the negative environmental impacts arising from this sector. This article provides an analytical literature review based on searches carried out in four databases, for the period of 2015 to 2020, focusing on concepts about sustainability and new sustainable materials used for the production of textiles. In the section "3. Concepts of sustainability and the new possibilities of materials for textiles", the concepts for a more sustainable sector such as upcycling and the possibilities of new materials through the use of microorganisms and investment in smart textiles are discussed through the researched literature. Reinforcing in this way, how these analyzed contents can contribute to the future of the textile industry. A total of 75 research articles were found, published in 40 journals, which were grouped by subject: "Upcycling", "Living Organisms and Biotechnology" and "Smart Textiles", noting that the highest occurrence of articles related to the themes came from the United Kingdom and China, mainly in the period of 2019. Finally, the concepts and materials found and their coherence with the sustainable development goals established by the United Nations in the 2030 Agenda were analyzed.

keywords: Clothing; New Materials; Sustainability; Sustainable Development Goals.

1. Introduction

The competitive dynamics of the markets associated with the fashion industry is mainly driven by the rapid shifting of trends and the wide range of options offered by entrepreneurs (fast fashion) (Haslinger et al., 2019; Yasin and Sun, 2019). As a result, products have a short life cycle coupled with improper disposal, leading to challenges regarding the sustainability aspect of the fashion industry (Hu et al., 2018; Moretto et al., 2018).

Annual water consumption by the fashion industry amounts to 79 billion cubic meters and only around 20% of clothes are reused or recycled (Pal and Gander, 2018). Approximately 80% of textile waste goes to landfill and/or is incinerated (Barbero-Barrera et al., 2016, Hu et al., 2018; Nikolić et al., 2017). According to Hossain et al., (2018), in Bangladesh alone, for example, it is estimated that by 2021 the textile industry plants will produce approximately 2.91 million metric tons of textiles and around 349 million m^3 of wastewater due to traditional dyeing practices.

According to Dissanayake et al., (2018), Neto et al., (2019) and Shiwanthi et al.,(2018), the textile industry is one of the largest polluters on the planet, being associated with high water and energy use and generating chemical waste. It is therefore necessary to conduct research aimed at achieving sustainability in the textile production chain. One of the ways to improve practices in the textile industry in order to mitigate its negative environmental impacts and to align this activity with the sustainable development goals (SDGs) of the 2030 Agenda (UN) is to develop new materials and rethink existing materials (Neto et al., 2019; Ribeiro et al., 2015).

According to the United Nations, the 2030 Agenda was designed to protect human rights and equality and preserve the planet, balancing the three pillars of sustainability by addressing social, economic and environmental issues. To this end, 17 goals were developed with 169 targets. Sustainable development goal (SDG) 12 aims to ensure sustainable production and consumption standards, such as reducing waste generation, improving waste management capacity (capacity development) and rationalizing inefficient fossil fuel subsidies (PNUD, 2015).

According to Camere and Karana (2018), materials from renewable, recycled and reused resources are increasingly appearing as production alternatives since, due to economic growth and overconsumption, raw materials are becoming scarce and environmental degradation continues to increase (Bridgens et al., 2018). The reuse of materials can prevent or mitigate the negative impact of solid waste and its successful implementation requires a review of the life cycle of a product, seeking one or more opportunities for reuse based on the market (Fortuna and Diyamandoglu, 2017).

Therefore, as stated by Tonn et al. (2014), considering an industrial ecosystem, based on reuse, recycle and renew (IR 3), contributes to a reduced need for raw materials, leading to reductions in the levels of production and energy emissions. In addition, researchers working in the areas of biotechnology (Camere and Karana, 2018; Scarlat et al., 2015) and biofabrication have been exploring innovative production alternatives, such as the use of microorganisms to manufacture textiles for clothing, including footwear (Camere and Karana, 2018; Saraç et al., 2019).

In addition to the use of biotechnology for the manufacture of new textiles, it has been noted that research on electronic textiles, called smart fabrics, has been growing in recent years (Saraç et al., 2019). According to Busi et al. (2016) and Li et al. (2018), nanotechnology has a high technological potential for application in the textile sector, with the rising trend in the development of smart wearable electronic textiles, as that at personal health monitoring.

In this context, the section “Concepts of sustainability and the new possibilities for textile materials” reviews materials in the textile area and the emergence of new products and technologies together with their applicability in the clothing sector, in order to explain how these analyzed contents can contribute to the future of the textile industry. The discussion section presents an analysis of the concepts and materials presented and how they would be framed in relation to the sustainable development goals (SDGs), in order to ascertain whether the materials and technologies described meet the goals and targets of the 2030 Agenda established by the United Nations.

2. Methods

The procedure applied to produce this article was a bibliographic review of an analytical nature, based on academic databases accessed via the CAPES (Brazilian governmental agency) periodical literature portal. Bibliometric analysis was used to map information obtained from bibliographic records of documents stored in the databases. This analysis is applied to obtain information regarding the authors, title, year of publication, methodology, objectives, concepts, results and future implications of selected articles (Campbell et al., 2010).

The databases chosen for the searches to produce this article were: Scopus, Emerald Group Publishing, ProQuest and Science Direct. To carry out the literature review, 11 combinations of search terms were selected, including “clothing”, “new materials” and “textile industry” along with terms related to sustainability, such as “sustainable”, “eco”, “fashion sustainability”, “fashion sustainable” and "green". The combination of terms that led to the largest number of articles for this review was: “clothing” and “new materials” and “sustainable”. Figure 1 exemplifies the method used for the selection of research articles for this review.

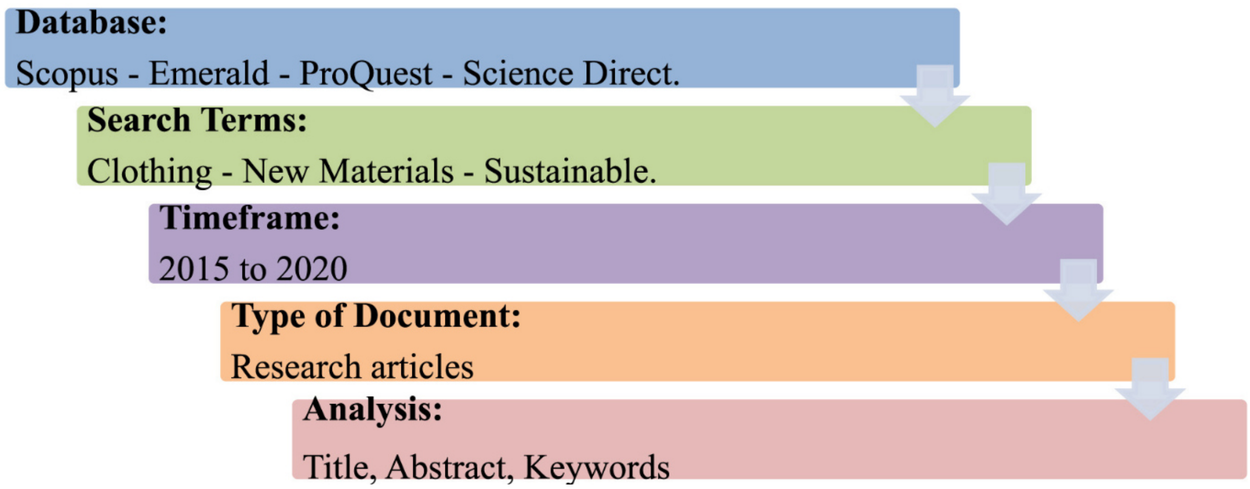

Fig. 1. Exemplification of the method used for the selection of research articles. **Source:** Authors.

As seen in Figure 1**,** It should be noted that the peer reviewed articles were selected by opting for a timeframe between 2015 and 2020, giving preference exclusively to research articles eliminating other categories of documents. Thus, inclusion and exclusion criteria were employed, which were the readings of the title, abstract and keywords, selecting only those articles that were compatible with the research theme of concepts of sustainability and the new textile materials.

3. Concepts of sustainability and the new possibilities for textile materials

This section describes a systematic review aimed at providing a broad overview of the scientific literature related to the concepts used to build a more sustainable production sector and the possibilities for the development of new textile materials aimed at achieving sustainability in the current scenario of the textile and fashion industry.

3.1 Upcycling

Globally, the increase in consumption in recent decades has raised numerous issues related to sustainability challenges, and a new approach to solid waste management is now required (Calvo et al., 2020; Dissanayake et al., 2018; Nagajyothi et al., 2019; Singh et al., 2019) In this context, the textile industry is a complex sector due to its intense participation in activities that cause major negative environmental impacts. These include the use of pesticides, large amounts of energy and water for the manufacture of products, chemicals used for dyeing that are subjected to inappropriate disposal (Luo et al., 2020; Nagajyothi et al., 2019; Pal and Gander, 2018; Rahbek et al., 2015; Singh et al., 2019; Tumpa et al., 2019).

Besides the environmental concerns, the fashion industry is directly related to issues such as the mistreatment of animals and exploitation of people through poor working conditions (Moretto et al., 2018; Rahbek et al., 2015). In Delhi, northern India, for instance, there are reports of female workers taking their preschool children to work, to avoid leaving them unsupervised, where they are exposed to noisy and dangerous fabric shredding machines as well as black dust and fumes (Norris, 2015). Finally, highlights the recent collapse of the Rana Plaza in Bangladesh, which killed more than 1,100 poor workers in precarious conditions (Rahbek et al., 2015).

Thus, to achieve a more sustainable consumption scenario, it is necessary to find solutions to reduce the negative environmental, social and economic impacts, not only through industrial changes but also by the consumer addressing behavioral and ethical issues (Bocken and Short, 2016; Freudenreich and Schaltegger, 2020; Ingulfsvann, 2020; Masoudipour et al., 2017; Clancy et al., 2015; Todeschini et al., 2017). According to Bocken and Short (2016) and Todeschini et al. (2020), the fundamental issue is the management and integration of relationships and interests of shareholders, employees, consumers, suppliers, community and other groups.

At the United Nations Rio +20 Conference on Sustainable Development, companies observed a new way of thinking about economics, through concepts such as "green economy", "green growth" and "sustainable growth" (Khmara and Kronenberg, 2018). Therefore, rethinking the life cycle of a product, which is associated with a circular economy (Bocken and Short, 2016; Ingulfsvann, 2020; Masoudipour et al., 2017; Shirvanimoghaddam et al., 2020; Singh et al., 2019), renovation, recycling and reuse of materials and products, is crucial in order to mitigate negative environmental, social and economic impacts (Barbero-Barrera et al., 2016; Bridgens et al., 2018; Cai and Choi, 2020; Singh et al., 2019; Kunamaneni et al., 2019; Todeschini et al., 2017; Todeschini et al., 2020).

The take-make-waste linear economic model, which has prevailed for decades in the production scenario of the global economy, has major negative impacts due to the continuous growth in production and the extraction of natural resources (Bridgens et al., 2018; Kuah and Wang, 2020; Kuzmina et al., 2019; Vermunt et al., 2019). To counter the linear economy approach, the circular economy has emerged, that replaces the end of the useful life of a product with concepts such as reducing, reusing, recycling, recovering materials in production processes and distribution logistics (Calvo et al., 2020; Kuah and Wang, 2020; Masoudipour et al., 2017; Ranta et al., 2019; Sandvik and Stubbs, 2017; Shirvanimoghaddam et al., 2020; Vermunt et al., 2019).

Circular economy (EC) is an economic system that represents a paradigm shift in the way society relates to nature and aims to prevent the depletion of resources (Ingulfsvann, 2020; Tate et al., 2019; Todeschini et al., 2017; Shirvanimoghaddam et al., 2020). It also offers opportunities for innovation in product design, services and business models and establishes basic elements for a resilient long-term system (Todeschini et al., 2017; Shirvanimoghaddam et al., 2020). According to Pal and Gander (2018), CE represents a transformation in the logic of seeing production and consumption as separate ends of a tube, by connecting them to form a loop in which resources circulate.

Business advantages in the face of the circular economy may include reduced reliance on external resources through the recovery of materials, improved company image by extending the life of a product and economic profit by exploiting the residual value of discarded materials (Calvo et al., 2020; Masoudipour et al., 2017; Ranta et al., 2019; Vermunt et al., 2019). It should be noted that despite the different possibilities for recycling products, the materials and objects were not designed to be reused or recycled, but were destined for disposal, according to the linear economic model (Bridgens et al., 2018).

The recycling process is directly linked to the social, economic and political context in which it occurs and can be considered an ancient activity in the history of mankind (Bridgens et al., 2018; Sung et al., 2019). During the Second World War, recycling was strongly encouraged due to the scarcity of products, for instance, the insufficient supply of textiles led to the reuse of limited fabrics and worn clothes to avoid waste (Bridgens et al., 2018).

In the 1990s, the term upcycling emerged, which means reusing discarded objects or materials to create a new material or product of higher quality (Bridgens et al., 2018; Calvo et al., 2020; Sung et al., 2019). The product reuse process makes a positive contribution to waste management, resource restoration and reducing the emission of greenhouse gases. It also avoids used products being sent to landfill, thus extending their life cycle (Fortuna and Diyamandoglu, 2016; Fortuna and Diyamandoglu, 2017). However, the reuse of materials is associated with some preconceptions regarding quality due to the stereotype of "appearing to be a homemade product" (Bridgens et al., 2018) or a "marginal activity" (Kuah and Wang, 2020; Sung et al., 2019).

It should be noted that the upcycling process requires adequate skills, equipment, environment and time, as the reused material may run the risk of "contaminated interaction", for example, the use of a pizza box to manufacture a lamp present hygiene problems, or result in unacceptable finishes (Bridgens et al., 2018). Therefore, design plays an important role in relation to the upcycling production process because, by giving importance to the aesthetics and functionality of a product, the designer is able to effectively promote the culture of reuse in consumers (Bridgens et al., 2018; Clancy et al., 2015; Wilkes et al., 2015).

In the case of textile waste management, the waste can be classified as post-industrial (garment cutting waste, excess fabric and rejects due to quality issues) or post-consumer (disposal after use) (Dissanayake et al., 2018). Regarding post-industrial waste, some researchers have noted the practice of reuse in other sectors, such as the production of thermal insulators (Dissanayake et al., 2018; Gounni et al., 2019), textile waste in concrete reinforcement (Merli et al., 2020) or decorative products, such as pillows (Sung et al., 2019). Therefore, the importance of interdisciplinarity is emphasized, that is, there needs to be a consistent dialogue between areas like design, engineering and material sciences, so that new products are developed with desired properties while promoting sustainability (Sauvé et al., 2016; Wilkes et al., 2015).

In relation to post-consumer waste, new products can be promoted through platforms such as reuse companies, collaborative consumption, sharing economy, material exchange, online platforms and direct exchange through sales, leases or donations of second-hand clothes (Fortuna and Diyamandoglu, 2017; Geissinger et al., 2019; Holtström et al., 2019; Lang and Joyner Armstrong, 2018). Houdini Sportswear, a Swedish brand, collects used polyester clothing and transforms it into new clothing items. It also offers repair services, clothing rental and second-hand sales (Holtström et al., 2019).

3.2 Living organisms and biotechnology

The inclusion of living biological systems in the field of nanotechnology and materials science has led to strategies and solutions being created through extensive research. This area of study arose from the understanding of many scholars that there is a need for the development of new sustainable materials that will not be a source of environmental pollution. Thus, simultaneously with these alternative materials, important new opportunities emerge in the sectors of biotechnology and biofabrication (Camere and Karana, 2018; Costa et al., 2019).

It can be argued that both biotechnology and biofabrication are related to the study and development of genetically-modified living organisms and are considered to be uniquely effective when compared to other material production technologies, since they do not require the removal of valuable and virgin materials from the earth's crust (Camere and Karana, 2018; Scarlat et al., 2015). Also, renewable resources can be used as food for the living organisms used to produce the material (Camere and Karana, 2018; Kamiński et al., 2020).

Researchers looking for materials that can be produced from renewable sources have taken an interest in polyhydroxyalkanoates (PHA), which are polyesters obtained through the fermentation of sugar and their biosynthesis is performed through bacterial cultures, resulting in considerable amounts of polymer (Kamiński et al., 2020; Roberts et al., 2019; Zhu et al., 2016). An interesting method of producing bacterial cellulose is the use of a symbiotic consortium of bacteria and yeast (SCOBY), widely known as Kombuchá (Kamiński et al., 2020). Acetic acid bacteria (particularly those of the *Gluconacetobacter* genus) produce cellulose and with the aid of biotechnology this can be manufactured on a large scale (Costa et al., 2019; García and Prieto, 2019; Roberts et al., 2019).

The cellulosic membrane formed by bacteria is biodegradable (García and Prieto, 2019; Kamiński et al., 2020; Zhu et al., 2016), and thus its application is consistent with the concept of ecologically-friendly products (Freudenreich and Schaltegger, 2020). This has notable differences in relation to synthetic polyester because, despite its durable and malleable properties, its degradation is slow, with a life cycle of 50 years, and its use in the fast fashion market is very common (Pedersen et al., 2019).

In addition, the manufacture of bacterial cellulose requires relatively small amounts of water and energy and thus the materials and products manufactured by the textile industry can be considered as an eco-friendly (Kamiński et al., 2020; Yim et al., 2017). Bacterial cellulose after its preparation and drying, visually resembles leather and has similar flexibility. This material can be cut, sewn and dyed to produce clothing and accessories, such as footwear (Camere and Karana, 2018; Costa et al., 2019; García and Prieto, 2019; Kamiński et al., 2020).

3.3 Smart textiles

The development of so-called smart fabrics that offer high performance, with properties such as flexibility, durability, wash resistance, comfortable feel and lightweight components (Bocchetta et al., 2020; Qi et al., 2020; Qiang et al., 2019; Saraç et al., 2019), is a new, complex and inevitable trend (Wang et al., 2018). Is increasingly gaining the attention of research groups, especially in the area of smart clothes and the human-machine relationship (Li et al., 2019), wearable interactions are not yet easily found in urban centers (Wang et al., 2018).

According to Miodownik (2015), the ability to add electronic and optical fibers into the weave of a fabric, without compromising structural properties, promises to allow the in situ monitoring of crack propagation and perhaps even the deployment of self-repairing mechanisms. The use of innovative structures to produce smart textiles can be considered advantageous in relation to conventional approaches. They can capture various types of information, such as data on body activity and biological signals, and can monitor, in real time, remote or short-range environmental data without disturbing the user. Thus, they offer potential for use in sportswear or clothing to address certain health issues (Kim and Ahn, 2017; Yan et al., 2019)

Most flexible devices are based on ultrathin substrates produced from plastic such as poly(ethylene terephthalate), poly(ethylene naphthalate) and polyimide, due to their ink compatibility, flexibility and mechanical/thermal stability(Bocchetta et al., 2020). With regard to wearable applications based on textiles, Gore-Tex fabric shows superior performance compared to other natural (cotton) and synthetic (polyester) fabrics, due to its breathable and waterproof properties(Bocchetta et al., 2020).

During physical activity or everyday actions, humans expend significant amounts of energy that is dispersed in the environment, so devices are being studied to store the body's biomechanical and thermal energy (Choi et al., 2017; Huang et al., 2015; Kim and Ahn, 2017; Liu et al., 2018; Proto et al, 2017; Sharma et al., 2015). A potential use of generators and nanogenerators(Li et al., 2020; Proto et al., 2017), including triboelectric nanogenerators (Huang et al., 2015; Yan et al., 2019), is their application in smart wearable devices, where they could collaborate in health monitoring, mobile communication, biomedical sensing, environmental protection and internal security (Proto et al., 2017; Smith and Hosseini, 2019; X. Li et al., 2020).

Choi et al. (2017) carried out studies on energy capture technologies, aimed at extracting biomechanical energy from movements such as foot tapping, joint movement and upper limb movement. This technology is classified based on the principle of kinetic energy collection (piezoelectric, triboelectric and electromagnetic energy) and allows the use of high-powered wearable biomechanical energy (WBEHs), generating energy at the watt level (Choi et al., 2017).

Organic phase-change materials (PCMs) have also been reported in the literature. They offer a higher density of energy storage compared with inorganic materials, which is related to their melting and freezing temperatures, and can be used in electronic devices, refrigerators, air conditioners, solar air/water heaters, textiles and automobiles, as well as in the food and space industries (Sharma et al., 2015).

Wearable thermoelectric generators (WTEGs) showed great potential for use in capturing thermal energy generated by the human body, as well as being good substitutes for batteries (Smith and Hosseini, 2019). Materials such as chalcogenides, skutterudites, silicides, SiGe, clathrates, oxides, zintls and half-Heuslers, are cited as effective. According to Smith and Hosseini (2019), there are several factors to consider when designing a WTEG to be used in a garment or accessory, since a small change in the thermodynamic configuration can cause changes in its function and its placement on the body must be carefully considered.

Flexible thermoelectric generators (TEGs) applying eutectic liquid metallic interconnections of gallium indium (EGaIn) wrapped in a high-thermal-conductivity (HTC) elastomer have also been reported. According to Sargolzaeiaval et al., 2020), the liquid metal lines are wrapped in an elastic silicone elastomer doped with graphene nano-platelets and EGaIn to increase the thermal conductivity. A HTC elastomer not only reduces the thermal resistance of the encapsulation layer, but also serves as a heat spreader (Sargolzaeiaval et al., 2020).

Triboelectric nanogenerators (TENGs) have emerged as efficient sources of energy to capture electrical energy from environmental mechanical movements, highlighting potential studies on hydrogel-based elastic nanofiber membranes (Qi et al., 2020). Triboelectric clothing nanogenerators (TENGs) can be built with two triboelectric layers using thermoplastic polymeric materials. They can be transformed into nanofibers by the extrusion method and then modified to obtain tribo-electronegative and tribo-electropositive layers and increase their electrical output performance (Yan et al., 2019). TENGs can also be implemented in the manufacture of insoles composed of electrophilic polyvinylidene fluoride (PVDF) piezoelectric nanofibers attached to a pair of conductive tissue electrodes that effectively collect energy during walking (Huang et al., 2015). According to Huang et al. (2015) and Yan et al. (2019), TENGs that capture energy have been successfully developed, due to the compatibility between these materials and clothing.

Researchers have highlighted issues regarding human thermal comfort in relation to the development of bioclimatic projects and simulators (Karakounos et al., 2018). The thermal balance of the human body is influenced by external thermal impact and the body's thermoregulation system. Thus, to consider thermal comfort it is essential to understand the relationship between the human body and its environment (Karakounos et al., 2018; Yong et al., 2018). In this regard, the substitute human sensor (SHS) establishes a connection between the surface of human skin and the surrounding environment (Yong et al., 2018). The SHS was manufactured using black plastic corrugated board made of polypropylene, which is considered to be of low cost and can be useful to investigate the heat envelope in an entire city environment, being able to directly determine the impact of thermal behavior on climate variables (Yong et al., 2018).

Elastic and flexible electronics, for example, able to sustain mechanical stress and large deformations, can be applied in wearable systems that adapt to the human body and maintain their function while moving, while also being compatible with the importance of comfort (Huang et al., 2015; Proto et al., 2017). In this context, biomimetic, recyclable and elastic materials along with those incorporating self-repairing conductors appear as potential alternatives to wearable electronics (K. Li et al., 2019).

Technologies used in the textile industry have been widely applied in the medical field. Wearable smart sensors offer an ideal platform for activity monitoring or health care applications because they facilitate non-invasive sampling and analysis of body fluids, such as sweat, saliva and tears, and provide personalized diagnosis and accurate therapy (Bocchetta et al., 2020). In the treatment of post-surgical hematoma and wounds related to burns, chronic venous ulceration and other diseases, medical tissues can be used to avoid putting put pressure on human tissues (Z. Liu et al., 2019; Sandt et al., 2018).

According to Sandt et al. (2018), a strategy applied to obtain sub-bandages involves the addition of elastic optomechanical fibers. These fibers have a multi-layer elastomeric photonic coating that surrounds an extruded elastic core filament. These colorimetric fiber sensors are suitable for medical textiles, sportswear and other smart technologies and are especially useful in cases associated with a high degree of repetitive strain (Sandt et al., 2018). Textile engineering, like weaving, is of particular interest for the development of stents, which pose a challenge related to their thickness and permeability. Researchers have described a bifurcated stent graft (BSG) functionalized with silk fibroin (SF) and heparin using tissue forming technology. BSGs were modeled based on seamless weaving technology and the surface was modified with SF-loaded heparin under steam/air treatment to improve its permeability (Z. Liu et al., 2019).

Other devices have also been created with the intention of storing energy, such as light-emitting organic diodes (OLEDs), transistors, integrated circuits, sensors and photodetectors. However, they require the use of batteries and these do not last long and need to be periodically recharged or changed (Qu et al., 2017; Smith and Hosseini, 2019). Therefore, in order to achieve ecological and social objectives, it is necessary to rethink and improve the batteries in order to enter new markets (Sick et al., 2018). A suggestion from researchers in China is Zn-air batteries, due to their good environmental interaction, safety and low cost (Qu et al., 2017) and systems for recycling and reusing electric bicycle batteries, for example (Wang et al., 2020).

Bocchetta et al. (2020) noted that lithium ion batteries are the preferable option in portable devices due to their ecological character and superiority to other energy sources in terms of electrochemical performance (3.7 V) and theoretical capacity (3860 mAh • g^{-1}), besides offering a long service life and optimum safety.. The Li-ion battery, with its ubiquitous presence in modern society, is probably the best-known energy, but many technologies with positive results in laboratory tests have not yet been commercialized (Tabor et al., 2018).

Materials such as graphene have been used in the design of smart textiles, that is, those which demonstrate excellent thermal, electrical, optical and mechanical properties. These have generated great interest in the textile industry allowing the design of environmentally-friendly, flexible and washable fabrics (Qiang et al., 2019; Ryu et al., 2017). It has been observed that graphene can be used as an electrode material to improve garment performance, demonstrating excellent skin compliance and health safety; however, graphene, as yet, cannot be used for the absorption and emission of light, and thus has limited effectiveness in photoactive layers (Kim and Ahn, 2017). According to Bocchetta et al. (2020), one disadvantage of the use of graphene nano sheets is the high attraction between the sheets. However, studies on 3D porous graphene have shown high electrical conductivity, good chemical stability and high open surface area and also can be used as a textile for wearable supercapacitors.

Another alternative highlighted in the database search is self-cleaning textiles, which appear to allow reductions in the consumption of water, energy and chemicals, such as detergents (Busi et al., 2016). Due to their photocatalytic layer of nanocrystalline TiO_2 (able to destroy organic material through solar irradiation), they are easy to wash and to maintain (Busi et al., 2016). In addition, the use of computer modelling and nanotechnological methods to address concerns regarding the material performance highlights a growing cooperation between diverse areas, such as materials design and engineering (Wilkes et al., 2015). According to Ren et al. (2020) nanofibers with different mass ratios between Ag–Ag2O and TiO2 were synthesized via electrospinning technique and pH-induced precipitation. The manufactured nanofibers have high photocatalytic performance and the As (III) conversion can retain 88.6% of the original activity after repeating four cycles, indicating the good recyclability of the PAN @ AT4 nanofibers and can be a promising material in the field of environmental remediation.

Solovyeva et al., (2020) reported experiments on self-cleaning textiles using cotton and their results were encouraging. The cotton was modified with TiO_2 using the $TiOSO_4$ and Ti(O-i-Pr)$_4$ impregnation method. It was observed that volatile organic compounds (VOCs) on the material surface were oxidized under UV irradiation. Also, with the addition of nanocrystalline TiO_2 the photoactivity of the material increased and DNA contaminants were decomposed under UV irradiation. Therefore, self-cleaning textiles can be used to produce personal protective clothing, such as suits, coats and overalls (Solovyeva et al., 2020).

4. Results

4.1 Database

On searching the terms “CLOTHING” and “SUSTAINABLE” and “NEW MATERIALS”, 122 results were returned in the Emerald database. The filters “content type article” and “year from 2015 until 2020” was applied, 38 articles remained. In the Proquest database, 427 results were obtained searching with the above terms. Subsequently, applying the “type article” and the “years 2015 à 2020” filter reduced this to 91 articles. In the Science Direct database, 1,120 results were found using the above terms. The research article filter and the years 2015 to 2020 filter left 184 articles. Finally, in the Scopus database, 122 documents were found using the above terms. The “doctype article” filter and applying the “pubyear 2015 to 2020” filter, 51 articles remained. Figure 2 shows a comparison between the search results.

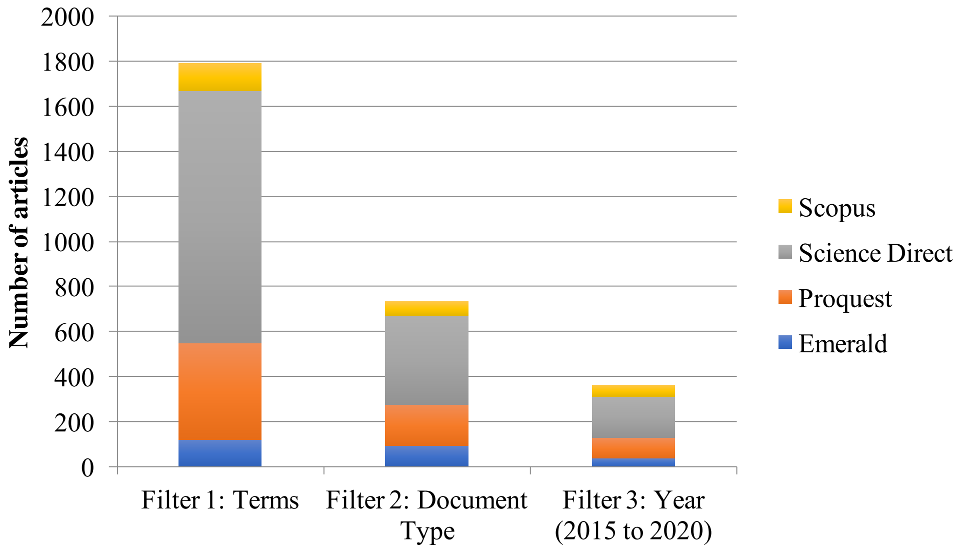

Fig. 2. Demonstrative graph of database search results and their filters. **Source:** Authors.

Figure 2 shows the highest occurrence of results in the Science Direct database using the terms *clothing* AND *sustainable* AND *“new materials”* and, even after applying the filters, Science Direct returned the largest number of articles. Finally, there were a total of 364 articles for the writing of the review article, highlighting the exclusion of 5 articles due to the repetition existing between the Science Direct, Proquest and Emerald databases.

4.2 Selection of articles

Step 1 involved reading the title, abstract and keywords of each article. The publications which were aligned with the search theme were then selected and 244 articles were excluded. Thus, a total of 120 articles were read in full. In step 2, a further 45 research articles that were not aligned with the proposal of this review were excluded, totaling 74 articles, were considered. Figure 3 shows the final process of the document selection for analysis to produce this review article.

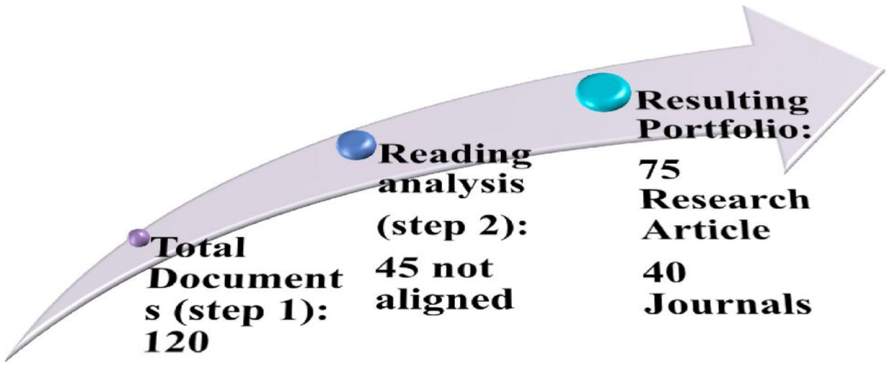

Fig. 3. Progression of the bibliometric analysis. **Source:** Authors.

Through the bibliometric process applied in this research, according to Figure 3, it was possible to select a set of articles that deal with the theme concepts for a more sustainable sector and of the emergence of new textile materials. After deleting the non-relevant articles, the Science Direct database remained the largest source of articles used to produce this review article. The profiles of the articles presented by Science Direct encompassed the three topics covered by this article; however, the largest number of articles found were related to “Upcycling”, followed by “Smart textiles”, and, lastly, microorganisms.

4.3 Classification of articles

The 75 articles analyzed for the writing of this article were classified according to the year of publication, impact factor of the publishing journal, the country where the article was produced and the contribution to the textile materials area. Table 1 provides data on the impact factor (IF) and the number of articles found in each journal. Impact factors were analyzed through the website of each journal and consulting the website Scimago Journal & Country Rank and the Journal Citation Reports.

Table 1. Table showing journals in which the relevant articles were published and their impact factor.

Journal	No. of articles	Impact factor
Journal of Cleaner Production	19	7.246
Nano Energy	6	16.002
Journal of Fashion Marketing and Management	4	1.706
Cellulose	3	4.210
Composites Part B - Engineering	3	7.635
Waste Management	3	5.448
Energies	2	2.702
Energy	2	6.082
Sustainable Production and Consumption	2	3.660
Applied Energy	1	8.848
Applied Thermal Engineering	1	4.725
ACS Sustainable Chemistry and Engineering	1	7.632
Business Horizons	1	3.444
Carbon	1	8.821
Colloids and Surfaces B – Biointerfaces	1	4.389
Chemical Engineering Journal	1	10.652
Critical Reviews in Environmental Science and Technology	1	8.302
Energy and Buildings	1	4.867
Energy Conversion and Management	1	8.208
Environmental Development	1	2.400
Futures	1	2.769
Geoforum	1	3.098
Industrial Marketing Management	1	4.695
International Journal of	1	1.662

Industrial Ergonomics		
International Journal of Environmental Research and Public Health	1	2.468
International Journal of Biological Macromolecules	1	5.162
Journal of Materials Science	1	3.553
Materials	1	3.057
Materials and Design	1	6.289
Measurement	1	3.364
MRS Bulletin	1	5.610
MRS Communications	1	1.997
Microbial Biotechnology	1	5.328
Nanoscale	1	6.895
Nature	1	42.778
Nature Reviews Materials	1	71.189
Process Biochemistry	1	2.952
Resources Conservation and Recycling	1	8.086
Science of the Total Environment	1	6.551
Trends in Biotechnology	1	14.343
Total	**75**	

Source: Authors.

Table 1 shows that 75 articles were identified in 40 journals, of which have an impact factor of >1.000.The journal with the largest number of articles was Journal of Cleaner Production with 19. It should be noted that the Journal of Cleaner Production contributed mainly to the subject "Concepts for a more sustainable sector", in line with the theme addressed by the magazines. Table 2 (see Appendix) shows the list of authors, year of publication, title of the article and the contribution corresponding to each type of theme mentioned in the theoretical framework and highlights the important observations reported in the articles published between 2015 and 2020.

Considering the 75 articles used for this review article, the keywords that had the highest occurrence were: "Circular economy", "Sustainability" and "Innovation", as seen in Figure 4.

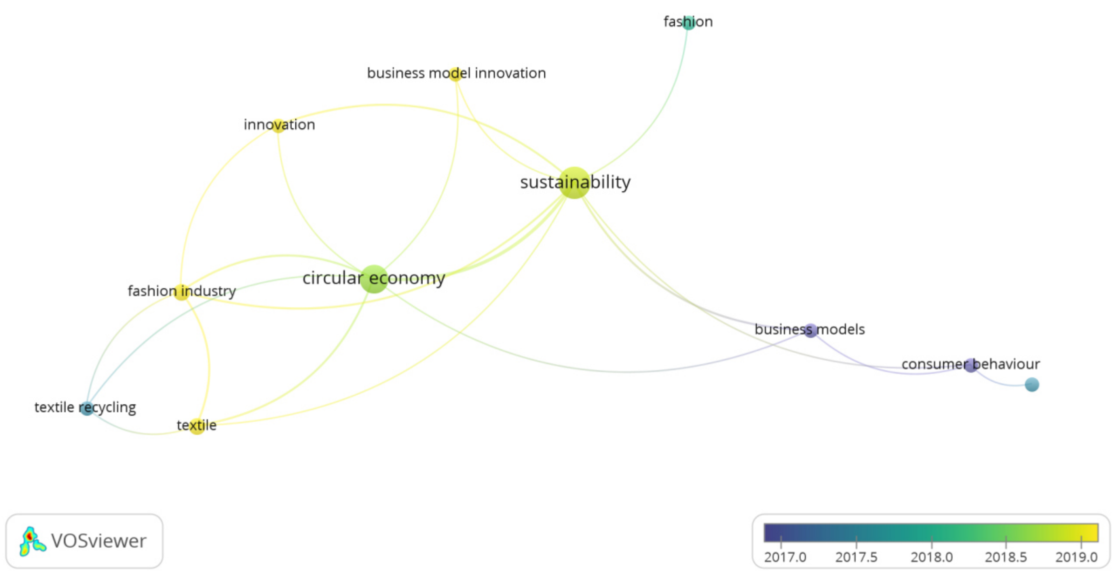

Fig. 4. Keywords with greatest occurrence in the 75 papers selected. **Source:** Authors.

It can be observed in Figure 4 that "circular economy" was a focus of discussions in 2018, mainly in the first semester. Subsequently, "sustainability" became a major theme in the transition between 2018 and 2019 and from the first half of 2019 onwards, discussions on "innovations" and "business model innovation" gained importance. Figure 5 shows the number of publications for each topic per year.

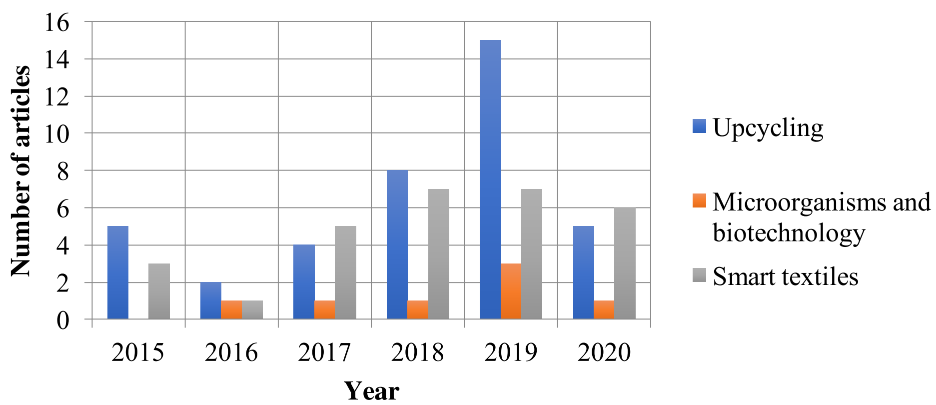

Fig. 5. Publications between 2015 and 2020 on "upcycling", "microorganisms and biotechnology" and "smart textiles".
Source: The authors.

It can be observed in Figure 5 that the three subjects covered, that is, "Upcycling", "Microorganisms and biotechnology" and "Smart textiles", obtained the largest number of publications in 2019. Thus, academic discussions on this subject are relatively recent and are consistent with the aspects shown in Figure 4 on the terms "sustainability" and "innovations", which gained greater focus in 2019. Lastly, it should be noted that articles related to "Upcycling" and "Smart Textiles" accounted for the largest number found. Regarding the use of microorganisms, despite the range of innovative research themes in this area, few studies were identified applying the terms used in this review. Figure 6 shows an analysis of the number of published articles and the country of origin of the researchers.

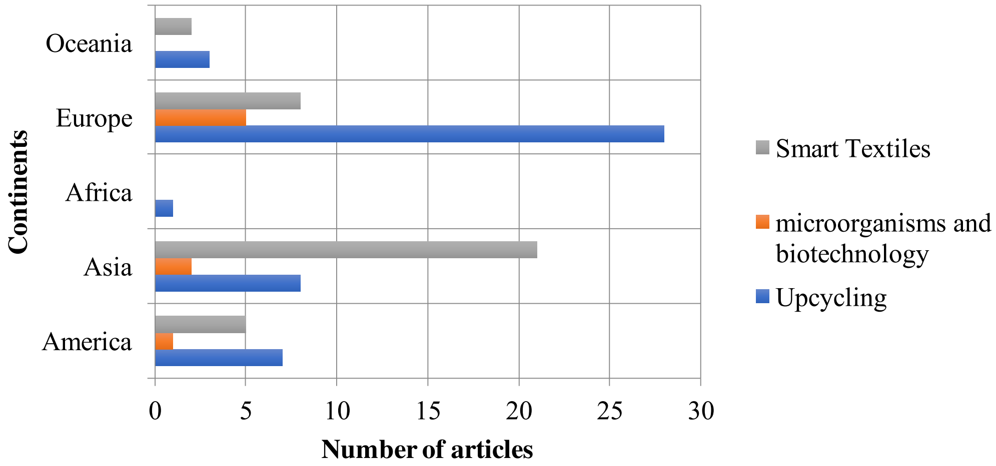

Fig. 6. Number of publications on “smart textiles”, “microorganisms and biotechnology” and upcycling by location.
Source: Authors.

As seen in Figure 6, the largest number of publications on the subject of “Upcycling” and “Microorganisms and biotechnology” were from Europe (notably the United Kingdom). However, regarding the topic “smart textiles”, the largest number of publications was from the Asian continent (mainly China). These data indicate the importance of the economic, social and environmental reality of the locations where the articles on sustainability and the emergence of new textile materials were produced. It is well known that both the United Kingdom and China invest annually in research on both sustainability and innovative and cutting-edge technologies.

5. Discussion

In the review of the articles on the subject of the new possibilities of textile materials, a survey was conducted on the materials and technologies cited by the authors of the articles and their relation with the 17 sustainable development goals (SDGs) and their 169 targets established in the United Nations document titled 2030 Agenda. This resulted in Figures 2, 3 and 4 being created to associate the concepts and materials and technologies with the SDGs. These are followed by a discussion of the figures.

Figure 7 represents the concepts addressed on sustainability in the theoretical framework on “Upcycling”.

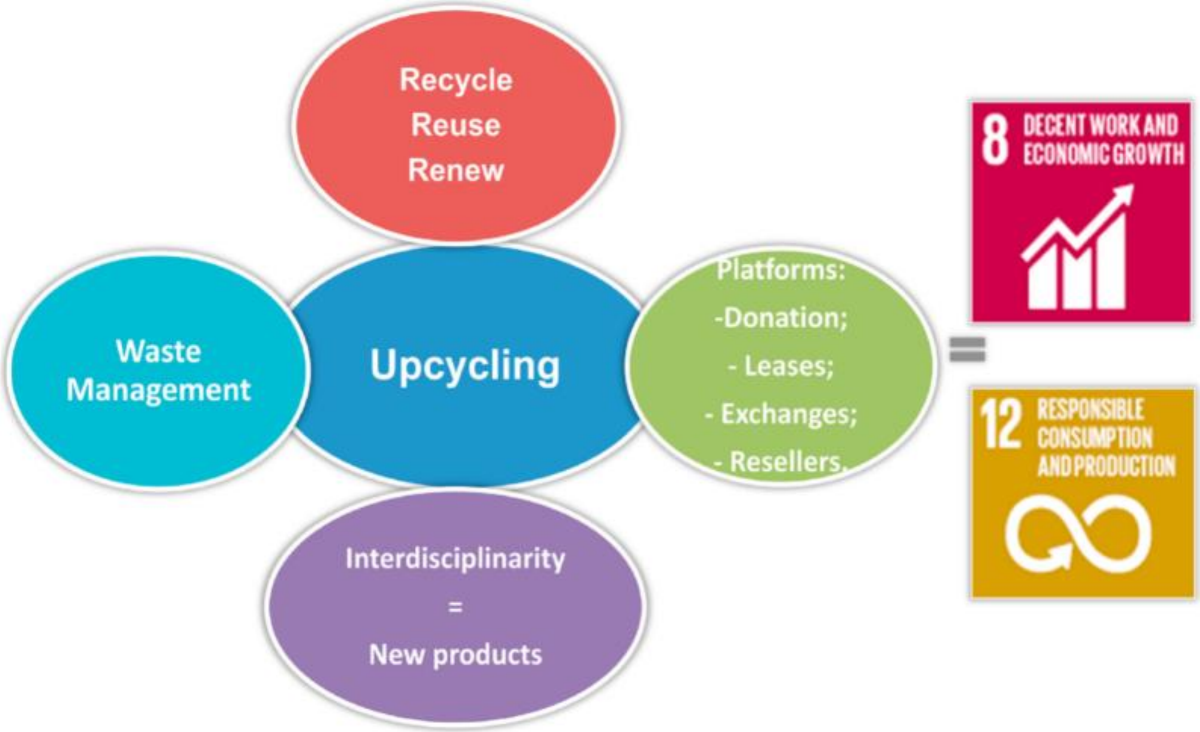

Fig. 7. Upcycling and their relationship with the SDGs of 2030 Agenda (UN). **Source:** Authors.

As mentioned in the theoretical framework, the textile industry is not only associated with environmental degradation but also social and economic issues. SDG 8 (Decent work and economic growth), which promotes sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all (UNDP, 2015), addresses the issue of the exploitation of people in an unhealthy work environment (Moretto et al., 2018; Norris, 2015; Rahbek et al., 2015). Some companies and organizations are aware of the need for social, environmental and economic changes and improvements (Fortuna and Diyamandoglu, 2016; Holtström et al., 2019).

However, goals like 8.7, that is, to take measures to eradicate forced labor, end slavery and human trafficking, including child labor (UNDP, 2015), and goal 8.8, to protect labor rights and promote safe work environments (UNDP, 2015), will only be achieved with further government control over brands and companies. Lastly, we highlight goal 8.4, which aims to improve, in a progressive manner, efficiency with regard to the consumption and production of global resources and to dissociate economic growth from environmental degradation (PNUD, 2015). This goal encourages the commitment of professionals who strive for economic growth through more sustainable means, consistent with the circular economy approach.(Ingulfsvann, 2020; Pal and Gander, 2018; Tate et al., 2019; Todeschini et al., 2017; Shirvanimoghaddam et al., 2020).

SDG 12 (Responsible consumption and production) has several interesting goals related to the sustainability of industry, brands and consumers (Cai and Choi, 2020). Goal 12.4, that is, to increase the environmentally-sound handling of chemicals and all wastes by 2020 and significantly reduce their release into air, water and soil (UNDP, 2015), needs greater effort, despite changes in the production processes having been implemented in some industries (Luo et al., 2020; Pal and Gander, 2018; Singh et al., 2019).

Goal 12.5 states that by 2030 the aim is to substantially reduce the generation of waste through prevention, reduction, recycling and reuse (UNDP, 2015) and several publications demonstrate the effectiveness of waste management and successful approaches to upcycling (Barbero-barrera et al., 2016; Bridgens et al., 2018; Dissanayake et al., 2018; N. Singh et al., 2017; Singh et al., 2019); Todeschini et al., 2020). Likewise, with regard to goal 12.6, which encourages companies, especially large and transnational companies, to adopt sustainable practices and integrate sustainability information in their reporting cycle (UNDP, 2015), some brands and organizations have become concerned with improving their social, environmental and economic practices and conduct (Bocken and Short, 2016; Ingulfsvann, 2020; Khmara and Kronenberg, 2018; Merli et al., 2020; Masoudipour et al., 2017; Singh et al., 2019).

Lastly, the mobilization by NGOs, companies and industries will not be sufficient if the awareness of the end consumers is not enhanced and their attitude towards the current issues surrounding a more sustainable life improved (Freudenreich and Schaltegger, 2020; Ingulfsvann, 2020; Masoudipour et al., 2017; Todeschini, et al., 2017). In this context, goal 12.8 states that the aim is to ensure that by 2030 people everywhere will have the relevant information and awareness regarding the importance of sustainable development and achieving lifestyles that are in harmony with nature (UNDP, 2015).

The Figure 8, associates the materials, technologies, benefits and SDGs with reference to the theoretical framework of microorganisms, biotechnology and biofabrication.

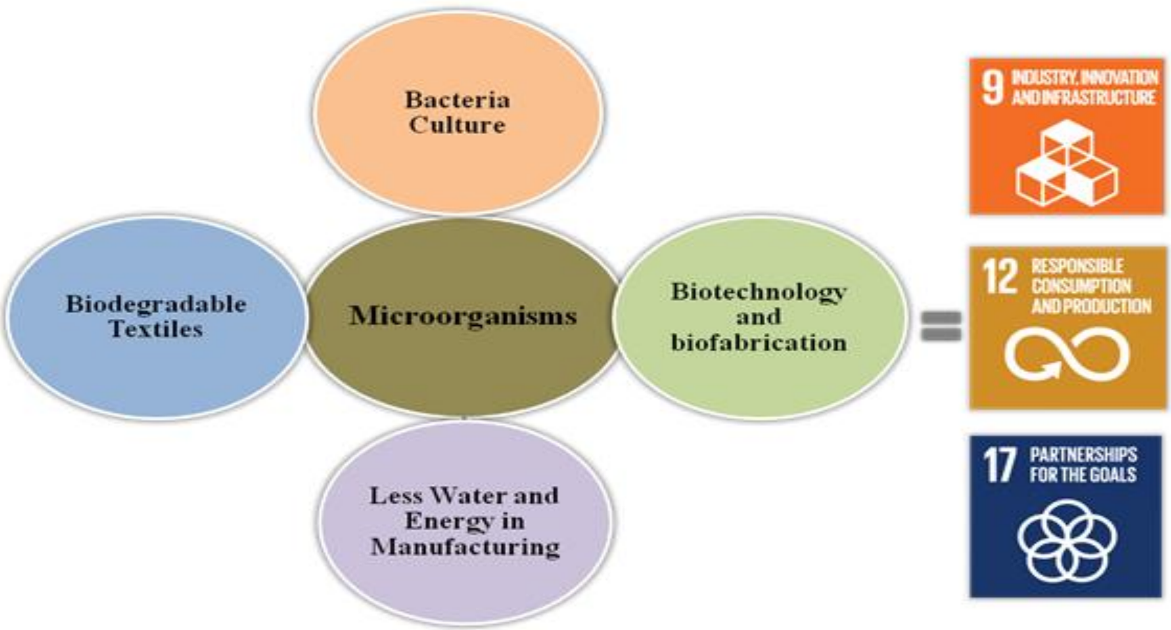

Fig. 8. Relation between materials obtained from microorganisms along with the associated technologies and SDG 9, 12 and 17. **Source:** Authors.

Biotechnology, biofabrication and the use of microorganisms to produce biodegradable clothing have been found to be consistent with cleaner technology, dispensing with the need to exploit natural resources, such as oil (Camere and Karana, 2018; Costa et al., 2019; García and Prieto, 2019), and requiring less water and energy for the production process (Yim et al., 2017). Based on the analysis, there is a relationship between this production process and SDG 9 (industry, innovation and infrastructure), which aims to build resilient infrastructures, promote inclusive and sustainable industrialization and foster innovation (PNUD, 2015). In particular, this is relevant to target 9.4, which seeks to strengthen the modernization of infrastructure and the rehabilitation of industries to make them sustainable, with increased resource efficiency and greater adoption of clean and environmentally sound industrial technologies and processes (PNUD, 2015).

Also included is SDG 12 (responsible consumption and production), which aims to ensure sustainable production and consumption standards (PNUD, 2015), especially target 12.5, which aims to substantially reduce waste generation through prevention, reduction, recycling and reuse and target 12.c, seeking incentives to rationalize inefficient fossil fuel subsidies and minimize negative environmental impacts (PNUD, 2015). Finally, SDG 17 (partnerships and means of implementation) promotes the strengthening of means for the implementation and revitalization of global partnerships for sustainable development, notably target 17.7, which seeks to promote development, the transfer, dissemination and diffusion of environmentally sound technologies to developing countries, leading to the possibility that research may be carried out in other developing locations, contributing to the propagation of measures that provide sustainable conditions (PNUD, 2015).

With regard to smart textiles, Figure 9 shows the main fields of research and their relationship with the SDGs.

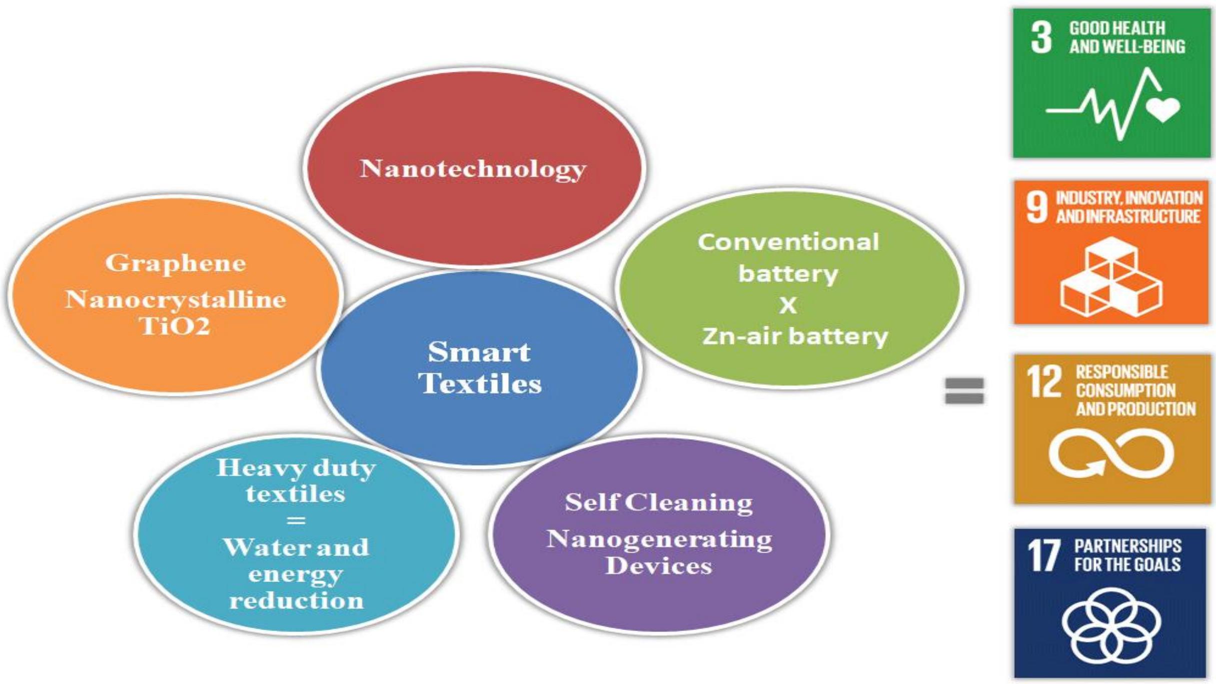

Fig. 9. Smart textiles and their relationship with the SDGs of 2030 Agenda (UN). **Source:** Authors.

It has been established that smart textiles are associated with SDG 3, because the goal is to achieve health and well-being, ensuring a healthy life and promoting well-being for all at all ages (PNUD, 2015). The articles analyzed focus on developing these materials so that the vital signs of the fabric wearer can be monitored through sensors (Proto et al., 2017; Huang et al., 2015; Kim and Ahn, 2017). As noted in the theoretical section, textile technologies have been widely applied in the medical field for activity monitoring or health care applications (Bocchetta et al., 2020; Z. Liu et al., 2019; Sandt et al., 2018).

Issues regarding thermal comfort also encompass health concerns. Due to the high rate of urbanization and the expansion of built environments, heat islands are formed. However, in addition to improving the state of human comfort, this directly influences our energy consumption efficiency, which is an issue strongly linked to sustainable development (Karakounos et al., 2018; Yong et al. 2018). Also, self-cleaning textiles (Busi et al., 2016) can aid in maintaining good hygiene levels.

A relationship with SDG 9 (industry, innovation and infrastructure) was also observed, since microorganisms (Camere and Karana, 2018) can promote the construction of resilient infrastructures, promote inclusive and sustainable industrialization and foster innovation (PNUD, 2015), using smart textile technologies that are concerned with water quality and reductions in water and energy use through nanotechnology (Busi et al., 2016), citing as an example the capture of energy by movement of human movements (Choi et al., 2017; Huang et al., 2015; Smith and Hosseini, 2019).

Also included is SDG 12 (responsible consumption and production), aimed at ensuring sustainable production and consumption standards, in particular, target 12.2, which aims to achieve sustainable management and efficient use of natural resources (PNUD, 2015) with the good use of elements, such as graphene (Qiang et al., 2019; Kim and Ahn, 2017) and nanocrystalline TiO_2 (Busi et al., 2016). Regarding the use of batteries, the authors make it clear that this remains an issue to be addressed, rethinking new battery formats, as mentioned by the Zn-air battery (Qu et al., 2017) and lithium ion batteries due to its ecological character (Bocchetta et al., 2020) because conventional batteries are still environmentally aggressive (Qu et al., 2017; Sick et al., 2018).

Finally, SDG 17 (partnerships and means of implementation) can be included, as it aims to strengthen the means of implementation and revitalize the global partnership for sustainable development (PNUD, 2015). This is related to biomaterials and their biotechnologies and developing countries need to be a part of this and obtain knowledge on the technologies that aim to improve the quality of life and that are concerned with the environment.

Table 3 shows the interaction between the types of materials discussed and the sustainable development goals (SDGs), in order to facilitate the visualization of their relationship.

Table 3. Relationship between textile groups and the SDGs of the 2030 Agenda (UN).

Textile materials group	SDG 3: Good health and well being	SDG 4: Decent work and economic growth	SDG 9: Industry innovation and infrastructure	SDG 12: Responsible consumption and production	SDG 17: Partnerships for the goals
Upcycling		✓		✓	
Living Organisms and Biotechnology			✓	✓	✓
Smart Textiles	✓		✓	✓	✓

Source: Authors.

It can be noted that the three textile groups relate to SDG 12 (Responsible Consumption and Production), thus realizing the relevance of the most sustainable forms of production and consumption. Highlighting not only the textile industry, but for all sectors of the economy.

6. Conclusions

The manufacture of textiles has long been part of human activity; however, with the development of the sector the levels of waste have been increasing along with water consumption, further degrading the environment and leading to the textile industry being one of the world's largest polluters. In this regard, research is emerging to show that there is a possibility for the use of new sustainable materials to produce clothing for the common consumer and for professionals in various areas.

As the garment industry and academic research make great strides in integrating various elements for the development of new materials, technological challenges arise in parallel, requiring new solutions. Therefore, new materials should be selected taking into account not only their mechanical, physical and chemical characteristics or the added financial value, but environmental issues and their life cycle, analyzing in particular the amount of waste that will be discarded in the production phases (Ribeiro et al., 2015)Therefore, although there are strategies aimed at achieving sustainability, such as upcycling, and companies concerned with waste management, it is important to rethink a generation of products that do not produce waste or that considerably decrease it.

In this context, relating new materials to the sustainable development goals of 2030 Agenda (United Nations) is necessary due to the important issues presenting challenges at the global level, in relation to the economic, social and environmental pillars of sustainability. Therefore, the need for more research in the textile area is evident, since the sector represents one of the largest productive and economic chains in the world and its practices need to be rethought in favor of sustainability.

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Appendix

Table 2. Organization of articles by year, title, authors, list of textile materials and country where research was carried out.

Year of publication	Title	Authors	Concepts and new materials	Countries
2015	Human body as fashion space: fashion accessories, design and woven fabrics	Ribeiro et al.	Upcycling	Portugal
2015	Sustainability innovators and anchor draggers: a global expert study on sustainable fashion	Pedersen et al.	Upcycling	Denmark
2015	Materials for the 21st century: What will we dream up next?	Mark Miodownik	Smart Textiles	United Kingdom
2015	The limits of ethicality in international markets: Imported second-hand clothing in India	Norris	Upcycling	United Kingdom
2015	Design tools for interdisciplinary translation of material experiences	Wilkes et al.	Upcycling	United Kingdom and Thailand
2015	Ecolabels as drivers of clothing design	Clancy et al.	Upcycling	Sweden
2015	Human walking-driven wearable all-fiber triboelectric nanogenerator containing electrospun polyvinylidene fluoride piezoelectric nanofibers	Huang et al	Smart Textiles	China
2015	Developments in organic solid–liquid phase change materials and their applications in thermal energy storage	Sharma et al.	Smart Textiles	Malaysia and India
2016	Sustainable polymers from renewable resources	Zhu et al.	Microorganisms and biotechnology	United Kingdom
2016	A novel method for material characterization of reusable products	Fortuna et al.	Upcycling	United States
2016	Textile fibre waste bindered with natural hydraulic lime	Barbero-Barrera et al.	Upcycling	Spain
2016	Environmental sustainability evaluation of innovative self-cleaning textiles	Busi et al.	Smart Textiles	Italy
2017	Wearable Biomechanical Energy Harvesting Technologies	Choi et al.	Smart Textiles	Korea

2017	Nanogenerators for Human Body Energy Harvesting	Proto et al.	Smart Textiles	Italy and Czech Republic
2017	Structure and properties of graphene oxide/cellulose hybrid fibers via divalent metal ions treatment	Ryu et al.	Smart Textiles	Korea, South Korea and Canada
2017	Optimization of greenhouse gas emissions in second-hand consumer product recovery through reuse platforms	Fortuna et al.	Upcycling	United States
2017	Innovative and sustainable business models in the fashion industry: Entrepreneurial drivers, opportunities, and challenges	Todeschini et al.	Upcycling	Brazil and Italy
2017	A novel closed-loop supply chain based on the quality of returned products	Masoudipour et al.	Upcycling	Iran
2017	Recycling of plastic solid waste: A state of art review and future applications	Singh et al.	Upcycling	India, United States and Italy
2017	Graphene for flexible and wearable device applications	Kim and Ahn	Smart Textiles	Republic of Korea
2017	Electrochemical approach to prepare integrated air electrodes for highly stretchable zinc-air battery array with tunable output voltage and current for wearable electronics	Qu et al.	Smart Textiles	China
2017	Production and characterization of bacterial cellulose fabrics by nitrogen sources of tea and carbon sources of sugar	Yim et al.	Microorganisms and biotechnology	South Korea
2018	Accelerating the discovery of materials for clean energy in the era of smart automation	Tabor et al.	Smart Textiles	United States
2018	Fabricating materials from living organisms: An emerging design practice	Camere et al.	Microorganisms and biotechnology	Netherlands
2018	Developing a compression moulded thermal insulation panel using postindustrial textile waste	Dissanayake et al.	Upcycling	Sri Lanka
2018	Modelling environmental value: An examination of sustainable business models within the fashion industry	Pal and Gander	Upcycling	Sweden and United Kingdom
2018	Creative upcycling: Reconnecting people, materials and place through making	Bridgens et al.	Upcycling	United Kingdom
2018	Designing a roadmap towards a sustainable supply chain: A focus on the fashion industry	Moretto et al.	Upcycling	Italy

2018	Collaborative consumption: The influence of fashion leadership, need for uniqueness, and materialism on female consumers' adoption of clothing renting and swapping	Lang and Armstrong	Upcycling	United States
2018	A requirement-scenario-experience framework for evaluating wearable and fashionable design: Presenting underlying factors of user loss	Wang et al.	Smart Textiles	China
2018	Surrogate human sensor for human skin surface temperature measurement in evaluating the impacts of thermal behaviour at outdoor environment	Lee et al.	Smart Textiles	Malaysia and Japan
2018	The influence of bioclimatic urban redevelopment on outdoor thermal comfort	Karakounos et al.	Smart Textiles	Greece
2018	Start-ups as technology life cycle indicator for the early stage of application: An analysis of the battery value chain	Sick et al.	Smart Textiles	Australia and Germany
2018	Evaluation of the environmental and economic performances of three selected textile factories in Biyagama export processing zosne	Shiwanthi et al.	Upcycling	Sri Lanka
2018	Thermal and economic evaluation of new insulation materials for building envelope based on textile waste	Gounni et al.	Upcycling	Morocco and France
2018	Triboelectric Charge Density of Porous and Deformable Fabrics Made from Polymer Fibers	Liu et al.	Smart Textiles	China
2018	Degrowth in business: An oxymoron or a viable business model for sustainability?	Khmara et al.	Upcycling	Poland
2018	Stretchable Optomechanical Fiber Sensors for Pressure Determination in Compressive Medical Textiles	Sandt et al.	Smart Textiles	United States and Japan
2019	Circular fashion supply chain through textile-to-textile recycling	Sandvik et al.	Upcycling	Australia
2019	From singular to plural: exploring organisational complexities and circular business model design	Pedersen et al.	Upcycling	Denmark and United Kingdom
2019	Business model development for sustainable apparel consumption The case of Houdini Sportswear	Holtström et al.	Upcycling	Sweden
2019	Bacterial cellulose as a potential bioleather substitute for the footwear industry	García et al.	Microorganisms and biotechnology	Spain
2019	Developing Interventions for Scaling Up UK Upcycling	Sung et al.	Upcycling	United Kingdom

2019	Microencapsulated organic coconut oil as a natural phase change material for thermo-regulating cellulosic fabrics	Saraç et al.	Smart Textiles	Turkey
2019	Synthetic biology for fibers, adhesives, and active camouflage materials in protection and aerospace	Roberts et al.	Microorganisms and biotechnology	United Kingdom
2019	Dyeing of bacterial cellulose films using plant-based natural dyes	Costa et al.	Microorganisms and biotechnology	Brazil
2019	Future scenarios for fast-moving consumer goods in a circular economy	Kuzmina et al.	Upcycling	United Kingdom
2019	How B2B suppliers articulate customer value propositions in the circular economy: Four innovation-driven value creation logics	Ranta et al.	Upcycling	Finland and Australia
2019	Seeing the forest and not the trees: Learning from nature's circular economy	Tate et al.	Upcycling	United States, Denmark and Germany
2019	How sustainable is the sharing economy? On the sustainability connotations of sharing economy platforms	Geissinger et al.	Upcycling	Sweden
2019	Exploring barriers to implementing different circular business models	Vermunt et al.	Upcycling	Netherlands
2019	Evaluating approaches to resource management in consumer product sectors - An overview of global practices	Singh et al.	Upcycling	United Kingdom and Sweden
2019	What does the brand tell us? e Sustainability and responsibility in a circular perspective	Ingulfsvann	Upcycling	Norway
2019	Circular economy and consumer acceptance: An exploratory study in East and Southeast Asia	Kuah and Wang	Upcycling	Singapore
2019	Developing sufficiency-oriented offerings for clothing users: Business approaches to support consumption reduction	Freudenreich and Schaltegger	Upcycling	Germany
2019	Promoting reuse behaviour: Challenges and strategies for repeat purchase, low-involvement products	Kunamaneni et al.	Upcycling	United Kingdom
2019	A heparin-functionalized woven stent graft for endovascular exclusion	Liu et al.	Smart Textiles	China ans United Kingdom
2019	Biomimetic, recyclable, highly stretchable and self-healing conductors enabled by dual reversible bonds	Li et al.	Smart Textiles	China
2019	Post-fabrication modifications of thermoplastic polymeric nanofiber membranes with electroactive polymers for triboelectric nanogenerators	Yan et al.	Smart Textiles	China

2019	Green synthesis: Photocatalytic degradation of textile dyes using metal and metal oxide nanoparticles-latest trends and advancements	Nagajyothi et al.	Smart Textiles	Republic of Korea
2019	Environmental Prospects for Mixed Textile Recycling in Sweden	Peters et al	Upcycling	Sweden
2019	Wearable solid-state capacitors based on two-dimensional material all-textile heterostructures	Qiang et al.	Smart Textiles	China and United Kingdom
2019	Human Body Micro-power plant	Smith and Hosseini	Smart Textiles	United States
2020	Addressing Sustainable Social Change for All: Upcycled-Based Social Creative Businesses for the Transformation of Socio-Technical Regimes	calvo et al.	Upcycling	Spain
2020	Soft Materials for Wearable/Flexible Electrochemical Energy Conversion, Storage, and Biosensor Devices	Bocchetta et al.	Smart Textiles	Italy, Spain, India and Korea
2020	Death by waste: Fashion and textile circular economy case	Shirvanimoghaddam et al.	Upcycling	Australia and Singapore
2020	Sustainable indigo dyeing and improvement of rubbing fastness of dyed cotton fiber using different fixing agents for obtaining ecofriendly cowboy products	Luo et al.	Upcycling	China
2020	Collaboration practices in the fashion industry: Environmentally sustainable innovations in the value chain	Todeschini et al.	Upcycling	Brazil
2020	Recycled fibers in reinforced concrete: A systematic literature review	Merli et al.	Upcycling	Italy
2020	Integrating offline logistics and online system to recycle e-bicycle battery in China	Wang et al.	Smart Textiles	China and Australia
2020	Hydrogel-based hierarchically wrinkled stretchable nanofibrous membrane for high performance wearable triboelectric nanogenerator	Qi et al.	Smart Textiles	China e United States
2020	Monitoring and forecasting the development trends of nanogenerator technology using citation analysis and text mining	Li et al.	Smart Textiles	China
2020	Hydrogel bacterial cellulose: a path to improved materials for new eco-friendly textiles	Kaminiski et al.	Microorganisms and biotechnology	Poland
2020	Facile preparation of PAN@Ag–Ag2O/TiO2 nanofibers with enhanced photocatalytic activity and reusability toward oxidation of As(III)	Ren et al.	Smart Textiles	China

2020	Flexible thermoelectric generators for body heat harvesting – Enhanced device performance using high thermal conductivity elastomer encapsulation on liquid metal interconnects	Sargolzaeiaval et al.	Smart Textiles	United States

Source: Authors.

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CAPÍTULO 3

CIRCULAR ECONOMY FOR FASHION INDUSTRY: USE OF WASTE FROM THE FOOD INDUSTRY FOR THE PRODUCTION OF BIOTEXTILES

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Abstract: In the context of current environmental, social and economic issues, it is imperative to perform more in-depth studies on waste management and the life cycle of a product. Thus, the concept of circular economy, aimed at transforming traditional patterns of production and economic growth, is extremely important. One way to mitigate negative environmental impacts that is consistent with a circular economic system is to encourage interdisciplinarity between sectors, that is, one production sector can provide a function for waste from another. In this context, this article gathers scientific information on two sectors relevant to the global economy (textiles and food), with the aim of reusing waste from the food industry to manufacture a new textile product with added value. Specifically, the focus is on the use of bacterial cellulose from the probiotic drinks from Kombuchá, for the manufacture of biotextiles for fashion industry. A discussion is also presented, relating the circular economy concept to the UN Sustainable Development Goals, in order to understand which goals can be achieved with this approach.

Keywords: Circular Economy. Textile waste. Food waste. Biotextiles. Eco-fashion. SDGs.

Graphical Abstract

1. Introduction

In order to achieve a more sustainable society, it is important to conduct in-depth studies and research on issues such as waste management, product life cycle assessment (LCA) and circular economy (Mak et al., 2020; Viau et al., 2020; Wang et al., 2020). The extremely high levels of consumption that have been reached are directly associated with the purchasing power of a region and increase in population, and as the demand for products increases so do the levels of waste generated (Yıldız-Geyhan et al., 2019; Ravindran and Jaiswal, 2016; Stanchev et al., 2017).

Minimizing the use of materials and rethinking the raw materials employed for manufacturing in order to favor recycling presents challenges for designers. Camere and Karana (2018) noted the different types of alternative materials available: 1) Materials from renewable resources, with an acquisition rate below the growth rate; 2) Recycled materials, obtained from reprocessing resources that have already been incorporated into products; and 3) Revived materials, that is, those comprised of resources discarded from industrial production flows, such as agricultural waste.

One of the most notable types of waste, globally, is that generated by the food industry (Kibler et al., 2018; Ravindran and Jaiswal, 2016). It has been estimated that in the countries of Latin America and the Caribbean, organic waste accounts for the highest proportion of the waste generated (approximately 50%), although it receives very little management (UN, 2019). However, studies have verified that food waste is a precious bio-resource that can be used to obtain various useful chemicals, materials and fuels (Garcia-garcia et al., 2019).

Along with the food industry, the fashion industry has problems associated with the generation of waste. According to Franco (2017), the textile and clothing industry is an essential consumer goods manufacturing, however, it is also considered one of the most polluting and socially challenged industries due to four specific issues: 1) non-recoverable materials and it´s blends; 2) abundant use of water; 3) use of dangerous chemicals; and 4) poor human rights record.

The textile manufacturing process is characterized by a high consumption of natural resources, fuel and a variety of chemicals, involving a long process from spinning, bleaching to dyeing, generating a significant pollutant load to the environment (Parisi et al., 2015). Due to the severe negative impacts related to the textile industry one of the main concerns is to achieve sustainability in the textile chain through cleaner production, thus mitigating environmental problems (Neto et al., 2019).

Bacterial cellulose (BC) is an ecologically-friendly, renewable and organic raw material (Sederavičiūtė et al., 2019; Shi et al., 2014) that is safe for contact with the human body, inspiring many design projects and drawing the attention of the fashion industry (Sederavičiūtė et al., 2019). BC or nanocellulose has unique characteristics, such as a high degree of crystallinity, tensile strength, thermal stability, biodegradability, elasticity and porosity (Machado, Meneguin, et al., 2018).

Unlike cellulose extracted from plant cell walls, BC consists of pure cellulose and does not contain other polymers such as hemicellulose, lignin and pectin (Pigaleva et al., 2019; Reiniati et al., 2017). Researchers claim that the appearance of BC material is similar to leather and thus it represents a new type of sustainable fabric that can be manufactured from several sources (Sederavičiūtė et al., 2019).

It should be noted that agro-industrial waste serves as an economic substrate for the production of bacterial cellulose, and the use of red wine, beer, milk, juice and tea has been suggested as catalysts and culture medium for the production of BC material (Sharma and Bhardwaj, 2019). According to He et al. (2020)and Lin et al. (2020), rice husks, cotton fabric residues, distillery wastewater, industrial residues from citrus husk drinks and sugarcane bagasse, have also been used to increase BC production at low cost.

One way to obtain bacterial cellulose is from the production of the probiotic drink Kombuchá, through the fermentation of teas belonging to the *Camellia sinensis* family and a sweetener, with the addition of a culture based on the symbiosis of bacteria and yeasts (De Filippis et al., 2018; Cardoso et al., 2020). Through this fermentation process, a membrane called SCOBY (Symbiotic Culture of Bacteria and Yeast) is formed (Sederavičiūtė et al., 2019). The bacterial cellulose formed in the production of Kombuchá exhibits eco-friendly and sustainable properties, mainly since it is biodegradable (Camere and Karana, 2018; Costa et al., 2019; Sederavičiūtė et al., 2019; Yim et al., 2017).

In this context, this article aims to discuss the application of the circular economy between the segments of the food and textile industry. Because the amount of food waste generated that could be reused for the production of textiles, natural dyes or even for the production of bioenergy and wastewater treatment is abundant. Thus, through this research, it is possible to rethink the non-use of non-renewable resources such as fossil fuels, bringing information on the real possibilities of using these waste.

As a main highlight, this article analyzes the use of food waste for the manufacture of biotextiles using bacterial cellulose. This, considered an innovative resource despite its limitations, has received attention from researchers in recent years and deserves further research. Finally, it highlights the importance of linking the issues addressed in this article to the UN Sustainable Development Goals (SDGs), especially with regard to SDG 12, which aims to ensure sustainable standards of production and consumption.

2. Methodology

Since the research question seeks to understand the relationship of Circular Economy applied between the segments of the food and textile industry, an integrative literature review is conducted. An integrative review is a specific review method that summarizes past empirical or theoretical literature to provide a more comprehensive understanding of a particular phenomenon (Whittemore, 2005). An integrative literature review also is defined as a form of research that reviews, critiques, and synthesizes representative literature on a topic such that new frameworks and perspectives on the topic are generated (Torraco, 2005; Torraco, 2016).

To conduct this integrative review, the databases chosen for the searches were: Scopus and ScienceDirect, and included analyzes of documents of the Food and Agriculture Organization (FAO), United Nations (UN), Ellen Macarthur Foundation (EMF), Brazilian Association of the Textile and Clothing Industry (ABIT) and H&M Foundation. Although the article focuses on the production of bacterial cellulose from food waste for the production of biotextiles, we chose to realize an understanding of the whole, including themes that legitimize the real possibility between the sectors cited with different examples, the relationship between CE and the industries and EC with SDG's. Thus, to perform the literature review, 5 combinations of search terms were selected for writing the topics. Figure 1 exemplifies the method used to select research articles for this review.

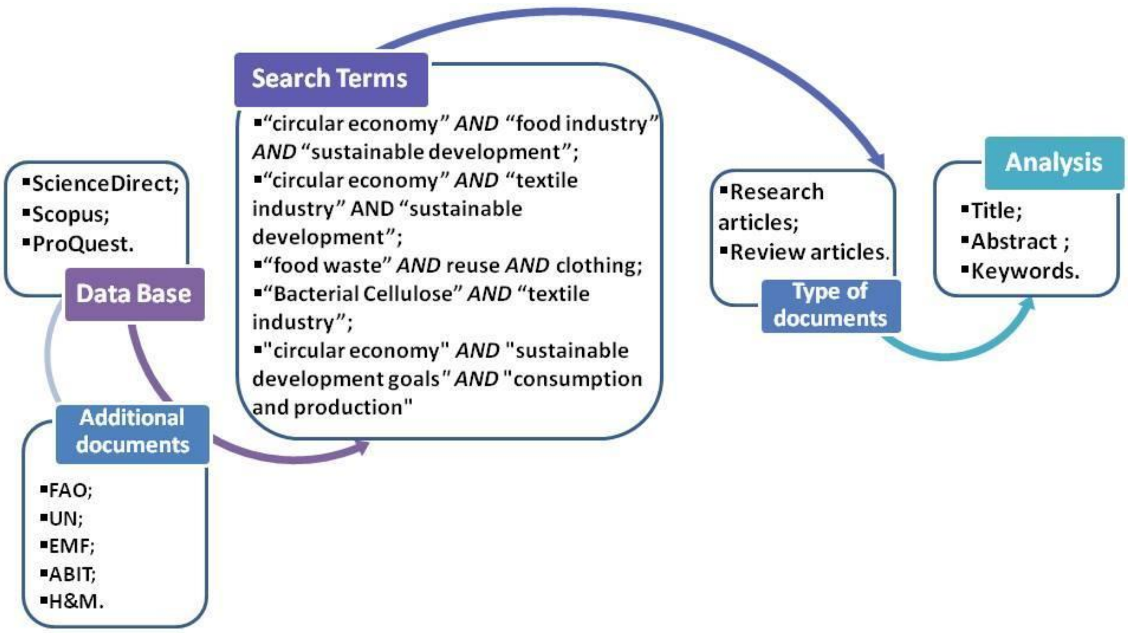

Fig. 1. Exemplification of the method used for the selection of research articles. Source: the authors

As seen in Figure 1, it should be noted that the peer reviewed articles were selected by opting for a timeframe between 2010 and 2021. Thus, inclusion and exclusion criteria were employed, which were the readings of the title, abstract and keywords, selecting only those articles that were compatible with the research theme. The complementary documents contributed to the dialogue between scientific research, government agencies and companies.

Therefore, the results and discussions of this review article are structured as follows:

a) "3. Results and Discussion": presentation of the quantitative results for the realization of the review article;
b) "3.1 Circular Economy Concepts": compilation of the researched concepts on Circular Economy according to the articles found, adding the complementary documents. The objective here is to understand in general the Circular Economy;
c) "3.2. Circular Economy and the Food Industry": compilation of research on Circular Economy in the food industry according to the articles found, adding the complementary documents. The objective here is to understand the Circular Economy and the advances in the Food Industry;
d) "3.3. Circular Economy and the textile and Clothing Industry": compilation of research on Circular Economy in the Textile Industry according to the articles found, adding the complementary documents. The objective here is to understand the Circular Economy and the advances in the Textile Industry;
e) "3.4 Possibilities for reusing food waste in the textile industry": compilation of research that deals with the reuse of food waste for application in the Textile Industry according to the articles found. The objective here is to show the real possibilities, positive results and what needs to be improved for future research;
f) "3.5 Manufacture of biotextiles using bacterial cellulose for a sustainable fashion industry": compilation of specific research on the use of bacterial cellulose for the manufacture of textiles. After all the contextualization on Circular Economy, Circular Economy in the Textile and Food Industries, and the reuse of food waste for use in the Textile Industry, the use of bacterial cellulose was chosen as an example, because BC can be produced through waste food or BC can be considered the waste of a Kombuchá beverage company;
g) "3.5.1 Economic aspects of biotechnology manufacturing": The objective here is to complement the results and discussions on the use of bacterial cellulose, bringing the economic aspects of its production according to the articles found;
h) "3.6 The Sustainable Development Goals and the Circular Economy": Finally, show the results and discussions on the importance of the Circular Economy to contribute to the SDGs, mainly the SDG 12, according to the articles found, adding the complementary documents.

3. Results and Discussion

On searching the 5 groups of terms and using the "document type" and timeframe "2010 to 2021" filters, 181 results were returned in the Scopus database, 1,043 results in the ScienceDirect database and 977 results in the database ProQuest database. Table 1 shows a comparison between the search results.

Table 1 - Comparison between the search results in the databases.

Search terms	Scopus	ScienceDirect	ProQuest
“circular economy” *AND* “food industry” *AND* “sustainable development”	60	312	351
“circular economy” *AND* “textile industry” *AND* “sustainable development"	36	154	127
“food waste” *AND* reuse *AND* clothing	4	149	103
“Bacterial Cellulose” *AND* “textile industry”	73	123	95
"circular economy" *AND* "sustainable development goals" *AND* "consumption and production"	8	305	301
Total	181	1,043	977

Source: the authors.

As shown in Table 1 was totaled 2,201 articles between 3 databases. For selection of articles, step 1 involved reading the title, abstract and keywords of each article. The publications which were aligned with the search theme were then selected and 1,914 articles were excluded. Thus, a total of 287 articles were read in full. In step 2, a further 132 research articles that were not aligned with the proposal of this review were excluded and the exclusion of 34 articles due to the repetition existing between the Science Direct, Proquest and Scopus databases, totaling 121 articles, were considered. Figure 2 shows the number of articles used to write each topic.

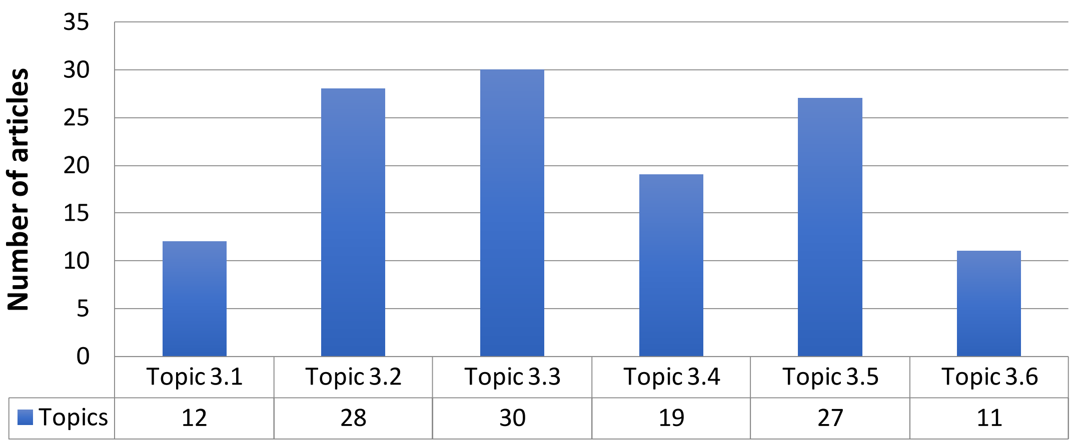

Fig. 2. Number of articles used to write each topic. Source: the authors.

Finally, as shown in Figure 2, 127 articles were used to write the 6 topics, 6 of which were used in more than one topic. The topics that most used articles were "3.2. Circular Economy and the Food Industry", "3.3. Circular Economy and the textile and Clothing Industry" and "3.5 Manufacture of biotextiles using bacterial cellulose for a sustainable fashion industry". This result is consistent with the purpose of the research that focuses on understanding the Circular Economy in the Food and Textile Industries, mainly around the discussion of bacterial cellulose for the production of biotextiles.

3.1 Circular Economy Concepts

The concept of circular economy (CE) aims to transform traditional patterns of production and economic growth, seen as linear systems, into circular dynamics that make connections between the use of resources and the waste generated, to prevent pollution and waste (Bilitewski, 2012; Buchmann-Duck and Beazley, 2020; Wang et al., 2020). In the face global environmental degradation and the urgent need for change, the concept has become popular around the world and this has led to the launching of national policies and strategies based on the idea of a circular economy (Buchmann-Duck and Beazley, 2020; Gupta et al., 2019; Morseletto, 2020).

In 2015, the Circular Europe Network pointed out that the concept of circular economy does not refer only to recycling, but is part of the basic 3Rs rule (Reduce, Reuse, Recycle) and makes it possible to reach the multi-R hierarchy (Rethink, Redesign, Repair, Redo and Redistribute, Recover) (Bilitewski, 2012; Jabbour et al., 2019; Kristoffersen et al., 2020). Fernandes et al., (2020) unites this with the concept of sustainable development, emphasizing that the proposal of the circular economy is to preserve natural resources, optimizing those we have and guaranteeing their availability for the future.

According to Kurdve and Bellgran (2020), Gupta et al. (2019) and Wang et al. (2020), a CE is a regenerative system where resource flows are minimized and speed is reduced, thus aiming at durable projects with a focus on maintenance, repair, reuse, remanufacturing, reconditioning and recycling solutions. In addition, the CE has the potential to lead to sustainable development, while decoupling economic growth from the negative consequences of resource depletion and environmental degradation (Durán-Romero et al., 2020; Jabbour et al., 2019; Morseletto, 2020). As such, CE has the potential to align eco-efficiency with economic profitability (Kiani et al., 2019; Kurdve and Bellgran, 2020). In recent years, several studies have been carried out on the concept of circular economy, which has allowed advances to be made (Gupta et al., 2019).

However, it should be noted that despite the relevance of the CE in current politics and in the economic debate, the concept remains open to interpretation (Morseletto, 2020; Suzanne et al., 2020) and currents of research from different scientific disciplines have given rise to several schools of thought regarding the circular economy (Suzanne et al., 2020). An example of this would be the challenge of some authors to recommend more research on the interaction between biodiversity and the circular economy, and that the defenders of the CE approach recognize that the system has limitations (Buchmann-Duck and Beazley, 2020).

Researchers at the Ellen MacArthur Foundation (EMF) are commonly cited for their work on the circular economy, as they research and describe the technical and biological inputs for a functional circular system (Buchmann-Duck and Beazley, 2020). Through the EMF website it is possible to access content about the existing schools of thought associated with the circular economy, their concepts and precursor authors (https://www.ellenmacarthurfoundation.org/).

Schools of thought like Regenerative Design by John T. Lyle, Performance Economy by Walter Stahel, Cradle to Cradle by Michael Braungart and Bill McDonough, Biomimicry by Janine Benuys and Blue Economy by Gunter Pauli are cited. Thus, it is clear that the concept of circular economy cannot be linked to a single theory or author. According to EMF, its practical applications in modern economic systems and industrial processes have acquired new dynamics since the late 1970s, led by a small number of academics, intellectual leaders and companies. Thus, the generic concept was refined and developed by several schools of thought (EMF).

3.2 Circular economy and the food industry

Research shows that the global generation of food waste (FW) is estimated at $ 1 trillion, increasing to $ 2.6 trillion when social and economic costs are considered (Slorach et al., 2019). According to the UN Food and Agriculture Organization (FAO), approximately one third of the food produced is lost every year along the journey from the field to the plate (FAO, 2018; Teigiserova et al., 2020). This waste is not only undesirable from an ethical and social point of view, it also results in the loss of natural resources, such as water, energy and fertilizers, which are necessary for the production and processing of food (Teigiserova et al., 2020; Wilts, et al.; 2020). In addition, food waste causes an average of 10% of greenhouse gas emissions emitted globally (Weber et al., 2020; Wilts et al., 2020).

It has been observed that the growing need for energy and materials to meet the demands of a rapidly growing and resource-intensive population is forcing a shift from a linear economy to a circular economy (Teigiserova et al., 2020). One of the essential actions required in order to achieve a circular economy is to extract value from residues, for instance, by recycling agrifood waste streams (Campalani et al., 2020; Teigiserova et al., 2020).

A survey carried out in Brazil showed that the food waste associated with tubers, for example, is 45%, which would be equivalent to 350,000 tons of sweet potatoes wasted annually (Weber et al., 2020). In the European Union, the International Panel of Experts on Sustainable Food Systems (IPES) identified that 20% of the food produced is wasted, at a cost of 143 billion euros annually, including wasted resources and environmental impact (Teigiserova et al., 2020).

Food waste is associated with issues related to the loss and/or waste of resources across the food chain, from primary production through retail and distribution to consumption in the food and hospitality sectors as well as households (Närvänen et al., 2020). It should be noted that food waste can be understood as both 'food waste', 'food loss' and 'excess food', the latter being a key factor in the current unsustainable food system (Närvänen et al., 2020). According to Sherwood (2020) and Sadeleer et al., 2020), minimizing food waste is one of the main challenges of a circular economy. Thus, projects and research studies on food waste and the CE are currently in vogue.

Many researchers recommend reusing waste for biorefineries, for example, as this is a sustainable business model and contributes to the development of the agricultural and food sectors, reduces greenhouse gas emissions and achieves the objectives of the circular economy (Teigiserova et al., 2020; Weber et al., 2020). In the case of domestic organic waste, as an example, several European cities have implemented the separation of this waste due to its energy content and the potential for its recovery through the production of biogas (Europe is the world's largest producer of biogas) (Sadeleer et al., 2020). Table 2 shows 20 current researches that address the reuse of food waste for technological applications.

Table 2 - Reuse of food waste for technological applications.

Year	Authors	Title	Application
2019	Xin et al.	Insights into microbial community profiles associated with electric energy production in microbial fuel cells fed with food waste hydrolysate	Energy
2019	Chen et al.	Upcycling food waste digestate for energy and heavy metal remediation applications	Energy
2019	Macintosh et al.	Successful strategies for increasing energy self-sufficiency at Grüneck wastewater treatment plant in Germany by food waste co	Wastewater treatment
2019	Lee et al.	Renewable routes to monomeric precursors of nylon 66 and nylon	Nylon 6 Nylon 66

		6 from food waste	
2020	Ranganathan et al.	Utilization of food waste streams for the production of biopolymers	Biopolymers
2020	Zan et al.	Integrated food waste management with wastewater treatment in Hong Kong: Transformation, energy balance and economic analysis	Wastewater treatment
2020	Hou et al.	Using an anaerobic digestion tank as the anodic chamber of an algae-assisted microbial fuel cell to improve energy production from food waste	Energy
2020	Yang et al.	Ball-milled, solvent-free Sn-functionalisation of wood waste biochar for sugar conversion in food waste valorisation	Biochar
2020	Twarogowska et al.	Upcycling of Belgian endive (Cichorium intybus var. foliosum) by-products. Chemical composition and functional properties of dietary fiber root powders	Dietary fiber
2020	Basturk et al.	Simultaneous remediation and fertility improvement of heavy metals contaminated soil by a novel composite hydrogel synthesized from food waste	Hydrogel
2020	Yan et al.	Bio-hydrogen and methane production from two-phase anaerobic digestion of food waste under the scheme of acidogenic off-gas reuse	Bio-hydrogen and methane
2020	Kosseva et al.	Biopolymers produced from food wastes: a case study on biosynthesis of bacterial cellulose from fruit juices	Biopolymers
2021	Hildebrandt et al.	The circularity of potential bio-textile production routes: Comparing life cycle impacts of bio-based materials used within the manufacturing of selected leather substitutes	Leather substitutes
2021	Mahssin et al.	Hydrothermal liquefaction bioproduct of food waste conversion as an alternative composite of asphalt binder	Bio-binder

2021	Lee et al.	Co-pyrolysis for the valorization of food waste and oriental herbal medicine byproduct	Biochar
2021	Peng et al.	Low temperature co-pyrolysis of food waste with PVC-derived char: Products distributions, char properties and mechanism of bio-oil upgrading	Biochar and bio-oil
2021	Khatami et al.	Bioconversion of food waste to volatile fatty acids: impact of microbial community, pH and retention time Kasra	Fatty acids
2021	Zhang et al.	Impact of storage duration and micro-aerobic conditions on lactic acid production from food waste	Lactic acid
2021	Feng et al.	Enhance biological nitrogen and phosphorus removal in wastewater treatment process by adding food waste fermentation liquid as external carbon source	Wastewater treatment
2021	Talan et al.	Food waste valorization: Energy production using novel integrated systems	Energy

Source: the authors.

Research on food waste should be encouraged, as it can play a significant role in the transition to an EC, contributing to the institutional and educational work needed to change the normative and cognitive-cultural pillars of institutions (Närvänen et al., 2020). According to Table 2 it is possible to observe the application of food waste in several sectors such as water treatment, energy production, production of biopolymers, among others.

Lastly, regarding the treatment of food waste, four methods can be considered: anaerobic digestion (AD), composting, incineration and landfill. Following the principles of circular economy and the waste management hierarchy, AD and composting are more favorable than incineration and landfill, highlighting the treatment of waste by anaerobic digestion, as this could save £ 251 m (pounds sterling) and 490 kt CO_2 equivalent (Slorach et al., 2019).

3.3. Circular economy and the textile and clothing industry

The textile and clothing (T&C) industry supplies essential consumer goods worldwide (Asada et al., 2020; Franco, 2017). Brazil is considered the second largest employer in the manufacturing industry and the second largest generator of the first job (ABIT, 2019). Globally, the value of the global fashion industry is US$ 3,000 billion, which represents more than 2% of the gross domestic product (GDP) (Shirvanimoghaddam et al., 2020). However, it is also considered one of the most polluting and socially challenged industries globally (Asada et al., 2020; Fischer and Pascucci, 2017; Franco, 2017).

The manufacture of textiles also requires large amounts of energy and water, the use of dyes (more than 100 L of water / kg of fabric) and the use of pesticides, herbicides and fertilizers during the cultivation phase, and socio-environmental issues include effluent contamination and poor conditions of work (Asada et al., 2020; Franco, 2017; Shirvanimoghaddam et al., 2020). Therefore, it is essential to rethink the textile chain in a circular and more sustainable way (Fischer and Pascucci, 2017; Shirvanimoghaddam et al., 2020).

In the past 15 years the textile industry doubled its production, with the annual average global consumption of textiles increasing from 7 to 13 kg per person, and consumption reached 100 million tons of textiles, with more than two thirds being disposed of in landfills at the end of use and only around 15% being recycled (Shirvanimoghaddam et al., 2020). Thus, in addition to the textile and fashion industry being among the most polluting and resource-intensive industries due to the great consumption of water, energy and chemicals, thus affecting the natural environment, the growth of the global population has led to an overall increase in the manufacturing of textiles.

According to Riba et al. (2020), European countries consume large amounts of clothes and textiles as a result of the current "buy-and-throw-away" culture. To recent industrial reports, US$ 400 billion in clothing is wasted every year worldwide (Shirvanimoghaddam et al., 2020)

To significantly reduce the environmental and social footprint of the textile industry, radical changes are required, especially in the way in which textiles and clothes are designed, produced, traded, used and recirculated. Thus, fashion and textiles should be part of a circular economy, thus allowing textiles and clothes life to be extended, to retain textile fibers within a closed circuit, so that they can be used again and again (Riba et al., 2020).

In 2017, the EMF published the report "A New Textiles Economy: Redesigning Fashion's Future" showing a vision for a new long-term integrated system, based on the principles of circular economy. The objective is to transform the textile and clothing economy into an opportunity that integrates better economic, social and ecological results (Fernandes et al., 2020; To et al., 2019). This new proposal with four main ambitions has been published and is consistent with the principles of a circular economy: 1) Phase out substances of concern and microfibre release; 2) Transform the way clothes are designed, sold, and used to break free from their increasingly disposable nature; 3) Radically improve recycling by transforming clothing design, collection, and reprocessing; and 4) Make effective use of resources and move to renewable inputs (EMF, 2017).

According to recent news released by the H&M Foundation, the fast fashion chain H&M (based in Sweden), in partnership with two Hong Kong companies, HKRITA (Hong Kong Textile and Clothing Research Institute) and spinning specialist Novetex Textiles, has developed a machine called Looop (H&M Foundation, 2020). The aim of this new technology is to transform discarded clothing, often provided by the consumers themselves, into new clothing items. The entire process takes around five hours to complete.

The piece is sanitized with ozone to eliminate microorganisms and then it is transformed into fibers, which will be crushed and filtered to remove dirt. In this step, the machine adds virgin material obtained from sustainable sources (in the least amount possible) and the process does not require the use of water or chemicals such as dyes. The effort addresses the increasing volume of global clothing waste and growing concerns regarding the role played by fast fashion in this scenario (H&M Foundation, 2020).

The reuse and recycling of textiles offer a sustainable approach to reducing solid waste in landfills, reducing the production of virgin materials and energy consumption, in addition to producing a smaller environmental footprint (Riba et al., 2020; Shirvanimoghaddam et al., 2020). Table 3 shows 20 current researches that address the reuse of textile waste for technological applications. However, the recycling of post-consumer textile waste is currently a complex process, since most fabrics are produced using mixtures of different types of fibers and, due to this complexity, most fabrics today are "downcycled", being transformed into rugs or rags (Franco, 2017).

Table 3 - Reuse of textile waste for technological applications.

Year	Authors	Title	Application
2019	To et al.	Recent trends in green and sustainable chemistry: rethinking textile waste in a circular economy	Green chemistry
2019	Yousef et al.	A new strategy for using textile waste as a sustainable source of recovered cotton	Recovered cotton
2019	Yousef et al.	A sustainable bioenergy conversion strategy for textile waste with self-catalysts using mini-pyrolysis plant	Energy
2019	Zeng et al.	Development of cellulose based aerogel utilizing waste denim—A Morphology study	Aerogel

2019	Islam and Bhat	Environmentally-friendly thermal and acoustic insulation materials from recycled textiles	Thermal and acoustic insulation
2019	Li et al.	Efficient succinic acid production using a biochar-treated textile waste hydrolysate in an in situ fibrous bed bioreactor	Succinic acid
2019	Haslinger et al.	Upcycling of cotton polyester blended textile waste to new man-made cellulose fibers	Man-made cellulose fibers
2020	Bourguiba et al.	Recycled duvets for building thermal insulation	Thermal insulation
2020	Yousef et al.	Sustainable green technology for recovery of cotton fibers and polyester from textile waste	Recovery of cotton fibers and polyester
2020	Çay et al.	Application of textile waste derived biochars onto cotton fabric for improved performance and functional properties	Functional textile
2020	Nayak et al.	Sustainable reuse of fashion waste as flame-retardant mattress filing with ecofriendly chemicals	Flame-retardant mattress filing
2020	Subramanian et al.	Environmental life cycle assessment of textile bio-recycling – valorizing cotton-polyester textile waste to pet fiber and glucose syrup	Pet fiber and glucose syrup
2020	Zhong et al.	Eco-fabrication of antibacterial nanofibrous membrane with high moisture permeability from wasted wool fabrics	Antibacterial nanofibrous membrane
2021	Dissanayake et al.	An environmentally friendly sound insulation material from post-industrial textile waste and natural rubber	Sound insulation
2021	Todor et al.	Development of fabric-reinforced polymer matrix composites using bio-based components from post-consumer textile waste	Polymer matrix composites
2021	Xu et al.	Conversion of cotton textile waste to clean solid fuel via surfactant-assisted hydrothermal carbonization: Mechanisms and combustion behaviors	Solid fuel
2021	Vidaurre-Arbizu et	From the leather industry to	Building sector

	al.	building sector: Exploration of potential applications of discarded solid wastes	
2021	Zhong et al.	Highly flexible, transparent film prepared by upcycle of wasted jute fabrics with functional properties	Highly flexible, transparent films
2021	Sadrolodabaee et al.	Characterization of a textile waste nonwoven fabric reinforced cement composite for non-structural building components	Reinforced cement composite
2021	Qi et al.	Clean solid fuel produced from cotton textiles waste through hydrothermal carbonization with FeCl3: Upgrading the fuel quality and combustion characteristics	Solid fuel

Source: The authors.

According to Table 3, it is possible to observe the application of textile waste in various sectors such as energy production, solid fuels, thermal and acoustic insulation, glucose syrup, among others. However, it is not enough just to think about reusing waste, but also to think about not producing waste. Thus, product design is also essential to achieve EC objectives (see Figure 3). Circular products need to be designed for life cycles and the relative sustainability of a product is strongly dependent on the choice of product materials and the production and planning processes for the entire cycle (Fischer and Pascucci, 2017; Franco, 2017).

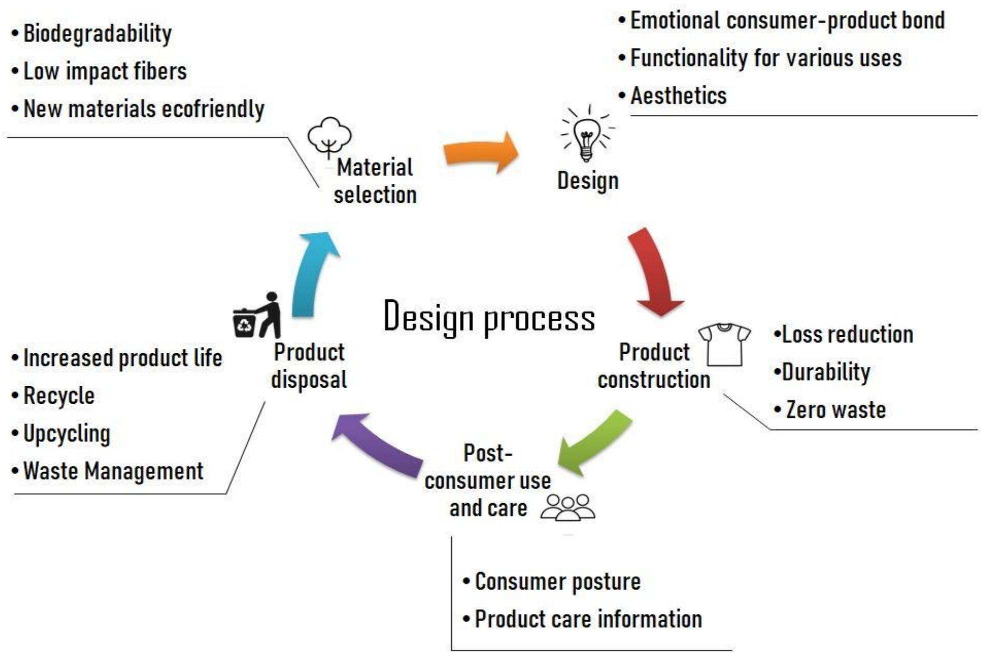

Fig. 3. Product design process based on the circular economy concept. Source: adapted from Elena Salcedo, 2014.

Aiming for a circular economy through a longer product life and the reuse of materials avoids excessive waste generation and increases the total value of products (Ingulfsvann, 2020; Shirvanimoghaddam et al., 2020; Tate et al., 2019; Todeschini et al., 2017). It is also worth noting that this approach offers opportunities for innovation in product design, services, business models and establishing basic elements for a long-term resilient system (Shirvanimoghaddam et al., 2020); Todeschini et al., 2017).

According to Fischer and Pascucci (2017), in addition to rethinking materials and their forms of production, it is important to develop strategies for implementing the CE concept to carry out the transition of a company with a traditional linear system. Studies conducted in Dutch textile companies identified two paths for this transition and to manage circular material flows. The researchers defined two concepts: a) Status Quo (SQ), when companies focus on optimizing up-cycling technologies and infrastructure in their circular relationships and collaborations; and b) Product as a Service (PAS) arrangements, to indicate a focus on supplying products in service contracts.

3.4 Possibilities for reusing food waste in the textile industry

Around 20% of the total use of water, cropland and fertilizers are used to produce surplus food ending as food waste, which could have been avoided upon adopting environmental and socially responsible business models (Hildebrandt et al., 2021; Teigiserova et al., 2020). Uncontrolled decomposition of agro-industrial waste leads to extensive contamination of water, land, and air. Valorization of the wastes not only reduces the volume of waste but also reduces the contamination to the environment (Seguí and Maupoey, 2018; Lee et al., 2019; Ranganathan et al., 2020). Further support in decision-making was suggested by the Commission EU's Member States as a way to monitor the progress of Circular Economy (Teigiserova et al., 2020).

Waste from food industries has great potential as primary or secondary feedstocks for biopolymer production by extraction or fermentation with pre-treatment or without pre-treatment by solid-state fermentation to obtain fermentable sugars. Various types of food waste can be used as substrates for the production of biomaterials (Ranganathan et al., 2020). Thus, the growing demand for environmental sustainability has encouraged research into biodegradable polymers, to minimize the environmental impact of conventional polymers (Balakrishnan et al., 2017; Lee et al., 2019; Tibolla et al., 2014).

Nylon 66 and nylon 6 are synthetic polymers that are widely used in daily life, synthesized by polycondensation of adipic acid and hexamethylenediamine (HMDA) and by ring-opening polymerization of ε-caprolactam, respectively. According to Lee et al. (2019) it is possible to manufacture monomeric precursors of nylon 66 and nylon 6 from food waste, but for that, it is necessary to first extract glucose, 5-hydroxymethylfurfural (HMF) and levulinic acid from food waste (Lee et al., 2019).

Nevertheless, the renewable routes from food waste to the nylon precursors are not yet competitive with petroleum-based processes, principally as the extraction of the starting materials (e.g., glucose, HMF, and levulinic acid) from food waste does not occur on a commercial scale. Instead, petroleum-derived intermediates of the processes could be replaced with renewable ones. This may ease the transition process from current petroleum-based manufacturing (Lee et al., 2019)

In other research, Hu et al. (2017)carried out the production of poly (lactic acid) fibers using fermentative lactic acid from food waste. Poly(lactic acid) was synthesized through ring-opening polymerization, in which the precursor lactide was produced by a novel catalytic method. Under optimal reaction conditions, lactide was produced at yields of 91–92% within 8 h, significantly improving the synthesis efficiency compared to the conventional tin-based catalytic method.

The pure lactide product facilitated the conversion of food waste derived lactic acid to high molecular weight poly(lactic acid) (150,000 g mol−1), which was subsequently spun to fibres with promising tensile and thermal properties for potential applications in textile and bioplastics. As the monomer of PLA, lactic acid (LA) can be derived from renewable biomass resources such as sugar beet and corn (Hu et al., 2017). According to Hildebrandt et al 2021, fiber PLA can be processed into nonwoven materials in combination with both fossil-based non-biodegradable polymer fibers and natural fibers and/or other bio-based biodegradable polymer fibers.

Other alternative solution, facilitated by the bio-textiles industry, is the introduction of vegan and bio-based leather substitutes for the production of shoes, handbags, clothing’s and upholstery i.e. on the basis of natural fibres, bio-based polymers, microbial cellulose and fungal mycelium composite products (Hildebrandt et al., 2021). Hildebrandt et al 2021 made comparisons between possible biomaterials to replace leather, as can be seen in Figure 4.

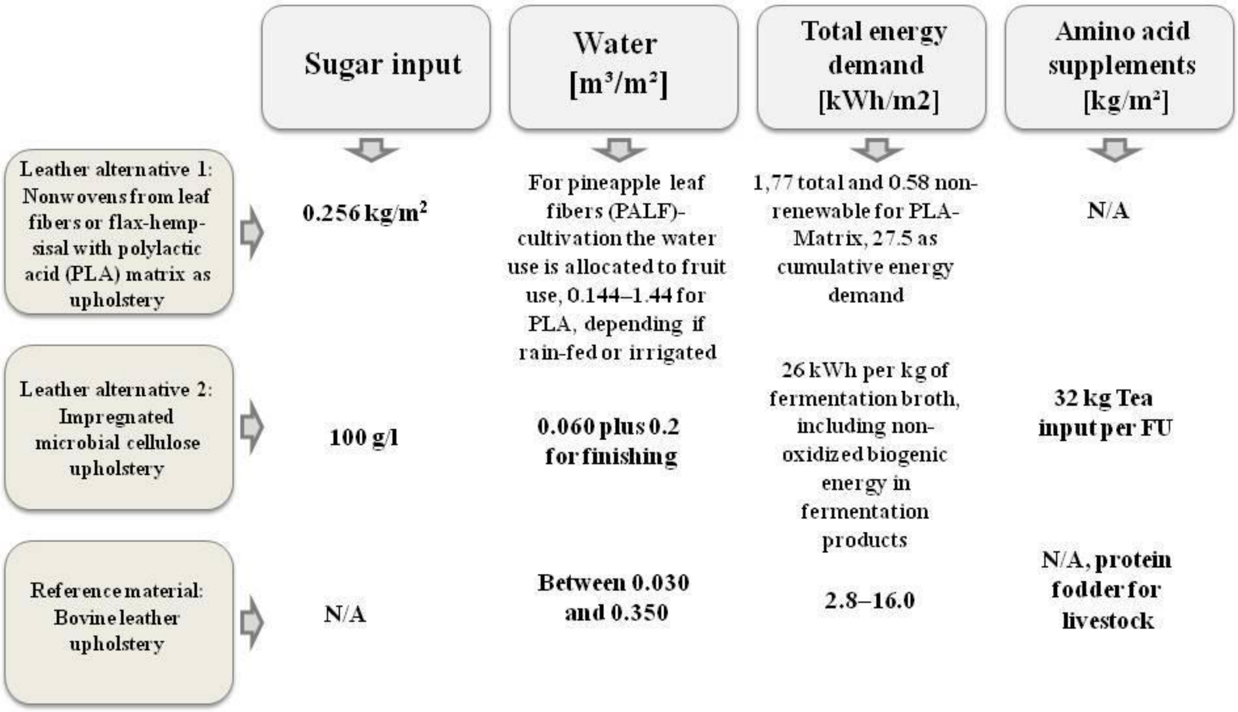

Fig. 4. Comparisons between possible biomaterials for replacing leather. Source: adapted Hildebrandt et al 2021.

According to authors the major material and energy flows associated with the biofabrication and manufacturing of leather, include the water footprint, the cumulative energy demand for drying, boiling, pressing, and confectioning of the materials, and the upstream material and energy demands for supplementary materials. Hildebrandt et al 2021 confirm that these alternative leather substitutes contribute to potential long-term strategies for reducing and replacing leather use, but only at a well-balanced mix when upscaling is predicted, and only with the leverage potential for deep impact decoupling. This demands that fast fashion applications do not compromise the attainable impact reductions but instead embrace further impact reduction strategies.

Plant fibers also are among the existing natural fibers, are an attractive material and its features resemble those of synthetic polymers, it could potentially replace its synthetic counterparts (Tibolla et al., 2014). European Union has passed the legislation to use bio fibres as reinforcement during automobile component manufacturing (Sabarinathan et al., 2020). The main reason for using natural fibre as reinforcement is that the energy consumed for the fibre production is less compared with synthetic fibre. The cost associated with the production of natural fibre is less, possibly due to the fact that natural fibres are mostly by-products from the industrial crops (Sabarinathan et al 2020).

For example, pineapple plants are largely grown in tropical and subtropical countries. In 2018, the global production of pineapples amounted to 27.92 million metric tons. Costa Rica, Philippines and Brazil were the top three pineapple producers worldwide. Its crown it consist of 80% cellulose, however it is considered as a waste material after the harvesting and is usually burned in the middle of the plantation at the end fruit harvest (Balakrishnan et al., 2017; Hazarika et al., 2017; Pereira et al., 2021).

During processing, large quantities of by-products, mainly from bark, peel, and bagasse are generated, which represents about 25–35% of the fruit weight. Therefore, these by-products constitute an abundant and low-cost raw material that could be used as feedstock for biomass conversion processes producing high-value bioproducts such as nanomaterials, which could be used, for example, as reinforcing agent in nanocomposite (Pereira et al 2021).

In Indian subcontinent, an attempt has been made to extract and soften pineapple leaf fibre by decortication of leaves followed by water retting. The retting time was optimized at 7 days. The retted fibres were then degummed and bleached for better processibility and aesthetic look. The degummed and bleached fibres were then successfully converted into textile quality thread of 90 tex through suitable mechanical processing system. Mechanical properties of thread were found to be suitable to make sustainable novelty fabrics for apparel (Hazarika et al., 2017). Pineapple waste, considered an abundant agro-industrial residue, is studied as a low-cost material for the generation of different value-added products (Seguí and Maupoey, 2018).

Food waste can also be a solution for the dyeing, wastewater treatment and energy production sectors. Verma et al. 2021 investigated the effect of biopolymer and dyeing treatment with natural dye (skin of onions) on the functional properties (antibacterial and UV protection) of cotton fabric. The reddish colour outer skin of onions was collected from hostel mess where it is discarded as a waste, and cleaned to remove debris and shade dried.

It was found that the chitosan treated onion skin dyed cotton fabric showed 97.20 percent and 98.03 % reduction in the growth of E. coli and S. aureus bacteria respectively. The chitosan treated dyed cotton fabric showed the higher ultra-violet protection factor (UPF) value (84.80) as compared to alum treated dyed cotton fabric (66.70) depicting that the chitosan treated dyed cotton fabric provided more ultraviolet protection than the alum treated dyed fabric (Verma et al., 2021).

Orange peel (OP) also is an abundant, cheap and readily available agricultural byproduct. OP extracts can be readily sorbed by wool directly, with aluminum or iron mordants, both of which are benign to the environment and human health. According to Hou et al. (2013), the optimum dyeing conditions included dyeing temperature of 100 °C, dyeing time of 120 min, pH 3 for direct dyeing and pH 7–9 for one-bath mordant dyeing. All the dyed wool fabrics demonstrated good colorfastness to washing with soap, good colorfastness to rubbing and acceptable colorfastness to light. The value of UV-protection Factor (UPF) of the wool fabric dyed with OP extracts using direct dyeing method was about 6 times higher than that of the wool fabric dyed with normal synthetic dyes with similar shade and depth of shade.

Yin et al. (2017) extracted in their research the extract natural colorant anthocyanin from purple sweet potato powder via ultrasound-assisted ammonium sulfate/ethanol aqueous two-phase system. The extracted natural colorant anthocyanin was used to dye silk fabric in a relatively ecological approach. Based on the single-factor extracting experiment, central composite design-response surface methodology was employed to optimize the ultrasound-assisted aqueous two-phase system extracting conditions including ultrasound temperature, ultrasound time and dosage of purple sweet potato powder. This study demonstrated that developed natural colorant extracted from plant could be successfully employed as an effective and eco-friendly alternative cleaner to replace synthetic colorant gradually using in textile dyeing industry.

Regarding wastewater treatment, in Turkey, a hybrid process was applied to pretreated real textile wastewater. Hybrid process included electrocoagulation (EC), adsorption, and photo Fenton-like oxidation methods. Walnutshell and corncob agricultural wastes were used for the preparation of the activated carbon. According to Bener et a., (2020), after adsorption step, the removal efficiency of the total organic carbon (TOC) was found to be nearly 75% and color, turbidity, and total dissolved solids achieved the standards for irrigation water. For researchers agricultural wastes used in preparation of catalysts and adsorbents were promoted to be innovative, environmentally friendly and economical.

Topare and Bokil (2021) also performed tests of adsorption of textile industry effluent using activated carbon prepared from agro-waste materials. They were used green coconut shell and bamboo using $ZnCl2$ as an activation agent in an adsorption column (fixed bed). The findings demonstrated that both breakthrough and exhaust times increase, with the height of the bed being increased, but decrease with the concentration of the dye inlet. It was observed that the bamboo activated carbon BAC has high carbon content, and has a high potential for dyes removal and may become capable substitutes for costly activated carbon. The adsorption capacities of green coconut shell and bamboo are at par with respect to each other, the overall process scheme may become economical as these materials are available as wastes and practically free of cost.

Finally, the energy efficiency and the development of environmentally correct policies are current topics, especially when applied to the industrial sector with the objective of increasing the competitiveness of the enterprises. One of the existing options for the growth and sustainable development of textile industry is through the use of biomass as an input (Nunes et al., 2015; Nunes et al., 2019).

For example, in Greece, the agricultural sector and primarily its cotton subsector are of great importance for Greece, due to the intensive agricultural activities. Thus, according to Zabaniotou and Andreou (2010)the wastes from cotton ginning plants are also considerable and can be valorized for bioenergy production. The substitution of conventional by green fuels, which can be produced from cotton ginning wastes, is a step towards: (a) economic and environmental sustainability for the textile industry and (b) the development of alternative energy supplies, contributing to the reduction of GHG emissions. Furthermore, it consists an especially attractive opportunity to invest in rural areas (Zabaniotou and Andreou, 2010)

3.5 Manufacture of biotextiles using bacterial cellulose for a sustainable fashion industry

With regard to waste management and circular economy, partnerships between sectors can be an excellent solution, since through interdisciplinarity one sector can provide a function for the waste generated in another (Sauvé et al., 2016; Wilkes et al., 2015). An example of this is the waste generated during the production of the probiotic drink Kombuchá, consisting of bacterial cellulose, which can be used as a potential biomaterial for textiles, footwear and other branches of design (Costa et al., 2019; Yim et al., 2017).

The inclusion of living biological systems in the field of nanotechnology and materials sciences has led to the creation of strategies and solutions through various research lines. This situation has arisen through the efforts of a large number of scholars who are concerned with the development of new sustainable materials that will not be a source of pollution for our planet (Camere and Karana, 2018; Costa et al., 2019).

Biotechnology and biofabrication are related to studies on microorganisms and are considered efficient when compared to other material production technologies, as they do not require the removal of virgin materials from the earth's crust (Camere and Karana, 2018; Scarlat et al., 2015). An example of the use of microorganisms is acetic acid bacteria, mainly from the genus Gluconacetobacter (Costa et al., 2019; García and Prieto, 2019). The cellulosic membrane formed by bacteria is biodegradable (García and Prieto, 2019; Zhu et al., 2016) and this biodegradability is consistent with developing ecologically-friendly products (Freudenreich and Schaltegger, 2020).

Many researchers have also been concerned with low to zero waste projects for the textile industry, especially for activities that involve cutting processes (Chan et al., 2018). It has been demonstrated that bacterial cellulose has a high potential to achieve sustainability through reaching zero waste (Camere and Karana, 2018; Chan et al., 2018). Biomaterials have interesting characteristics in addition to easy degradation, such as the possibility of being cultivated as needed (in various sizes and shapes) (Camere and Karana, 2018; Domskiene et al., 2019). Chan et al. (2018) performed tests using crop containers in the shape of the garment mold, a technique called vacuum molding, since the bacterial cellulose tissue membrane produced from the traditional cultivation container (rectangular or oval) requires additional cutting.

It should be noted that these microorganisms aerobically produce cellulose films that accumulate in the extracellular medium, which can be produced in different thicknesses and, when dry, produce a leather-like material (García and Prieto, 2019; Domskiene et al., 2019). Also, for the manufacture of BC, only small amounts of water and energy are needed (Cazón et al., 2020; Yim et al., 2017). Thus, the use of bacterial cellulose has gained the attention of designers in order to rethink materials, ways of production and contribution to sustainability.

The characteristics of the bacterial cellulose film led to the innovative idea of the cultivation of seamless clothing, due to its direct 3D formation as a leaf (Ng and Wang, 2016; Wang et al., 2015). It should be noted that the synthesis of BC can be conducted under static or dynamic conditions, resulting in different forms of cellulose, that is, three-dimensional interconnected reticular films and irregularly shaped, ball-like cellulose particles, respectively (Chan et al., 2018; Costa et al., 2019; Kamiński et al., 2020).

One way to obtain bacterial cellulose is from the production of the probiotic drink known as Kombuchá, this being considered a sustainable source for the manufacture of BC films (Filippis et al., 2018; García and Prieto, 2019; Costa et al., 2019; Kamiński et al., 2020). Suzanne Lee, founder of Biocouture, is a fashion designer and pioneer in the technique of using bacterial cellulose obtained through Kombuchá fermentation (https://www.launch.org/innovators/suzanne-lee) (Chan et al., 2018; Kamiński et al., 2020).

Although research on BC is growing rapidly, there are still many technical and practical problems associated with making clothes that need to be solved (Kamiński et al., 2020). Mechanical durability, comfort, material contamination, organic acids (responsible for the characteristic unpleasant smell), attack from microorganisms (Kamiński et al., 2020) and how to adapt these materials to the production of products on a large commercial scale (He et al., 2020; Domskiene et al., 2019) are some questions raised by researchers. Studies on alkaline treatment have been conducted, but the alkaline purification method requires the use of significant amounts of water and neutralizers to obtain materials with neutral pH (Cacicedo et al., 2016; Kamiński et al., 2020).

3.5.1 Economic aspects of biotechnology manufacturing

The success of building an economically viable bioprocessing method is strongly dependent on reducing the cost of the substrates, increasing the yield of the product and increasing the production rate (Reiniati et al., 2017). The high cost of culture media for the production of BC in the laboratory led some researchers to propose alternative strategies to overcome this disadvantage, aimed at industrial production (Islam et al., 2017; Machado et al., 2018).

Designs have been proposed for advanced reactors, like the rotary disk reactor, as well as additives that increase the production of bacterial cellulose, such as carboxymethylcellulose and organic acids (Ul-Islam et al., 2020). However, with regard to large-scale production, strategies involving cheap raw materials and carbon sources need to be proposed (Islam et al., 2017).

According to Barshan et al. (2019), considerable effort has been focused on finding new low-cost carbon sources. The use of vinasse, for example, is a promising practice as it increases productivity and reduces the costs and volume of effluent generated. Revin et al. (2018) observed the accumulation of a large amount of bacterial cellulose (6.19 g/L) in fine wheat vinasse after 3 days of cultivation under dynamic conditions, almost three times greater than in the standard Hestrin and Schramm medium (2.14 g/L).

The possibility of using cheap raw materials as substrates makes the production of bacterial cellulose more attractive and viable, and potential candidates would be agricultural and industrial food residues, including saccharified food residues, grape medium, pineapple juice, grape marc, glycerol from biodiesel and low quality syrup (Reiniati et al., 2017). It should be noted that the use of residues or by-products from agroforestry and the food industry as sources of carbon and nitrogen for new compositions of culture media, in addition to reducing the cost of production, allows the high quality of the BC produced to be maintained (Machado et al., 2018).

In this context, the production of bacterial cellulose through the production of the probiotic drink Kombuchá is an attractive option in relation to costs. As noted earlier, the main raw material used to make the drink is green tea (*Camellia sinensis*), which can be sweetened with organic products, such as sugar cane molasses or sugar for domestic use (Machado et al., 2018; Song and Kim, 2019).

According to Hildebrandt et al 2021 market oversaturation of Kombuchá tea can lead to decreasing Kombuchá tea prices, thereby influencing the allocation by price as a higher share of revenues will be from alternative leather sales. To increase the circularity within microbial cellulose production, the use of waste substrates, e.g., from secondary brewing of waste substrates from tea brewing and instant tea production in the beverage industry or pasteurized fruit waste from fruit jelly production, could allow for a circular supply chain strategy. Furthermore, integrating starch producing companies, such as potato starch production, with enzymatic saccharification combined with a later integration into existing wastewater infrastructures should be considered.

3.6 The Sustainable Development Goals and the Circular Economy

The concept of circular economy has the potential to contribute to several UN Sustainable Development Goals (SDGs) (Durán-Romero et al., 2020; Centobelli et al., 2020). According to

Kristoffersen et al. (2020), in relation to CE, eliminating or reducing structural waste decreases the demand for virgin finite material as well as the contamination of the natural environment through the dumping of used resources. Therefore, CE practices are strongly linked to SDG 12 (responsible consumption and production), SDG 6 (clean water and sanitation), SDG 7 (clean and accessible energy), SDG 13 (climate change) and SDG 15 (life on earth) (Durán-Romero et al., 2020; Centobelli et al., 2020; Chen et al., 2020; Kristoffersen et al., 2020; Schöggl et al., 2020).

Currently, 40% of the world's population is seriously negatively impacted by water scarcity and pollution, due to both the presence of toxic industrial chemicals and global warming (Chen et al., 2020). Therefore, cleaner production practices need to be adopted, prioritizing those which are consistent with a circular economy and contribute to the SDGs (Durán-Romero et al., 2020; Centobelli et al., 2020). Figure 2 shows the relationship between the circular economy and the SDGs, promoting a more sustainable society through a circular system.

Therefore, in the case of production processes and industries, SDG 12 has been the most targeted goal as a starting point for the implementation of the CE concept (Giannetti et al., 2020; Schöggl et al., 2020). SDG 12 is composed of 11 targets, which aim to implement the Ten-Year Plan of Programs on Sustainable Production and Consumption, addressing, for instance, how to correctly manage waste and rationalize inefficient fossil fuel subsidies (UNDP, 2015).

According to Corrado et al. (2020), in a globalized economy, where raw materials and semi-finished and finished products are widely traded, the growing demand for products in developed countries generates considerable pressures on the environment and causes serious impacts. Therefore, life cycle assessment and environmental impact due to the production and consumption of goods and services is a crucial step towards achieving sustainable development goals (SDGs) (Corrado et al., 2020; Sala and Castellani, 2019).

One of the ways to mitigate negative environmental impacts is the adoption of cleaner production (CP) practices and this is in line with SDG 12. These practices contribute to the preservation of raw materials and energy, reducing or eliminating the emission of toxins and waste during production processes. Thus, the implementation of CP practices should be a priority in the textile, clothing and leather industries (Neto et al., 2019).

In China, a monitoring framework for the implementation of the CE concept (macro level) has been developed, based on a Chinese statistical system and previous research linked to economy material flow accounts (EW-MFA). For this monitoring, indicators were used, such as the pattern of consumption and use of material per capita (SDG 12.2) along with the production, circularity, recycling rate and total waste throughout the life cycle and amount of waste sent to landfill (SDG 12.5) (Wang et al., 2020).

The European Commission (EC) has pledged to fully integrate the SDGs into the EU policy framework and EU priorities, assessing the current status and identifying the most relevant sustainability concerns (Corrado et al., 2020). Waste prevention, for instance, is considered a priority under the European waste policy. Reducing food waste has recently been recognized as a priority area at the international and European levels and in Norway (Sadeleer et al., 2020). Thus, the aim is to reach target 12.3, which aims to "halve per capita global food waste at the retail and consumer levels and to reduce food losses along the production and supply chains, including post-harvest losses" (UNDP, 2015).

Lastly, a consideration of the interdisciplinarity between the food sectors through the use of bacterial cellulose in the textile and fashion industries for the manufacture of biotechnologies, should include target 12.5, which aims to substantially reduce the generation of waste through prevention, reduction, recycling and reuse, and target 12.c, which seeks incentives to rationalize inefficient fossil fuel subsidies and minimize negative environmental impacts (UNDP, 2015). Figure 5 shows the possible relationship between the textile industry, food industry and the ODS 12 thinking of a Circular Economy.

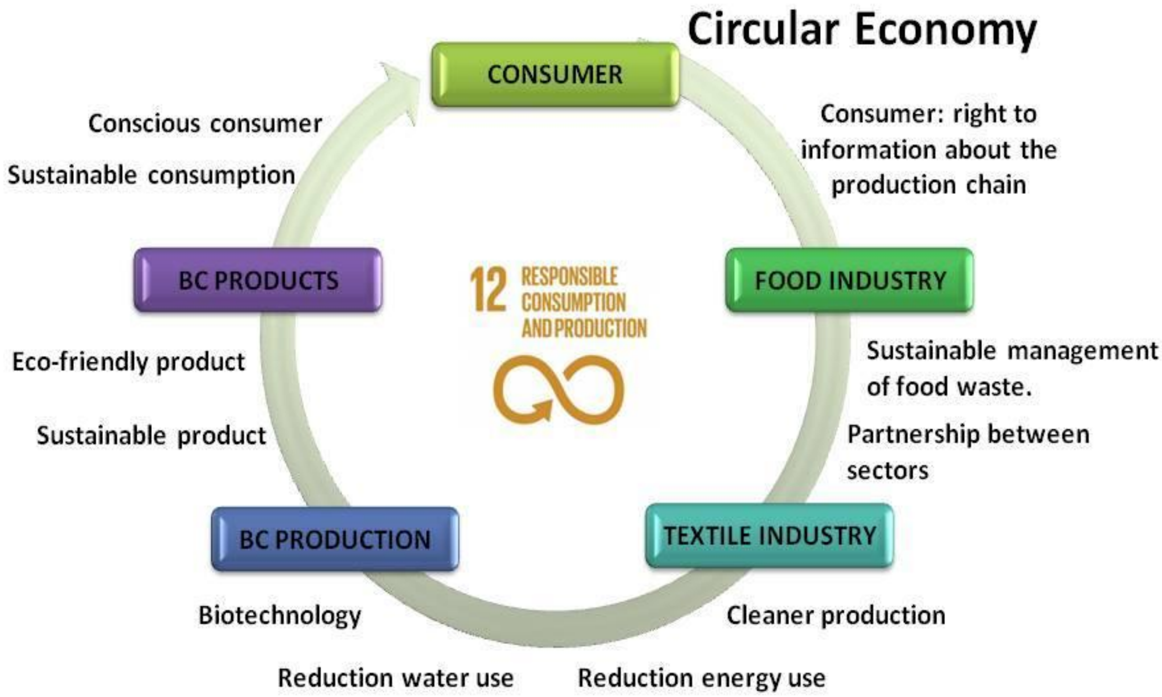

Fig. 5. Possible relationship between the textile industry, food industry and the ODS 12. Source: the authors.

Figure 5 illustrates the possibility of thinking about a Circular Economy between the food and textile sectors through the production of a biotextile. As well as the importance of adhering to the Sustainable Development Goals, in this case, SDG 12 and including its waste management goals, cleaner production, and ensuring that people everywhere have the relevant information and awareness for the sustainable development and lifestyles in harmony with nature.

5. Final considerations, trends and future research

The aim of this study was to review and shed light on the current state of research on the circular economy concept, relating it to the food and textile industries, in order to propose a dialogue between the two sectors regarding the reuse of waste. Theoretical studies on the concepts of CE, CE in the food industry and CE in the textile, clothing industry were discussed and examples of research that addressed the reuse of food waste for the production of biopolymers were discussed.

Subsequently, the applicability of the CE concept to the food and textile sectors was analyzed, using as an example the reuse of bacterial cellulose waste from the production of the drink Kombuchá in the development of biotechnologies for the textile industry. It should be noted that this action is consistent with a circular economic system and favors the achievement of UN Sustainable Development Goals, such as SDG 15, SDG 13, SDG 7, SDG 6 and, especially, SDG 12.

Through this study, the real possibility of making new textiles and re-valuing millennial natural fibers from plant residues such as pineapple was observed, but also about the limitations and difficulties, mainly thinking about replacing products from limited natural resources such as oil. Therefore, it was demonstrated the importance of future theoretical and practical studies on the reuse of waste from one sector to another, through interdisciplinarity. As well as further studies on energy and water savings, production yields, among other challenges.

In this regard, the use of bacterial cellulose in clothing production can be highlighted as a good example, offering ecofriendly characteristics. In future research, the limitations associated with large-scale commercial production also need to be addressed for the utilization in fashion industry.

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CAPÍTULO 4

TEXTILE INDUSTRY AND ENVIRONMENT: CAN THE USE OF BACTERIAL CELLULOSE IN THE MANUFACTURE OF BIOTEXTILES CONTRIBUTE TO THE SECTOR?

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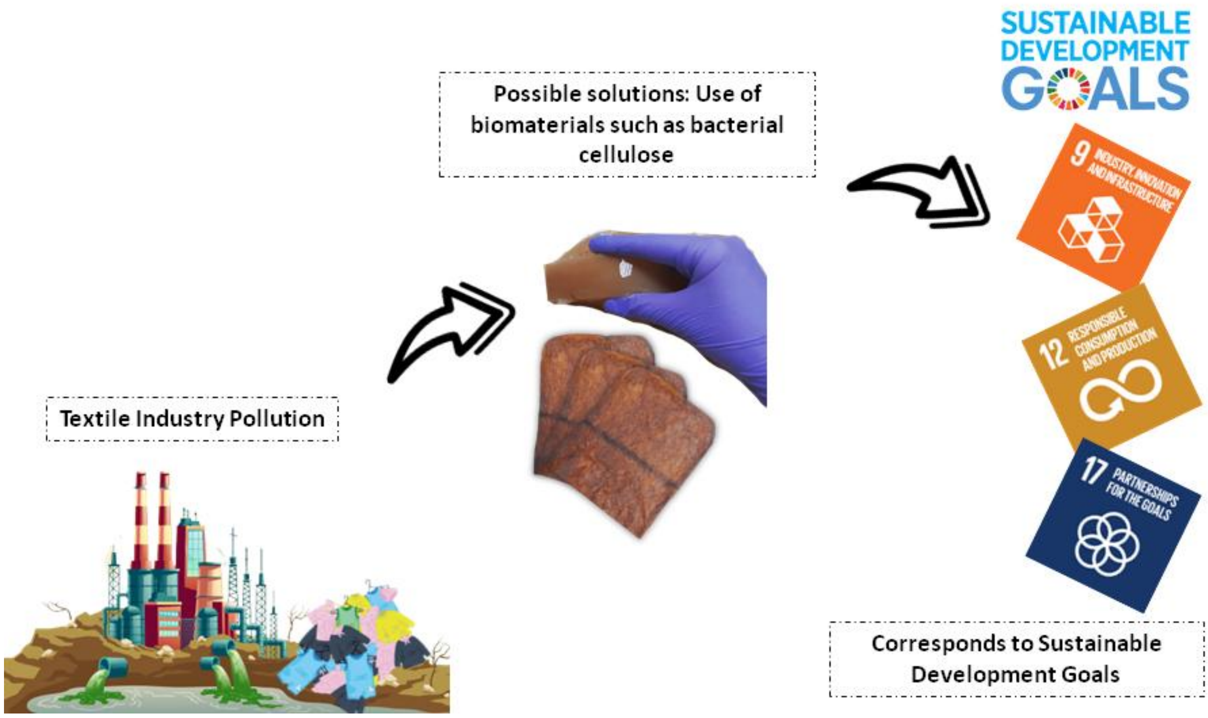
TEXTILE INDUSTRY AND ENVIRONMENT: CAN THE USE OF BACTERIAL CELLULOSE IN THE MANUFACTURE OF BIOTEXTILES CONTRIBUTE TO THE SECTOR?

Abstract: The textile industry is one of the most complex sectors in relation to environmental degradation, both with regard to the materials used from petroleum and its chemical processes and during its manufacture and disposal. Therefore, new possibilities for more sustainable materials are emerging. One of the options is the use of microorganisms, as the biomaterial formed is considered biodegradable and has potential use for several sectors, including the fashion industry. The bacteria of the *Komagataeibacter xylinus* family present in the probiotic drink Kombuchá, are a great source for the production of bacterial cellulose (CB) and has the potential to replace fabrics in the production of clothing and accessories. Therefore, this article carried out an integrative literature review, addressing in the results and discussions the problem surrounding the pollution generated by the Textile Industry, the advantages and disadvantages of bacterial cellulose as a bio-textile and how these issues can contribute to the Sustainable Development Goals (SDGs). Finally, it is believed that the textile industrial system should be revised, as it is still incongruous on both environmental and social issues. Therefore, thinking about new, more sustainable materials such as bacterial cellulose is a form of mitigation and consistent with the SDGs.

Keywords: Bacterial cellulose. Bio-textiles. Sustainability. Sustainable Development Goals.

Graphical Abstract



Introduction

The increase in consumption in recent decades has raised numerous questions related to the challenges of sustainability and the management of solid waste (Calvo et al. 2020; Dissanayake et al. 2021). The increase in the global population, climate change, widespread urbanization and widespread industrial development have led to water and energy shortages, consequently these factors will affect people, industries, agriculture, the ecosystem and the economy in general (Ul-Islam et al., 2020). The textile industry, for example, is a complex sector, due to its intense participation in activities that cause major negative environmental impacts such as the use of pesticides, huge amounts of energy and water, chemicals used in processes and inappropriate discharges (Luo et al. 2020).

Thus, to achieve a more sustainable consumption scenario, it is necessary to find solutions to reduce negative environmental, social and economic impacts, not only through industrial changes, but also by consumers, addressing ethical and behavioral issues (Freudenreich and Schaltegger 2020; Todeschini et al. 2020). Therefore, the adoption of Cleaner Production Practices (CPP) is necessary, as it makes it possible to increase the efficiency of raw materials, water and energy, not to generate, reduce or recycle waste from manufacturing processes (Patrício Silva et al. 2020).

According to Camere and Karana (2018), materials from renewable, recycled and reused resources are increasingly in vogue as production alternatives. After all, due to the growth of the economy and increased consumption, raw materials are becoming scarce and, consequently, favoring environmental degradation. Areas such as biotechnology and biofabrication, explore alternatives such as the use of microorganisms for the manufacture of textiles, both for clothing and for the footwear industry (Scarlat et al. 2015).

Bacterial cellulose (CB) was first reported by Brown in 1886 during the fermentation of vinegar and described as "a kind of moist, swollen, gelatinous and slippery skin". Brown also noted that the substance called “vinegar plant” had the same structure, composition and reactivity as vegetable cellulose (Sharma and Bhardwaj 2019). In 1931, Hibbert and Barsha analyzed the chemical and structural composition of BC, and found that it was identical to vegetable cellulose (VC) in the molecular formula, however, it has particular characteristics (Cazón et al. 2020). Researchers claim that bacterial cellulose has better mechanical properties compared to vegetable cellulose, since VC has the structure combined with hemicellulose and lignin, while BC is highly pure, has greater resistance to traction, compressibility, elongation, greater porosity, greater crystallinity and biodegradability (He et al. 2020; Lin et al. 2020).

The use of the BC membrane can be observed in several areas such as biotechnology, pharmacy, biomedical sciences, cosmetics industry, bio-based packaging, paper, food industry and wastewater treatment (Cazón et al. 2020). It should also be noted that bacterial nanocellulose belongs to the category of products generally recognized as safe (GRAS) and can be useful for several applications (Sharma and Bhardwaj 2019a). Therefore, bacterial cellulose, considered ecological, renewable, organic and safe for the human body, inspired many design projects and caused a lot of attention in the fashion industry (Sederavičiūtė et al. 2019).

One of the forms of BC production is through the fermentation process of the ancient probiotic drink Kombuchá, of Chinese origin (Chan et al. 2018; Cardoso et al. 2020). Tea is produced as a nitrogen source for its culture medium, produced by dry leaves of *Camellia sinensis* and, for its fermentation, sugars with a symbiotic association of lactic acid bacteria are used as a carbon source (*Lactobacillus, Lactococcus*), acetic bacteria (*Acetobacter xylinum, Acetobacter xylinoides* or *Bacterium gluconicum*) and yeasts (*Saccharomyces cerevisiae* , *Zygosaccharomyces bailii*, *Schizoschachae bailii, Schiz*) (Ben Taheur et al. 2020; Velásquez-Riaño and Bojacá 2017).

Through fermentation of the Kombuchá culture, a floating biofilm develops over the fermented liquid, where they remain embedded, but can be transferred to other containers to propagate the inoculum (Filippis et al. 2018). It should be noted that agro-industrial waste serves as an economic substrate for the production of bacterial cellulose such as the use of red wine, beer, milk, juice and tea (Sharma and Bhardwaj 2019b). According to He et al. (2020), rice husks, cotton fabric residues, distillery wastewater, industrial residues from citrus bark drinks and sugarcane bagasse, have also been used to increase BC production at lower costs.

Therefore, this article aims to discuss the potential use of bacterial cellulose (BC) in the textile industry and studies on the applicability of BC to clothing and accessories. The research emphasizes the importance of reflections on waste generated in the manufacture of textile products, the problem surrounding the pollution generated by the sector, as well as, highlights the benefits of the biomaterial in line with the Sustainable Development Goals (SDGs).

Method

Since the research question seeks to understand the properties of bacterial cellulose, its applicability in the textile industry segment, the generation of waste and the relationship of the biomaterial with the Sustainable Development Goals (SDGs), an integrative literature review is conducted. An integrative review is a specific review method that summarizes past empirical or theoretical literature to provide a more comprehensive understanding of a particular phenomenon (Whittemore 2005). An integrative literature review also is defined as a form of research that reviews, critiques, and synthesizes representative literature on a topic such that new frameworks and perspectives on the topic are generated (Torraco 2016).

To conduct this integrative review, the databases chosen for the searches were: SpringerLink, Scopus and ScienceDirect, and included analyzes of official United Nations documents such as the SDGs and the United Nations Environment Program and the 2030 Agenda. Thus, to perform the literature review, 3 combinations of search terms were selected to write the topics, from a time frame from 2015 to 2021. Figure 1 exemplifies the method used to select the research articles for this review.

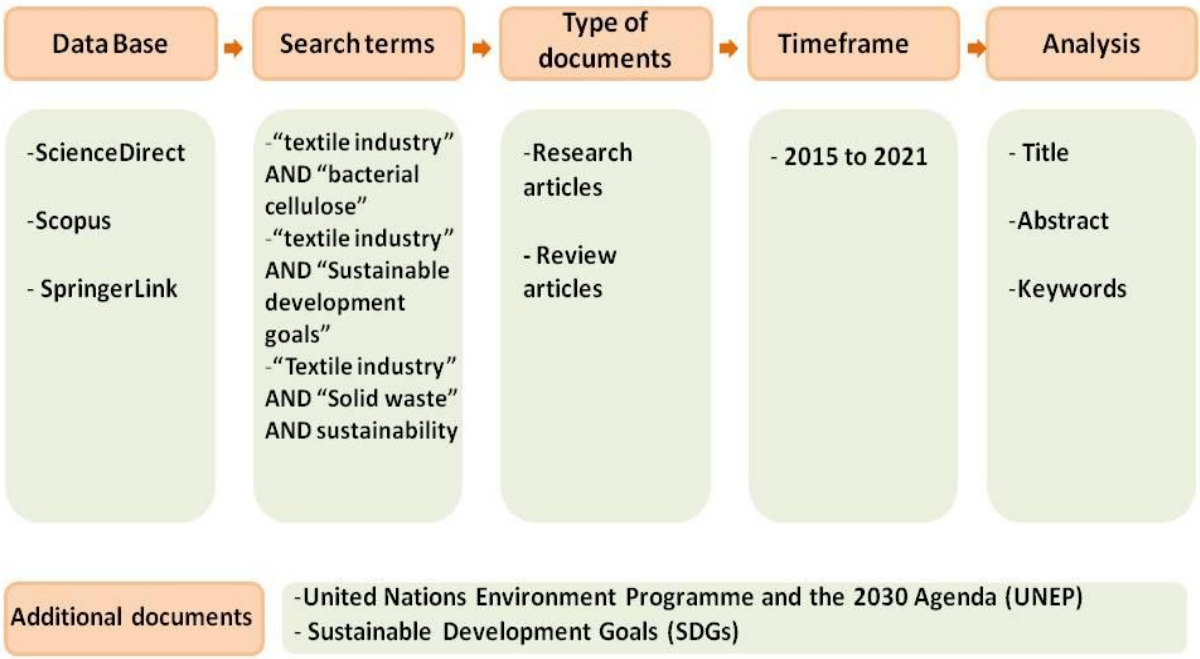


Fig 1 Exemplification of the method used for selection of research articles.

As seen in Figure 1, it should be noted that the peer reviewed articles were selected by opting for a timeframe between 2015 and 2021. Thus, inclusion and exclusion criteria were employed, which were the readings of the title, abstract and keywords, selecting only those articles that were compatible with the research theme. The complementary documents contributed to the dialogue between scientific research and government agencies.

Therefore, the results and discussions of this review article are structured as follows:

a) "Results and Discussion": presentation of the quantitative results for the realization of the review article;
b) "Textile industry and the problem of waste": compilation of studies found on the Textile Industry and the problem of pollution. The objective here is to understand in general the context of the pollution generated by the Textile Industry;

c) "Bacterial cellulose as an alternative for the manufacture of sustainable products in the textile industry": compilation of studies found on bacterial cellulose. The objective here is to understand in general the advantages and disadvantages of bio-textiles for the Textile Industry;

d) "The relationship of biomaterial with the Sustainable Development Goals (SDGs)": compilation of studies found on the Sustainable Development Goals (SDGs) and the potential of biomaterials. The objective here is to understand how biomaterials can contribute to achieving the goals.

Results and discussion

On searching the 3 groups of terms and using the "document type" and timeframe "2015 to 2021" filters, 92 results were returned in the Scopus database, 501 results in the ScienceDirect database and 318 results in the SpringerLink database. Table 1 shows a comparison between the search results.

Table 1 - Comparison between the search results in the databases.

Search terms	Scopus	ScienceDirect	SpringerLink
“textile industry” *AND* “bacterial cellulose”	40	59	67
“textile industry” *AND* “Sustainable development goals”	38	119	51
“Textile industry” AND “Solid waste” AND sustainability	14	323	200
Total	**92**	**501**	**318**

As shown in Table 1 was totaled 911 articles between 3 databases. For selection of articles, step 1 involved reading the title, abstract and keywords of each article. The publications which were aligned with the search theme were then selected and 763 articles were excluded. Thus, a total of 148 articles were read in full. In step 2, a further 84 research articles that were not aligned with the proposal of this review were excluded and the exclusion of 8 articles due to the repetition existing between the Science Direct, SpringerLink and Scopus databases, totaling 56 articles, were considered.

Textile industry and the problem of waste

The textile and apparel (T&C) industry provides essential consumer goods worldwide and the value generated by the global fashion industry is estimated at US$3,000 billion, which represents more than 2% of gross domestic product (GDP). However, it is also considered one of the most polluting and socially challenged industries. The manufacture of textiles requires large amounts of energy and water, the use of dyes (more than 100 L of water / kg of fabric) and the use of pesticides, herbicides and fertilizers during the cultivation phase, and socio-environmental issues include effluent contamination and poor conditions of work (Provin et al. 2021).

According to Stanescu (2021), a problem with big environmental impact in the textile field is the disposal of the products at the end of their life. Judicious management of the solid textile waste is absolutely necessary for a sustainable development of the textile industry. For waste, an important issue is the collection and sorting of the used clothes to manage their valorization so that positive changes come in this area. Concerning waste, an important role is played by the consumers in resisting consumerism and helping the recycling process.

The textile industry produces many pollutants in the form of liquid discharges, solid wastes, and air emissions to the environment. A variety of solid waste (fibers, yarn, woven, nonwoven, and knitted) is generated throughout textile production. The clothing sector creates a huge quantity of waste increasing each year due to fast fashion change. A quantity of 92 million tons of global fashion went waste in 2015, and an increase to 148 million tons is expected in 2030 (Stanescu 2021).

Man-made (synthetic) fibers, for example, have become the preferred choice over natural fibers over the past century. However, cotton is still the most common natural raw material in textile industry with more than 30% share. During the growth period of cotton, nutrients and pesticides are used to increase yield and product quality. Approximately 25% of global pesticide consumption in agriculture corresponds to cotton cultivation. Moreover, cotton is known as one of the most water-consuming crops with an average global water footprint of 4029 m3 /ton. In addition to the cultivation stage, a significant amount of water is required for processing as well. Water consumption of wet processing and the finishing stages of cotton textile production is 360 m^3/ton and 136 m^3/ton, respectively (Kazan et al. 2020).

Leather industries are also keenly monitored owing to their environmental pollution. Although they contribute significantly towards economic development, pressure from pollution control authorities and increasing environmental awareness has cornered them to adopt various sustainable strategies like cleaner processing methods using ecofriendly enzymes, waste minimization, etc.. United Nations Industrial Development Organization states that leather products are consumed by more than one-fourth of the world's population. In India, about 20–30 % of leather is discarded as waste during footwear and leather goods production (Senthil et al. 2015).

To Silva et al. (2021), the large number of textiles produced and discarded in the world is quite alarming, especially if linked to the development of fashion items, be they accessories, footwear, or clothing, which are characterized by a short life cycle. Approximately $ 172 million worth of garments is estimated to be disposed of in landfills each year, with large quantities of them being discarded after simple wear. In addition, despite the relevance of synthetic fibers as a raw material for modern life, their production, use, washing and disposal have caused environmental damage of enormous proportions. Studies have revealed that microplastics released from these synthetic textiles, as well as the incorrect disposal of fashion items and artifacts, cause irreversible damage to the ecosystem and its inhabitants.

According to Xu et al. (2020), microplastics (MPs, plastic particles < 5 mm) are an ever-increasing global issue due to their widespread occurrence in the environment and negative effects on organisms. Currently, more than 96% of MPs studies are related to marine systems, however, the majority of marine MPs pollution has been confirmed to originate from land-based sources. According to the different studies both in China and abroad, microfibers derived from textile washing attributed approximately 35% of the MPs identified in the aquatic system.

Deng et al. (2020) conducted an investigation of microplastic in water and sediment collected from a textile industrial area in Shaoxing City, China. The abundance of microplastics varied from 2.1 to 71.0 items/L in surface water samples, and from 16.7 to 1323.3 items/kg (dw) in sediment samples. The polymer was dominated by polyester both in water (95%) and sediment (79%). The majority of the detected microplastics was predominantly colored fibers smaller than 1 mm in diameter. The high level of microplastic pollution detected in local freshwater and sediment environments was attributed to the production and trading activities of textile industries, for which severe regulations should be envisaged in the future to effectively reduce the local microplastic pollution.

Due to the fact that the textile industry is one of the most expressive manufacturing sectors and consumes a large amount of water in its processes - between 60 and 100 kg of water per kilo of dyed and washed fabric, large amounts of effluent are generated that contain spent or unutilized resources from different stages of the textile process. Textile effluent is characterized by high chemical oxygen demand (COD) and temperature, and high loads of colour, inorganic salts, total dissolved solids (TDS), salinity, and complex chemicals, making water reuse a challenge (Couto et al. 2017).

According to Jadhav et al. (2015), textile industry is the major source of colored effluent because major chemical pollutants present in textile wastes are ‘‘dyes’’, while others include toxic heavy metals, pentachlorophenol, chlorine bleaching, halogen carriers, carcinogenic amines, free formaldehyde, biocides, salts, surfactants, disinfectants, solvents, and softeners etc. Several hazardous effects of textile effluent are reported worldwide on aquatic flora and fauna, animals, and even on humans.

Thus, with the increasing environmental awareness worldwide, companies are encouraged to design "greener" processes and products. Industrial biotechnology is especially emphasized on reductions of environmental impacts and risks, particularly in terms of climate change and fossil resource depletion, envisaging new economic viable and low impact bioproducts and bioprocesses (Forte et al. 2021). Figure 2 shows a comparison of decomposition between textile fibers and bacterial cellulose.

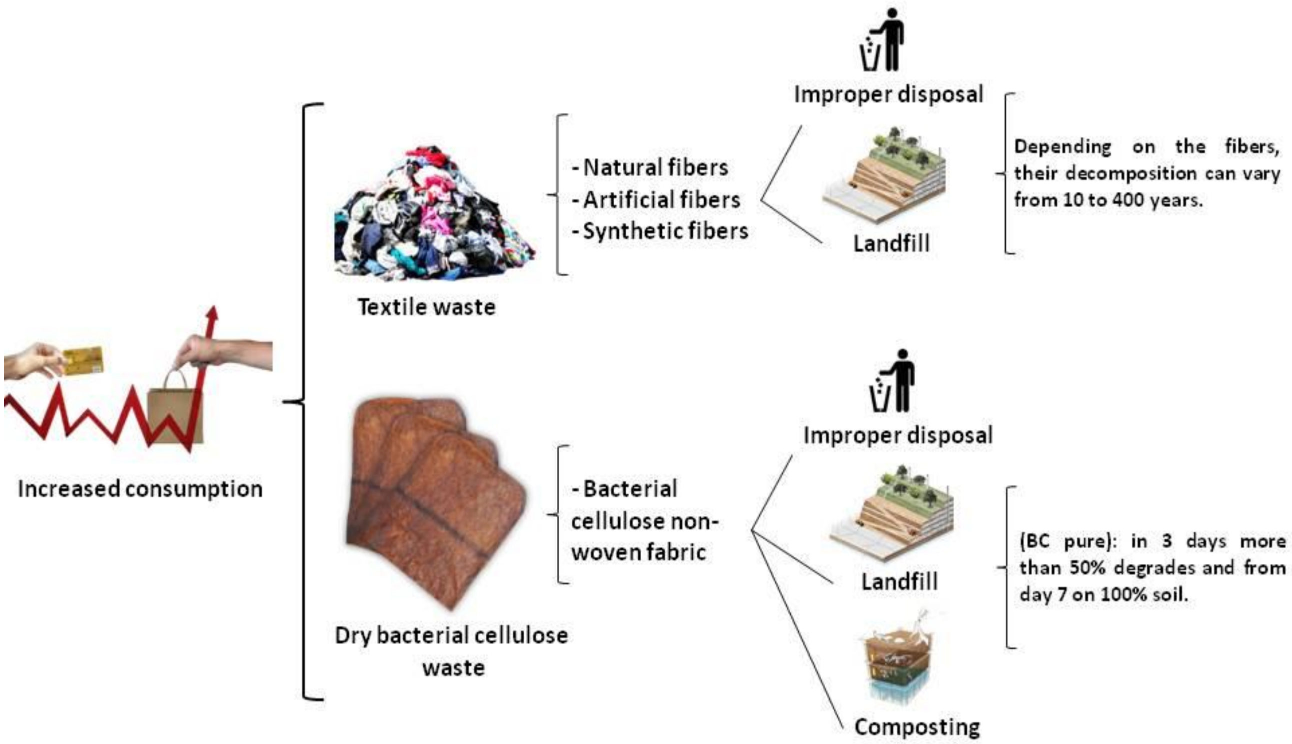


Fig. 2 Comparison of decomposition between textile fibers and bacterial cellulose.

According to scientific and technical research, textile fibers, especially synthetic fibers, take a long time to degrade, while bacterial cellulose has a rapid decomposition. However, future research on BC biodegradation, due to treatments used for the efficiency of the biomaterial, as well as the shelf life for a fashion product, should be carried out. Thus, the development of new products is always a great challenge that becomes even more complex when the aim is also to consider the sustainability implications of that product (Nemet et al. 2016).

According to Forte et al. (2021), dealing with bacterial cellulose (BC) (one of the sources of biomaterials for the manufacture of bioproducts), although the current production worldwide is quite small as compared to the plant cellulose based industries, assessing the environmental impacts of BC production may lead to better options in process design and optimization, considering the massive production for different market applications, while also considering the environmental sustainability.

Bacterial cellulose as an alternative for the manufacture of sustainable products in the textile industry

Textile manufacturing represents one of the oldest sectors in the world and still remains in constant growth (Buscio et al. 2019). It has a significant impact on economic development, job offers, produces differentiated products for domestic consumers and generates revenues from exports (Zhao and Lin 2019).

Industrial textile products can be subdivided into categories such as industrial textiles, medical textiles, geotextiles, agro-textiles, construction textiles, protective clothing, packaging textiles, sports textiles, automotive and aerospace textiles (Roy et al. 2020). However, the textile industry is a complex sector, due to its intense participation in activities that cause major negative environmental impacts such as the use of pesticides, large amounts of energy and water for the manufacture of articles, chemicals and inappropriate waste disposal (Luo et al. 2020).

When it comes to fashion, specifically on the Fast Fashion system, the idea of launching trends and products as quickly as possible with affordable prices has led to a great demand for the manufacture of various types of textiles (Haslinger et al. 2019). It was also observed that excessive consumption, waste of clothes and inappropriate disposals have become common phenomena (Chan et al. 2018; Hu et al. 2018). Due to the problems related to environmental degradation, scientists, designers and fashion designers seek to make their businesses more sustainable, turning their attention to biomaterials and their compatible properties (Domskiene et al. 2018)

Researchers have been concerned with projects from low to zero textile waste, but most (especially those that require cutting processes) are limited to special clothing patterns, so studies are focusing on exploring innovative textile materials (Chan et al. 2018). Bacterial cellulose, for example, has the potential to achieve sustainability from zero waste, being considered as a future material and green resource (Camere and Karana 2018).

Therefore, one solution would be to invest in areas such as biotechnology and biofabrication that explore alternatives, such as the use of microorganisms, for the manufacture of textiles, both for clothing and in the footwear industry (Saraç et al. 2019). The biofabrication of bacterial cellulose is regarded as a major bioeconomy technology, meaning its sustainability and associated footprint in the downstream processing and finishing phases should be closely monitored (Hildebrandt et al. 2021).

The use of biomaterials in the fashion sector can be promising, as the biomaterial can be grown as needed, reusing food and textile waste, and it is easily degraded (Sederavičiūtė et al. 2019). It is noteworthy that these microorganisms aerobically produce cellulose films that accumulate in the extracellular medium, can be generated in desired sizes and thicknesses and, when dry, produce a resistant material such as leather (García and Prieto 2019).

As the manufacture of leather depends on animal skins, the leather goods business has been discussed numerous times in relation to sustainability. Raising and slaughtering millions of animals whose skins feed the industry, can be considered inefficient, cruel and have an enormous environmental cost. A single pair of leather boots requires the use of> 50 m² of land and> 25,000 L of water for their production and can be toxic due to the presence of chromium VI compounds formed through the oxidation of chromium III used in the tanning process (García and Prieto 2019). The tannery industry faces several challenges associated with high environmental impact, scarcity of raw materials and increasing consumer demand for environmentally friendly products. Worldwide, for bovine skin, 370 billion liters of water are consumed annually, generating 6.5 million tons of solid waste (Fernandes et al. 2019).

The idea of BC as a potential leather substitute rests on the industrial production of cellulose fibres by members of the genera *Komagataeibacter* (also known as *Acetobacter xylinum*) (Rathinamoorthy and Kiruba 2020). This bacteria ingested as part of Kombuchá tea and other fermentations, enjoys Generally Regarded As Safe (GRAS) status (Sharma and Bhardwaj 2019a). These can be generated at desired thicknesses and when dried produce a resilient leather-like material with properties that resemble the type of animal leathers used in the footwear industry (García and Prieto 2018). According to Hildebrandt et al. (2020) the choice of the feedstock for bacterial conversion is very important as it affects the environmental footprint of the entire production process, as well as the properties of the final products, e.g., flame retardancy and hydrophobic properties.

Therefore, the use of bacterial cellulose has become a trend among designers in order to rethink materials, ways of production and contribution to sustainability. The probiotic Kombuchá drink, as mentioned earlier, is a sustainable source for the manufacture of these microorganisms (Costa et al. 2019). Suzanne Lee, founder of Biocouture, is a fashion designer and pioneer in the technique of using bacterial cellulose through fermentation of Kombuchá (https://www.launch.org/innovators/ suzanne-lee) (Kamiński et al. 2020).

The cellulosic membrane formed by bacteria is biodegradable and this biodegradability can be considered a successful application for a consistent approach within ecologically friendly products. Consequently, for the manufacture of bacterial cellulose, little water and energy is needed for its manufacture and is considered as an eco-friendly possibility for the textile industry (Yim et al. 2017).

Researchers are studying several innovative techniques for producing textiles using bacterial cellulose, one of which is “tailor-shaped cultivation”, as CB has the capacity to be cultivated and grow in any waya (Chan et al. 2018). Chan et al. (2018) they carried out tests using cultivation containers already in the shape of the garment mold called the vacuum molding technique, since the bacterial cellulose tissue membrane produced from the traditional cultivation container (rectangular or oval) requires additional cutting and generates waste.

The characteristics of the bacterial cellulose film, provided an innovative idea for the cultivation of seamless clothing, due to its direct 3D formation as a leaf (Ng and Wang 2015). It should be noted that the synthesis of CB can be conducted under static or dynamic conditions, resulting in different forms of cellulose, that is, three-dimensional interconnected reticular films and irregularly shaped cellulose particles, respectively, respectively (Chan et al. 2018; Costa et al. 2019).

According to Domskiene et al. (2019), investigating the unique features of BC film, researchers provided innovative ideas to grow seamless garments as direct 3D formation of BC sheets. Thus, scientists, working in the textile field, recently got interested in BC material, however, only a few studies are investigating this material as a new type of textile fabric for the fashion industry.

The functionalization and modification of BC have been achieved through chemical or mechanical alteration of the polymer, and by making adjustments to the conditions of cultivation. By controlling the growth of the producing bacteria, the BC generated could be tailored to have properties desired by the footwear industry (sheets of BC measuring 40 x 40 cm – a size compatible with footwear manufacturing requirements). If the solubility limitations of BC can be overcome, a BC-based printable fluid might be produced and used to 3D print shoes (García and Prieto 2018).

Ng and Wang (2015) performed tests related to the comfort and appearance of tissues obtained from bacterial cellulose. A total of 150 individuals participated in the test and the factors considered were comfort associated with touch, comfort associated with flexibility and comfort related to breathability. The result regarding the patterns analyzed was positive and it was possible to produce some prototypes of pieces of continuous 3D fashion (Ng and Wang 2015).

Although research on CB is growing fast, there are still many technical and practical problems associated with making clothes that need to be solved. Mechanical durability, comfort, contamination of the material, organic acids (responsible for the characteristic unpleasant smell), microorganisms (Kamiński et al. 2020) and how to adapt these materials to the production of large-scale commercial products (He et al. 2020) are some questions raised by researchers. The mentioned smell and brown color can be removed with the use of alkaline treatment, however, the alkaline purification method requires the use of significant amounts of water and neutralizers to obtain materials with neutral pH (Cacicedo et al. 2016).

Figure 3 illustrates the formation of clusters of the terms of the articles used in the research on bacterial cellulose and demonstrates which expressions were most cited, the relationships between them and the year in which they were most evident.

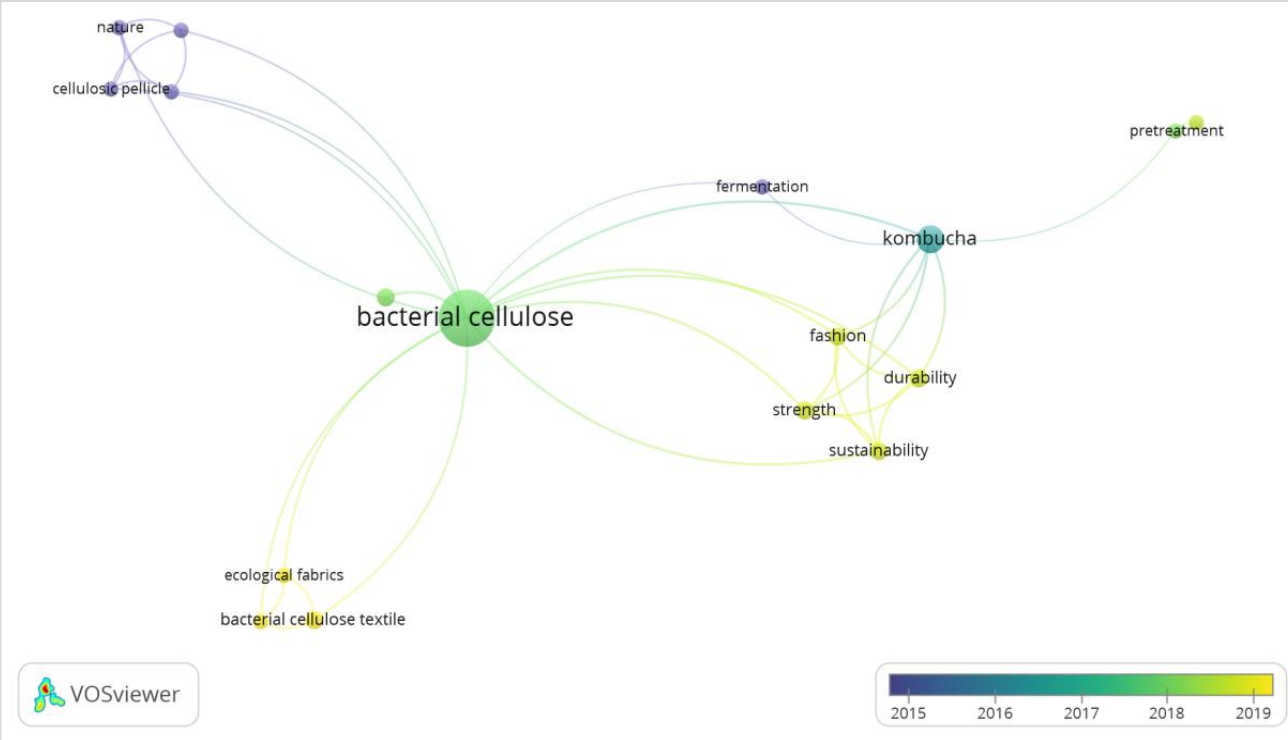


Fig. 3 Clusters of the terms of the articles used in the search.

In Figure 3, through the data collected in the scientific articles used for this research (in a timeframe between 2015 and 2021), it is possible to perform a chronological analysis of studies. Between 2015 and 2016, the terms of the study that obtained the highest number of occurrences were "Natural", "Cellulosic film", "Fermentation" and "Kombuchá". Between 2017 and 2018, the highest occurrences are observed in articles with the terms "bacterial cellulose" and "pretreatment" and, finally, the most recent articles include "fashion", "durability", "strength", "sustainability", "Ecological fabrics" and "bacterial cellulose textile" as expressions with more occurrences.

According to Cacicedo et al. (2016), despite its discovery in the 19th century, it is only in the last few decades that the attention of the research community in the academic and industrial fields has turned to this biomaterial. Especially with regard to investment in research related to the textile and fashion industries, these can be considered quite recent. Figure 4 shows the main advantages and disadvantages of bacterial cellulose in the textile industry pointed out by the studies read for this review article.

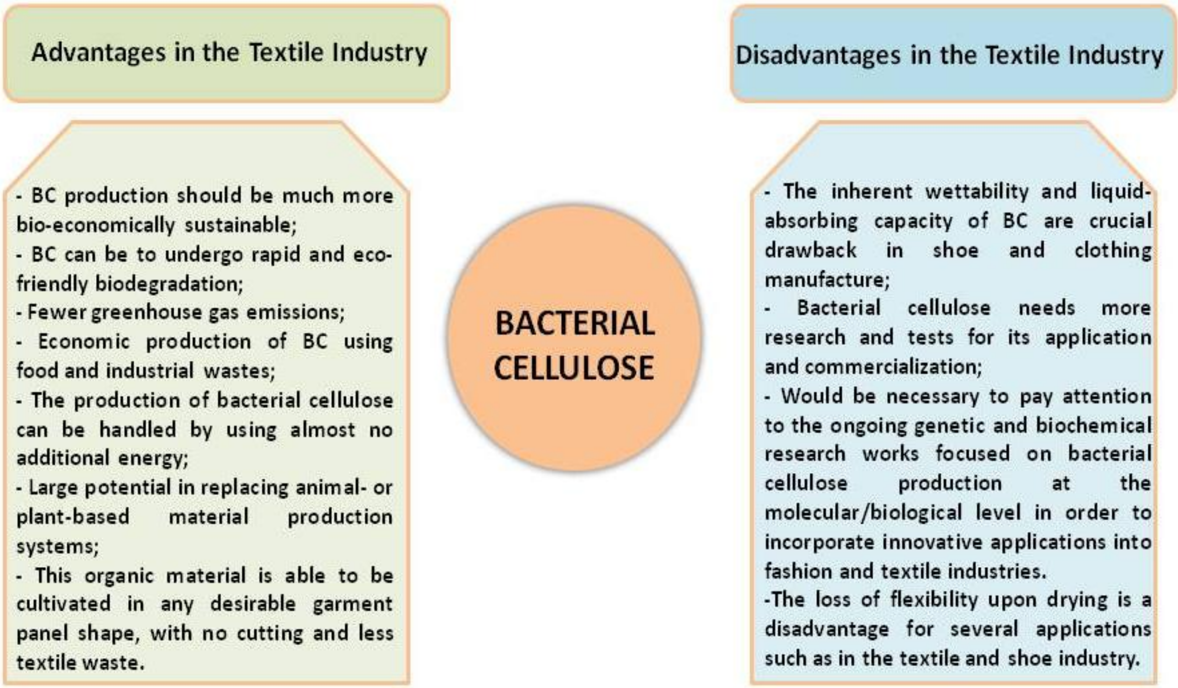


Fig. 4 Advantages and disadvantages of bacterial cellulose for textile application.

Thus, it is clear that further studies on the applicability of BC in the textile area are needed so that this biomaterial can be applied effectively and on a large commercial scale. Finally, according to Camere and Karana (2018), engineering seeks solutions that can be expanded, rather than to produce unique artistic pieces. Interdisciplinary collaborations are indispensable in confronting the complex challenge of sustainability, and experimentation through individualistic practices, as is the case of artisanal production, will not be effective. The results of this approach can often be applied to consumer products in the near future (Camere and Karana 2018).

The relationship of biomaterial with the Sustainable Development Goals (SDGs)

The textile industry is one of those responsible for the large volume of use of water, energy and the generation of chemical residues, therefore, it is necessary to implement the reach of sustainability in the textile chain (Neto et al. 2019). Industrial textiles are generally made of fiberglass fabrics and polyester fabrics. These are composed of macromolecules of repeated monomers making them less biodegradable and are not environmentally friendly.

It was observed that biotechnology and biofabrication, with the use of microorganisms for the production of biodegradable clothing, are consistent with cleaner technology without the need to exploit natural resources such as oil (Camere and Karana 2018), and, consequently, it needs less water and energy for its production (Yim et al. 2017). Thus, one of the ways of reflecting on the textile industry in order to reduce its negative environmental impacts was the emergence of new, more sustainable materials, as they are consistent with the SDGs (Neto et al. 2019; Subramanian et al. 2020).

In 2015, the United Nations formalized the 2030 Agenda, composed of 17 Sustainable Development Goals and 169 goals to be achieved (Undp 2015; Unep 2015). In order to "balance the three dimensions of sustainable development: economic, social and environmental", it is extremely important that the SDGs are discussed and explored in all their dimensions, both by universities and corporations. Therefore, understanding the SDGs is an essential achievement for estimating improvements in the three pillars of sustainability and directing future developments (Leal Filho et al. 2019)

According to the document "The United Nations Environment Programme and the 2030 Agenda", the UNEP Inquiry programme is looking into the design of a sustainable financial system, including policy options in support of financing a green economy (Unep 2015). Thus, in the case of the textile industry, environmental, social and economic issues must be rethought together with the 17 Sustainable Development Goals. However, this section will address some SDGs such as 9, 12 and 17, as they are related to issues such as the production process, materials, innovation and research incentives. Thus contributing to issues related to biotechnology.

According to SDG 9 (industry, innovation and infrastructure), the aim is to build resilient infrastructure, promote inclusive, sustainable industrialization and foster innovation. Mainly, regarding goal 9.4 which reinforces the modernization of infrastructure and rehabilitation of industries to make them sustainable, with increased efficiency in the use of resources and greater adoption of clean, and environmentally friendly technologies and processes (Undp 2015). Also included is goal 9.5, which aims to strengthen scientific research, improve the technological capabilities of industrial sectors in all countries, particularly developing countries (Undp 2015).

As seen in the literature, biotextiles are an innovation. Its production method can be characterized as a cleaner process, as it requires less water and energy for its manufacture (Yim et al. 2017). Despite numerous studies pointing out its ecofriendly properties, some limitations for its large-scale production are also highlighted (He et al. 2020). Therefore, investments in research and partnerships between universities and industries are necessary to achieve the necessary improvements for the use of biotextiles in the current market.

ODS 12 (responsible consumption and production) is also included, which aims to ensure sustainable production and consumption patterns (Undp 2015). Firstly, goal 12.5 stands out, which aims to substantially reduce the generation of waste through prevention, reduction, recycling and reuse (Undp 2015). Thus, the property of biodegradability is highlighted, therefore, biotextiles are not considered aggressive to the environment and can even be discarded in composters (Sánchez-Safont et al. 2018). As well as its moldability characteristic according to the container, the likelihood of low waste generation is immense (Chan et al. 2018). It is also worth mentioning the manufacturing process, as they can be produced using natural products (Velásquez-Riaño and Bojacá 2017) and, without the inclusion of toxic chemicals in the production process, it would avoid serious contamination of effluents.

Regarding target 12.c, which seeks incentives to rationalize inefficient subsidies to fossil fuels and minimize negative environmental impacts (Undp 2015), the manufacture of biomaterial is valuable, as it uses microorganisms without needing other natural resources such as oil (Scarlat et al. 2015). Thus, the importance of encouraging scientific and technological practices through goal 12.a, which aims to help developing countries to strengthen their scientific and technological capacities to move to more sustainable patterns of production and consumption (Undp 2015).

We also emphasize the importance of adding SDG 17 (partnerships and means of implementation), which promotes the strengthening of means of implementation and the revitalization of the global partnership for sustainable development (Undp 2015). Finally, goal 17.7 stands out, as it seeks to promote the development, transfer, dissemination and diffusion of environmentally friendly technologies to developing countries, making it possible for research to be carried out in other developing locations. collaborating for the spread of measures that provide conditions of sustainability (Undp 2015). Figure 5 illustrates this relationship between the biomaterial made from bacterial cellulose and the Sustainable Development Goals.

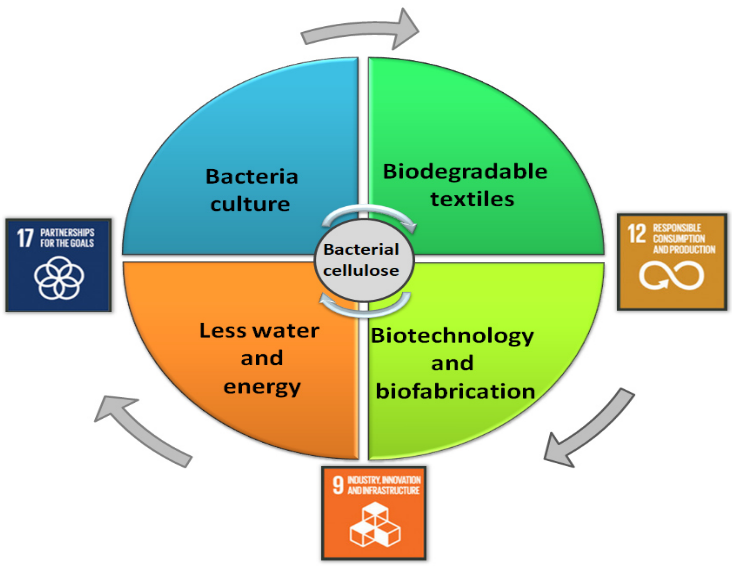


Fig. 5 Relationship of the biomaterial made from bacterial cellulose with the SDGs.

According to Silva et al. (2021), to achieve the proposed Sustainable Development Goals, it is necessary to use new technologies that aim to discover new raw materials, production processes, transformation, distribution and marketing. Biotechnology stands out for being a science capable of revolutionizing the production and supply of materials with the capacity for large-scale industrial applications, particularly to produce beverages, cosmetics, textiles and building materials.

To Dahiya et al. (2020), biobased products (biobased materials, bioenergy/biofuels, and biobased chemicals) are the futuristic replacement of fossil-based chemicals and considerably the best way of transiting towards a low-carbon economy (LCE) and which also can simultaneously mitigate the global challenges associated with the depletion of abiotic resources and climate change. The growing demand for environmental sustainability has encouraged research into biodegradable polymers, to minimize the environmental impact of conventional polymers (Balakrishnan et al. 2017).

According to the research carried out by Bentsen et al. (2019), the EU bioeconomy strategy aims to accelerate the European bioeconomy and its contributions to the United Nations Sustainable Development Goals and the Paris Agreement. Thus, it is possible to observe that national policies and strategies in many countries promote their bioeconomies and, an example of this is the importance of agricultural crops and their residues as a raw material for the bioeconomy, which is increasingly being recognized.

Highlighting the production of BC, waste from food industries and agricultural crops has great potential as primary or secondary feedstocks for biopolymer production by extraction or fermentation with pre-treatment or without pre-treatment by solid-state fermentation to obtain fermentable sugars. Various types of food waste can be used as substrates for the production of biomaterials (Ranganathan et al. 2020). Thus, one can observe the possibility of a Circular Economy through the use of waste from other sectors. With regard to waste management and circular economy, partnerships between sectors can be an excellent solution, since through interdisciplinarity one sector can provide a function for the waste generated in another (Wilkes et al. 2015).

Thus, fulfillment of the SDGs requires actions worldwide, not only from governments but also from the business and industrial sectors. An effective way to understand and improve the effects of business into the SDGs is the use of monitoring and evaluation systems. Such systems can serve as guidelines for improvement, since they can point out main business opportunities and threats in the road to SDG accomplishment (Almanza and Corona 2020).

Trends, future prospects and conclusions

The scarcity of raw materials and the need for waste recovery impose a new economic development policy which strives to keep the added values in the economy as long as possiblet.

Thus, the textile industry needs to be thoroughly reviewed and analyzed due to its importance as a generator of jobs and entrepreneurial opportunities for families.

However, it has a system with several negative environmental and social impacts that do not match the Sustainable Development Goals, suggested through Agenda 30 by the UN. The amount of waste generated by the Textile Industry is exorbitant, therefore, some aspects should be rethought: a) The non-generation of waste; b) Adequate management of existing waste; c) Creation of new biodegradable, sustainable materials that do not require the exploitation of natural resources.

Bacterial cellulose has been extensively researched and successfully used in many sectors such as healthcare and packaging. It is noteworthy that its use in the textile industry still needs more attention, as it has numerous advantages such as its biodegradability and its similarity to leather, but the issues of wettability, durability, among other treatments, still need research and tests for its commercialization.

Thus, thinking about biomaterials such as the use of bacterial cellulose, which is a biodegradable material, is a form of mitigation and is consistent with the SDGs. It is also worth mentioning the seriousness in stimulating and promoting scientific and industrial research for the good use and use of these biomaterials and wide dissemination to developing countries as proposed by the UN.

It is hoped that this review article can contribute to future studies, as this review tried to show the importance of investing in biomaterials such as bacterial cellulose and its coherence with the Sustainable Development Goals. However, as mentioned above, more research is needed around its properties, applicability and commercialization.

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CAPÍTULO 5

USE OF BACTERIAL CELLULOSE IN THE TEXTILE INDUSTRY AND THE WETTABILITY CHALLENGE - A REVIEW

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USE OF BACTERIAL CELLULOSE IN THE TEXTILE INDUSTRY AND THE WETTABILITY CHALLENGE - A REVIEW

Abstract: Bacterial cellulose (BC) has been studied as an alternative material in several segments of the food, pharmaceutical, materials and textile industries. The importance of BC is linked to sustainability goals, since it is an easily degradable biomaterial of low toxicity to the environment and is a renewable raw material. For use in the textile area, bacterial cellulose has attracted great interest from researchers, but it presents some challenges notably to its hydrophilic structure. This integrative review article brings together studies and methods related to minimizing the hydrophilicity of bacterial cellulose, in order to expand its applicability in the textile industry in its dry state. The databases consulted were Scopus, ScienceDirect, ProQuest and Web of Science, the documents investigated were scientific articles and the time period investigated was between 2015 and 2021. The results showed that although there are methods to make the BC membrane more hydrophobic, future studies in this regard and on other properties must continue so that bacterial cellulose can be commercially introduced in the textile sector.

Keywords: Textile Industry. Bio-textile. Sustainability. Bacterial cellulose. Wettability.

1. Introduction

The textile industry is associated with numerous environmental problems. Large amounts of harmful waste are generated at all stages of clothing manufacturing, with negative environmental and social impacts, such as landfill consumption, low resource efficiency and air/soil pollution (Chan et al., 2018; Correia and Silva, 2019; Sandvik and Stubbs, 2017). Although the garments are used for a relatively long period, even by several consecutive users, studies have demonstrated that the manufacture of cotton garments, for example, is extremely polluting.

To obtain 1 kg of cotton fiber, 29 tons of water are consumed. In total, 25% of all insecticides and more than 11% of pesticides used globally in agriculture are applied to cotton crops. The amount of material that requires disposal presents a real challenge for the fashion industry. This quantity has increased notably in the past 50 years, with around 15 million tons of used textile waste currently being generated each year in the USA (Domskiene et al., 2019).

The quest to make the fashion industry more sustainable has increasingly directed designers and scientists to focus on biomaterials such as bacterial cellulose (BC), and their biocompatible properties. BC is environmentally friendly, safe for the human body and considered a renewable raw material and one way to obtain it is through the Kombuchá fermentation process (Domskiene et al., 2019). It is a natural, non-woven material, with a firm structure, with an aspect that resembles leather when dry (Chan et al., 2018; Domskiene et al., 2019; Sederavičiūtė et al., 2019).

Biomaterials are mixtures of natural substances that offer biocompatibility and they can improve the quality of life of individuals and increase longevity and comfort (Costa et al., 2019b).

Domskiene et al. (2019) noted that the use of biomaterials in the fashion trade is very promising, since the material can be grown as required from waste food and used clothing can be easily decomposed and biodegraded (Domskiene et al. 2019). Cellulose is one of the most abundant polymers on Earth and most of it is plant cellulose (PC), however, bacterial cellulose (BC) offers an interesting alternative, such as biomaterials (Costa et al. 2019).

BC was first reported in 1988 by Brown, who identified a structure chemically equivalent to PC, through the growth of an unbranched film (Costa et al. 2019; Römling and Galperin, 2015; Sederavičiūtė et al. 2019). The most effective sources for the production of BC are *Acetobacter xylinum* (also called *Gluconacetobacter xylinum)*, *Acetobacter hansenii* and *Acetobacter pasteurianus*. Of these, *A. xylinum* has been most used for the production of commercially-available BC due to the high levels of productivity attained (Naeem et al., 2018; Wang et al., 2019).

One of the ways to produce BC is in the production of Kombuchá, a probiotic drink which, according to the earliest records, originated in northeastern China in mid-220 AD. It appeared during the Chin dynasty, when a Korean doctor called " Kombu " used the "che" for treatments, thus originating the name Kombuchá (Amarasekara et al., 2020). After the Second World War, the use of Kombuchá became popular in Western countries due to its multiple functional properties, and the drink subsequently spread worldwide (Dima et al., 2017; Dutta and Paul, 2019).

Fermentation is considered to be one of the oldest methods for obtaining drinks and involves a low cost energy conservation system (Dutta and Paul 2019). BC fermentation is carried out during the tea fermentation process, generating a cellulose-based biofilm at the air-liquid interface. This is generated by the symbiotic culture of bacteria and yeasts (SCOBY) and is considered as a waste product, but it represents an important potential source of BC (Dutta and Paul 2019; Kamiński et al. 2020; Leal et al. 2018; Villarreal-Soto et al., 2018).

Some authors have reported the applicability of bacterial cellulose for different purposes. Lin et al. (2020), in a recent review, address cellulose in the food industry, while Volova et al. (2019) suggested BC-based biotechnological dressings for the health sector. Furthermore, Costa et al. (2019) stated that BC is able to play a role as a substitute for other materials in the textile area and Araújo et al. (2015) developed a hydrophobic BC material which may have interesting applications for use in textile materials, clothes, flooring and other interior design materials (Araújo et al. 2015; Costa et al. 2019).

In the case of the textile industry, materials for the production of clothing must provide a required set of properties, such as strength, body fit and comfort. Scientists working in the textile field have recently become interested in BC, but this material presents challenges to be overcome before it can be widely applied as a new type of textile fabric for the fashion industry (Domskiene et al. 2019). Despite offering excellent hydrophilicity for some sectors, such as biomedicine and cosmetology, due to its porous structure, this characteristic poses a problem for some uses in the textile industry (Domskiene et al. 2019; Halib et al. 2019; Kamiński et al. 2020).

In this context, the objective of this article is to present an integrative review of the academic literature, understanding its hydrophilic property and the treatments available to make it hydrophobic. Despite numerous studies on hydrophobicity and bacterial cellulose membranes in several areas, research directed at the textile industry or on the dry BC membrane was selected. Thus, some potential applications of BC in the textile sector and the importance of future research with biomaterials are discussed.

2. Methods

Since the research question seeks to understand the wettability properties of bacterial cellulose and its applicability in the textile industry segment, an integrative literature review is conducted. An integrative review is a specific review method that summarizes past empirical or theoretical literature to provide a more comprehensive understanding of a particular phenomenon (Whittemore, 2005). An integrative literature review also is defined as a form of research that reviews, critiques, and synthesizes representative literature on a topic such that new frameworks and perspectives on the topic are generated (Torraco, 2005; Torraco, 2016).

To conduct this integrative review, the databases chosen for the searches were: Scopus, ScienceDirect, ProQuest and Web of science. Thus, to perform the literature review, 3 combinations of search terms were selected for writing the topics. **Figure 1** exemplifies the method used to select research articles for this review.

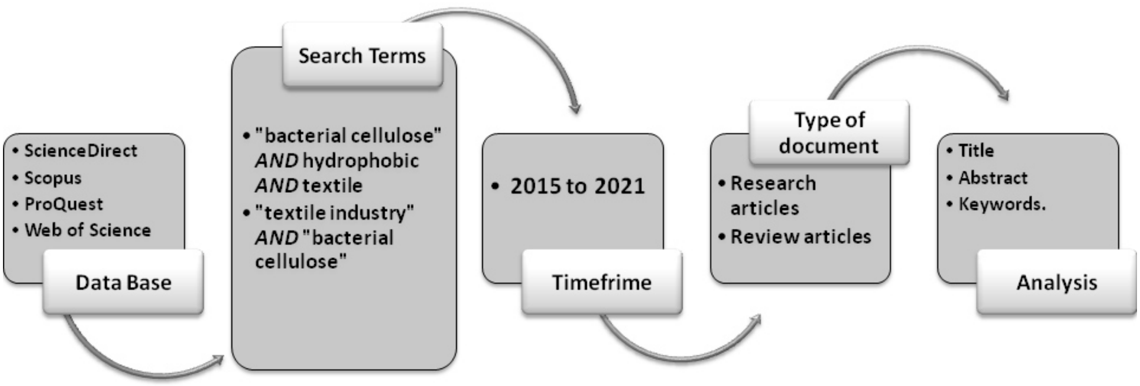

Fig. 1 Flow diagram of the method used for the identification of relevant articles.

As seen in **Figure 1**, it should be noted that the peer reviewed articles were selected by opting for a timeframe between 2015 and 2021. Thus, inclusion and exclusion criteria were employed, which were the readings of the title, abstract and keywords, selecting only those articles that were compatible with the research theme.

Therefore, the results and discussions of this review article are structured as follows:

a) "3. Results and Discussion": presentation of the quantitative results for the realization of the integrative review article;

b) "3.1 Analysis of databases";

c) "3.2 Final selection and analysis of articles";

d) "3.3 The hydrophilicity properties of bacterial cellulose": Description of the high hydrophilicity of bacterial cellulose. In this section, it is not just articles focused on the textile sector, but research that specifically describes the natural properties of bacterial cellulose.

e) "3.4 Studies and alternatives for hydrophobic bacterial cellulose": Description of methods for making bacterial cellulose more hydrophobic. In this section, only articles focused on the textile industry or experiments with dry bacterial cellulose that could contribute to the sector were included.

f) "3.5 Bacterial cellulose applications for the textile industry": Finally, in this section, the application possibilities, advantages and disadvantages of bacterial cellulose for the textile industry were described and discussed.

3. Results and Discussions

3.1 Analysis of databases

For each database, two groups of search terms were used: (“bacterial cellulose” AND hydrophobic AND textiles) and ("textile industry" AND bacterial cellulose). **Figure 2** shows the final results of the search, including the filters used, which were the search terms, timeframe and type of document.

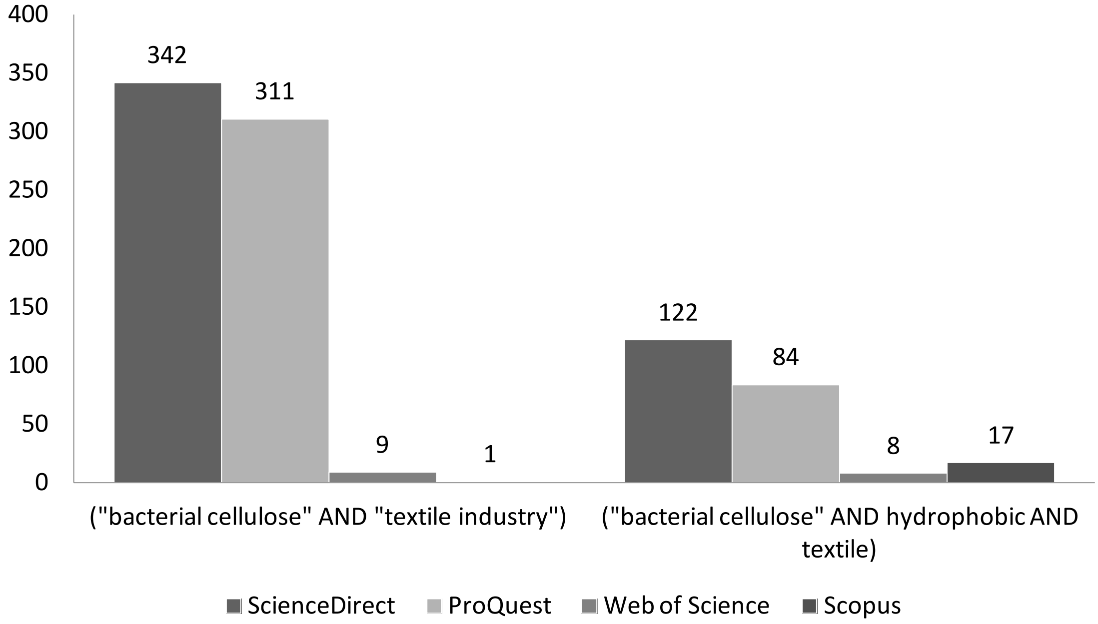

Fig. 2 Search results for the databases and after applying the filters.

As shown in **Figure 2**, a higher number of documents was identified in the ScienceDirect database, followed by ProQuest, using the search terms, document type and timeframe filters. The first group of terms ("textile industry" AND "bacterial cellulose") collected a total of 663 articles. The second group of terms ("bacterial cellulose" AND hydrophobic AND textiles), on the other hand, brought together 231. This data shows the small number of studies directed mainly at the second group of terms.

3.2 Final selection and analysis of articles

The final selection of the articles considered for the writing of this review was carried out in two stages. Stage 1 involved the reading of the title, abstract and keywords of each article. Those that were aligned with the search theme, that is, the articles that mentioned bacterial cellulose, its hydrophobicity and its use in textiles were selected. In step 2, the articles were read in full and based on the content only those that would aid the construction of the integrative review were selected.

In this process, the number of articles excluded from the first group of terms ("textile industry" *AND* "bacterial cellulose") was 641 among the four databases: ScienceDirect, ProQuest, Web of Science and Scopus. The number of articles excluded from the second group of terms ("bacterial cellulose" *AND* hydrophobic *AND* textiles) was 216 among the four databases. The exclusion criteria involved articles repeated between the databases and articles that were not compatible with the proposal of the present review article. Thus, 37 articles were considered for the review and the details of this final selection process can be seen in **Figure 3**.

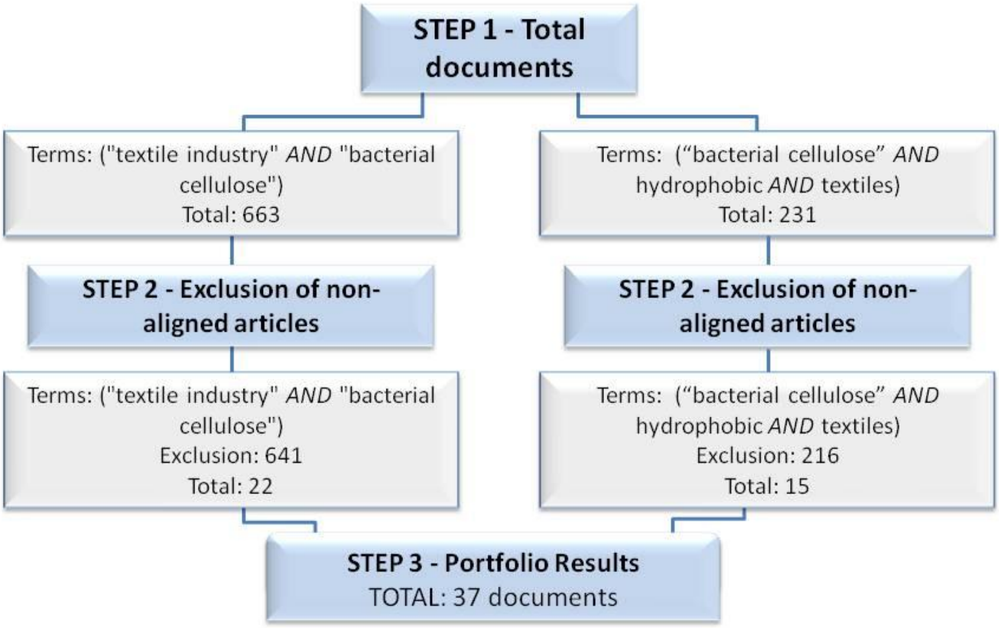

Fig. 3 Final selection of articles used for the review article.

From the process applied in this research, as shown in **Figure 3**, it was possible to select a set of articles that contributed to a better understanding of the natural properties of bacterial cellulose. In addition, the main focus of this article was the methods of obtaining more hydrophobic bacterial cellulose and its application in the textile industry.

3.3 The hydrophilicity properties of bacterial cellulose

Bacterial cellulose (BC), in addition to its mechanical resistance, has several attractive physical properties. It has higher purity compared to cellulose of plant origin, along with greater flexibility, greater hydrophilicity, tensile strength, biodegradability and transparency (Dima et al., 2017; Martins et al., 2020; Naeem et al., 2018). It should be noted that to review the literature on methods of hydrophobization of bacterial cellulose, it is necessary to understand the natural hydrophilic state of BC.

Researchers have reported that hydrophilic nature and water retention capacity of BC are influenced by the arrangement of the fibrils and the high surface area per unit of mass (Naeem et al., 2018; Shim et al., 2019a; Shim et al. 2019b). According to Paximada et al., (2020) and Sederavičiūtė et al. (2019), BC material has a high moisture content, since water binds to the OH groups of the material, making it hydrophilic. The moisture content results from the microstructure of the BC material and affects both the physical and mechanical properties, such as density, thickness, tensile strength and plasticity.

According to García and Prieto (2018), BC can store over 90% its own weight of water. In studies reported by Halib et al. (2019), BC molecules lead to a highly swollen three-dimensional (3D) network and pore structures that are capable of holding a maximum of 99% water, resulting in BC as a promising material for obtaining highly biocompatible tissue structures. The authors emphasize that the properties of BC can be altered by different chemical changes which can be used to improve the properties according to different applications.

According to Sederavičiūtė et al. (2019) and Martins et al. (2020), due to the hydrophilic nature of BC, the search for stability of the material dimensions is relevant, because during drying the sample can shrink. Domskiene et al. (2018) also describes in his research that although BC film has properties which attract great interest, studies show that it can undergo deformation and it is difficult to guarantee a uniform structure, thickness and porosity, and therefore the material is not durable.

As an example of these changes in relation to BC instability, in the research by Dima et al. (2017) and collaborators, a hydrophilicity of approximately 1 g of bacterial nanocellulose (BNC) was found: 100 ml of water, after samples of a stable aqueous suspension had been dried in an oven at 70 °C for 3 days. Although the hydrophilicity is an interesting property for some sectors, without hydrophobic treatment, it limits the use of this material.

In addition, the BC water retention capacity can be varied by using different combinations of culture media, which can alter its structure and thus modify its properties (Bagewadi et al., 2020). Recent research on hydrophilicity found that when this feature of BC is desirable, there is potential for increasing this property. Jiang et al. (2020) reported the biological modification of bacterial cellulose (BC) using various alginates with different molecular weights as a carbon source in the fermentation medium.

According to Jiang et al. (2020), the presence of sodium alginate (SA) had a strong influence on the microstructure of the components resulting from bacterial cellulose incorporated with sodium alginate (SA-BCs) and results indicated that the hydrophilicity of SA-BC was strengthened and suggested the presence of a carboxyl group.

Li et al. (2020) manufactured polymer-modified carbonization bacterial cellulose (CBC) electrodes using varying amounts of cation exchange polymers (glutaric acid (GA) and sulfosuccinic acid (SSA)). The polymer-modified CBC electrodes showed good wettability, due to the addition of oxygen-containing groups that increase the hydrophilicity of the CBC. The high content of the hydrophilic group contributes to the excellent electrosorption performance of the electrodes prepared.

These are some notes from the vast existing literature on the hydrophilicity of bacterial cellulose. Despite the extremely hydrophilic characteristic of BC, Wood (2019) noted that this property is not suitable for use under conditions of high humidity, which can increase with proximity to human skin. Thus, for the production of textile fabrics, the thickness and uniformity of the material are priorities of great importance in the drying process, but the BC dimensions change and it becomes highly hydrophilic during the drying step (Domskiene et al. 2019).

Studies have also shown that the material properties need to be altered prior to biosynthesis (in situ), which changes the intrinsic biophysical properties, in the case of cellulose fibers through the incorporation of bioactive molecules, modifying the porosity and/or crystallinity of BC (Fernandes et al., 2019). Also, the application of chemical finishing can reduce the hydrophilicity of the BC film surface, potentially allowing its application under different conditions. In this way, properties similar to those of clothing fibers can be produced, depending on the parameters of the fermentation process, the application of which is growing in the fashion industry (Domskiene et al. 2019).

3.4 Studies and alternatives for a hydrophobic bacterial cellulose

Regarding its application in the textile and footwear sectors, the first proof of concept of the use of BC as an alternative to leather emerged in the 1990s, in the Philippines. In the last decade, the designer Suzanne Lee has expanded the possibility of using BC in the manufacture of clothing and footwear, by resorting to the handmade production of BC (Fernandes et al., 2019). Bio-couture is a project that is being carried out to explore and experiment with different textile biomaterials or the production of textiles. It is based on the idea that minimal resources and chemicals are needed for production and are biodegradable (Laavanya et al., 2021).

Since then, other studies have mainly focused on comfort and appearance, overlooking important properties such as breaking strength, elongation at break or hydrophobicity (Fernandes et al., 2019; Rathinamoorthy and Kiruba, 2020; Song and Kim, 2019). The inherent wettability and liquid-absorbing capacity of BC are beneficial in some applications, but are crucial drawback in shoe manufacture (García and Prieto, 2018). In the textile industry, a hydrophobic cellulose is required because it has a wide range of applications, not only in conventional applications, such as in functional applications like in clothing, waterproof textile stain resistant (oils), among others (Araújo et al., 2015; Song and Kim, 2019).

However, some living organisms possess superhydrophobic surfaces that are being imitated by polymer chemists, and these may be bonded to BC to generate materials with super-antiwetting and even self-cleaning properties. Covalent functionalization, which generally involves reactive hydroxyl groups on the BC surface, is a favoured strategy. Melt processing, such as extrusion or injection moulding, may also be viable at the industrial level. However, the inherent incompatibility between hydrophilic cellulose and generally hydrophobic polymer matrices, as well as thermal stability issues, needs to be addressed (García and Prieto, 2018).

The use of exogenous molecules in BC production, through the *in situ* method, leads to different results for the BC properties. *In situ* modification is less commonly applied, since the application of hydrophobic matrices can result in weak interfacial bonds with cellulose (hydrophilic) and chemical compatibility is therefore a prerequisite (Fernandes et al. 2019). According to Fernandes et al. (2019), application is suitable only for cases of polymerization in liquid solutions, where cellulose can be distributed in the polymerization medium**. Figure 4** shows the methods of the authors found for the writing of this review article and which will be detailed throughout this section.

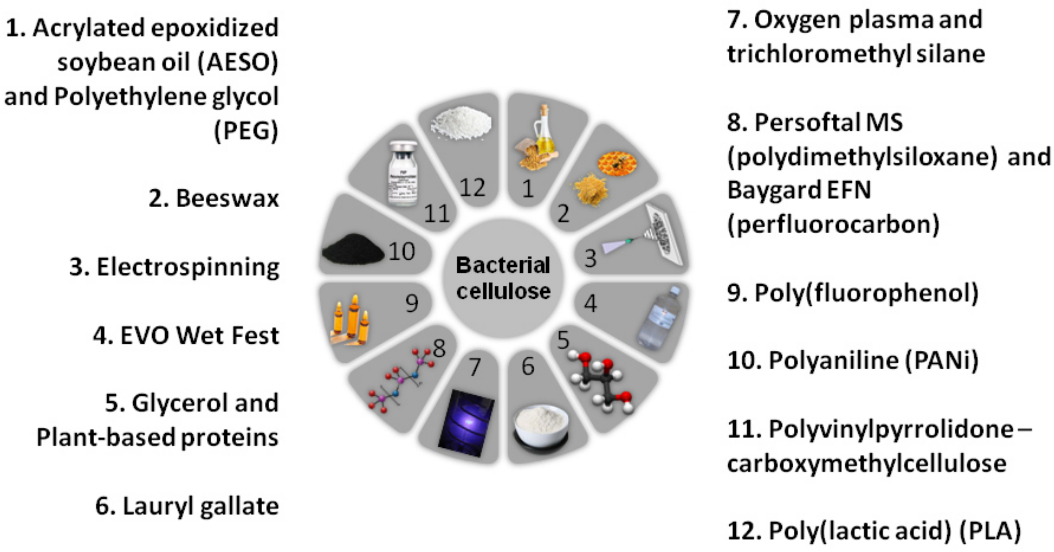

Fig. 4 Hydrophobization methodologies for bacterial cellulose.

3.4.1 Methods hydrophobic through commercial products

According to Fernandes et al. (2019), through a simple and cost-effective process, hydrophobized, robust, malleable and breathable nanocomposites based on BC were obtained, featuring promising properties for application in the textile and shoe industries. Hydrophobic surfaces may be obtained through the creation of hierarchical roughness or through the control of the surface chemistry, decreasing the surface energy. Samples were oven dried (WTC binder oven) at 25°C for 48 h, followed by a curing step for 30 min at 120°C. To avoid shrinkage of the samples during drying and curing, the composite BC membranes were attached to a zinc-plated wire support.

The research aimed at producing malleable, breathable and water impermeable bacterial cellulose based nanocomposites, by impregnating bacterial cellulose (BC) membranes with two commercial hydrophobic polymers used in textile finishing, Persoftal MS (polydimethylsiloxane) and Baygard EFN (perfluorocarbon), by an exhaustion process. The water contact angle (CA) was measured on BC (≅63.8°). After incorporation of the polymers, overall, higher contact angles were obtained (≅105º), indicative of more hydrophobic surfaces (Fernandes et al., 2019).

Araújo et al. (2015) and collaborators used commercial hydrophobic products from DyStar textile that were given to obtain the hydrophobic cellulose and the hydrophobic finishing agent is EVO Wet Fest. The hydrophobic finishing process, where used two different methods. The first method employed was that is customarily used in the textile industry, 6 BC samples were placed in a bath of 0.5ml softener, and then placed in a bath with hydrophobic finishing agent.

These hydrophobic finishing baths were composed of distilled water, acetic acid 60% and hydrophobic product with two concentrations 1.5ml/l and 6ml/l. The second method is the opposite of the first, the 6 samples were placed initially in a hydrophobic finishing bath and finally in a softener bath (followed the same amounts mentioned above for the various finishing hydrophobic baths). The different samples were dried in an oven at 120ºC for 1 minute (Araújo et al., 2015).

The test of the contact angle achieved proves that it is possible to obtain hydrophobic BC with minimal quantities of hydrophobic finishing agents. According to the authors, the control sample reached an angle of approximately 43º, while samples that passed through the hydrophobicity processes reached an angle of approximately 108º. With these results we can see that besides the added value to make BC a hydrophobic material it can be also obtained a more homogeneous surface morphology with a more uniform fiber surface (Araújo et al., 2015).

3.4.2 Hydrophobic methods using plant products

According to Fernandes et al. (2019), vegetable oils (OVs) were used. Vegetable oils (VOs) are abundant renewable resources with an increasing number of industrial applications. Basically, these biopolymers are composed of triglycerides.They offer the advantages of low cost, nontoxicity and biodegradability. Among the VOs, soybean oil is one of the most attractive due to its low price and abundant availability. To increase their reactivity, double bonds can be replaced by more reactive functional groups such as epoxide, acrylate, hydroxyl or maleate.

Most commonly, double bonds are epoxidized and then acrylated, reacting with carboxyl groups of acrylic acids, allowing free radical polymerization. Acrylated epoxidized soybean oil (AESO) has been studied extensively in the production of composites with high renewable content. AESO was used in this work to produce a hydrophobic composite with high bio-based content (Fernandes et al., 2019).

A mixture was prepared by adding different reactive monomers to AESO at room temperature. This mixture was composed of acrylated epoxidized soybean oil (50% m/m); lauryl methacrylate (40% m/m)-a fatty acid-based reactive diluent, potentially bio-based, which reduces the viscosity of the mixture; 1,6-hexanodiol diacrylate (5% m/m); and tri(propylene glycol m/m) diacrylate (5% m/m)-bifunctional monomers which can enhance the crosslinking. BC membranes (with about 3.0 cm in thickness, with a size of 12.0 × 2.5 cm and weighting 90 g) were each treated by exhaustion with 100 g of emulsified AESO mixture for 9 days at 40 °C followed by a 3 h curing step at 90 °C, to accelerate the cross-link of the emulsified AESO mixture. The composites were then dried at 40 °C in an oven (WTC series) for 5 days (Fernandes et al., 2019).

The wetting properties of the BC and BC-based composites were investigated by measuring the water contact angles (WCAs). BC has a highly hydrophilic surface, bearing the lowest water droplet angle (63.1°), which increased for the BC composites to values between 79.0° and 138.0°, indicating a significant increase in hydrophobicity. Values of 95.8° and 79.0° were observed for BC/AESO and BC/AESO/PEG, respectively. AESO, despite being more hydrophobic, the WCAs over time decreased quickly in these BC composites, as compared to BC (Fernandes et al., 2019).

This can be explained by the closed structure of the dried BC that limits the water diffusion through the tight space between the nanofibers, due to the strong and high number of cellulose–cellulose hydrogen bonds. Among the different polymers tested, AESO was the one that offered less hydrophobicity, and the incorporation of the polyethylene glycol (PEG), being hydrophilic as observed above, increased the value of the polar component (Fernandes et al. 2019).

Kim et al. (2021) and collaborators carried out a study with the aimed to develop eco-friendly bacterial cellulose (BC) bio-leather with improved durability using plant-based proteins, namely soy protein isolate (SPI) and mushroom protein (MP), which were physically entrapped inside the BC, respectively. The enhanced properties of mechanical strength and durability of BC bio-leather were measured in terms of changes in water resistance, tensile strength, flexibility, crease recovery, and dimensional stability. Before testing, BC bio-leathers were dried in a drying oven at 25 °C for 5 h.

The water resistance of BC bio-leather was measured by water contact angle (WCA) and the water absorption time. The original BC had the lowest WCA (79º). This is due to the free hydroxyl groups in BC, which exhibit hydrophilic properties. BC-glycerol also had a low WCA, which was related to the hydrophilic behavior of glycerol (81º). After physical entrapment of plant-based proteins inside BC, WCAs were increased significantly. The increased WCAs could be attributed to the formation of hydrogen bonding between BC fibers and plantbased proteins, reducing the number of free hydroxyl groups, and thus increasing the hydrophobicity of BC bio-leather (Kim et al., 2021).

It was also found that BC entrapped with both protein and glycerol had improved WCA than BC entrapped with protein only. According to authors, this could be explained by the rearrangement of hydrophobic moieties of protein molecules: Glycerol may strengthen the interactions with protein molecules by forming hydrogen bonds, resulting in the reorientation of hydrophobic moieties of proteins on the surface of BC bio-leathers. Moreover, both BC-SPI (with glycerol) and BC-MP (with glycerol) were found to have better WCAs when glycerol was added: BC-SPI (with glycerol)= 110º; BC-SPI (without glycerol)= 90º; BC-MP (with glycerol)= 110º; BC-MP (without glycerol)= 105º (Kim et al., 2021).

3.4.3 Hydrophobic methods for packaging that can contribute to the Textile Industry

Patwa et al. (2019) researched a hydrophobicity method for application in bacterial cellulose. The authors' research was also directed towards packaging and the membrane was studied for use in the dry state. This research can contribute to the textile industry, both for its use in clothing and for packaging in the fabric sector. BC films were carefully kept in vacuum oven 40 ºC for 12 h.

According to authors, the synthesis of lactic acid oligomer-grafted-untreated bacterial cellulose (OLLA-g-BC) by in situ condensation polymerization increased compatibilization between hydrophobic poly(lactic acid) (PLA) and hydrophilic BC, thus enhancing various properties of PLA-based bionanocomposites, indispensable for stringent food-packaging applications (Patwa et al., 2019).

The surface wetting characteristics of the PLA/OLLA-g-BC and bionanocomposite films was studied using the sessile drop contact angle measurements. The contact angle measured for PLA was around 83.5 ± 0.8º. Due to the in situ polymerization, condensation polymerization, the grafting process occurred where the polar (OH) groups on BC backbone were replaced by hydrophobic ester groups of OLLA. As a result of which, at low loadings of OLLA-g-BC fillers, that is, 5 wt % and 10 wt %, the contact angles were 102.5 ± 1.7º, 85.4 ± 1.7º, respectively. According to authors, upon further increasing the filler concentration, agglomeration of filler particles takes place which results in improper dispersion thus affecting the surface roughness and as a result of which the wettability of the films is similar to PLA (Patwa et al., 2019).

Bandyopadhyay et al. (2019) carried out a study to evaluate a bacterial cellulose and guar gum (BC-GG) hydrogel film based on polyvinylpyrrolidone - carboxymethylcellulose (PVP-CMC) as an alternative for food packaging. The GG was incorporated into the PVP-CMC-BC film to increase its mechanical and barrier properties. The samples were cut from the films in dimension 2 cm×2 cm and dried to constant weight at 60°C. The dry films were then immersed in 50 ml distilled water and kept in a BenchRocker™ 3D with low constant shaking (approx. 15 rpm) at RT 21°C and RH 57% for 24 h. The films were taken out from water after 24 h and dried to constant weight. The results showed an improvement in the elastic capacity of the PVP-CMC-BC films with the incorporation of GG and also in the barrier and hydrophobic properties. The authors reported that all films were 80% biodegraded after 28 days in vermicompost (Bandyopadhyay et al., 2019).

Another study aimed at packaging, but which can contribute to the textile industry was carried out by Indriyati et al. (2020) and collaborators. In this research, bacterial cellulose (BC) based films incorporated with beeswax (BW) were investigated. BC suspension was taken out from the refrigerator and let the temperature of the suspension equal room temperature, whereas BW was melted at 60–65 °C in wa- ter bath. Pure BC and BC-based films were prepared by mix- ing BC suspension under stirring condition at 60 °C until homogenized suspen- sion was achieved. Tween 80 was used as surfactant in the mixture containing BW. The mix- ture was then degassed to remove bubbles using vacuum pump, casted and dried in an oven at 45 °C for 16–20 h.

Different concentrations (10–40 wt% based on dry weight of BC suspension) of BW was added to enhance hydrophobicity and elasticity of BC-based films. Carboxymethyl cellulose at 20 wt% and Tween 80 at 30 wt% based on dry weight of BC suspension are also added as the homogenizer and the surfactant, respectively. Contact angle measurements confirm significant enhancement of hydrophobicity of BC films from 53° without BW to 124° for addition of 40 wt% BW. Tensile testing revealed that elasticity of the films also increased according to percentage of elongation at break for about 38% by addition of 40 wt% BW, whereas tensile strength decreases for about a quarter (Indriyati et al., 2020)

3.4.4 Other hydrophobic methods found in the literature: polyaniline, electrospinning, lauryl gallate oligomers, poly(fluorephenol) and oxygen plasma.

Shim et al. (2019) explored functionalized bacterial cellulose as a green material for technical textiles, wearables, and other applications. Conductive and colored bacterial cellulose (BC) was developed by entrapment of polyaniline (PANi) onto dry BC membranes. The polyaniline was produced by in situ green polymerization of aniline by Myceliophthora thermophila laccase at pH = 4, 25˚C, in the presence of a mediator, 1-hydroxybenzotriazol (HBT), using two different reactors, a water bath (WB) and an ultrasonic bath (US). According to authors, molecules entrapment and processing conditions might alter the hydrophilicity and disturb BC behavior. BC were dried in a drying convection oven (OF-21, Jeio tech Co.) at 35˚C.

The hydrophobicity acquired by the samples is favorable depending on the final applications envisaged. The untreated and bleached BC samples present high swelling capacity over 110%. With polyaniline incorporation, a significant decrease in the swelling capacity was observed under 60%, which might be attributed to the obstruction of the BC pores by polyaniline as well as to its hydrophobic nature. The swelling capacity of samples coated in the presence of laccase is slightly lower, confirming the higher amount of polyaniline entrapped inside BC that hinder the water absorption (Shim et al., 2019).

Naeem et al. (2019) have presented a simple method to prepare seamless tubular bacterial cellulose hybrid fabric, using electrospun nanofibrous membrane (BC/ENM), by wrapping regenerated cellulose (RC ENM) around a tubular polypropylene mesh template, followed by in-situ cultivation of BC. Functional and mechanical properties of as-prepared hybrid fabrics were also analyzed and discussed. The membranes were dried in a vacuum oven at 80ºC for 12h after electrospinning.

Regarding the contact angle, static water contact angle is considered as a representative parameter to evaluate the surface hydrophilicity or hydrophobicity of nanocomposite structures. The static water contact angle measurements were used to compare the wettability of BC/ENMs and ENMs. All three types of samples were subjected to a drop of deionized water. The contact angle values obtained for BC/ENM fabrics, in zero and 45 s of analysis, were 70.98º and 59.39º, respectively (Naeem et al., 2019)

Because of surface roughness and very fine fiber diameters, ENMs usually exhibit high surface hydrophobicity. ENM showed contact angle of 128.47º and appeared to be more hydrophobic. According to researchers, it might be because the comparatively crystalline electrospun fibrous membranes make the diffusion and transformation of water molecules difficult, resulting into a hydrophobic membrane surface. In case of hybrid fabrics, the BC nanofibrils largely covered the surface of hybrid fabrics, which might have resulted into improved hydrophilicity in comparison with ENMs (Naeem et al., 2019).

Song et al. (2019) and collaborators, carried out a study to improve the properties of bacterial cellulose nonwoven fabrics by physical entrapment of lauryl gallate oligomers. The lauryl gallate oligomerization process was conducted by laccase-mediated oligomerization. Lauryl gallate was chemically confirmed by matrix-assisted laser desorption/ionization with time-of-flight analyses. After treatment, BC nonwoven fabrics were washed for 0, 30, 60, and 180 min., then dried for 3 h at 25ºC. After drying, the WCA of treated BC nonwoven fabrics was evaluated.

The controlled oligomerization conditions were 160 U/mL of laccase and 20 mM lauryl gallate. After bacterial cellulose was treated by the physical entrapment of lauryl gallate oligomers, X-ray photoelectron spectroscopy analysis showed that the N1 atomic composition (%) of bacterial cellulose increased from 0.78% to 4.32%. This indicates that the lauryl gallate oligomer molecules were introduced into the bacterial cellulose nanofiber structure (Song et al., 2019).

Generally, untreated BC nonwoven fabric has a low water contact angle (WCA) value of 48.1 ± 1.5º with high surface energy (56.15 ± 0.4 mN/m) due to the numerous hydroxyl groups. After BC nonwoven fabric was entrapped with lauryl gallate oligomers, its surface became more hydrophobic with the increase of the WCA. This is because of the decline in the number of hydroxyl groups and moisture uptake, since lauryl gallate oligomers convert hydroxyl groups of BC nonwoven fabric to hydrophobic groups (Song et al., 2019).

According to authors, the more laccase concentration was added during lauryl gallate oligomerization, the more hydrophobic surface was indicated on treated BC nonwoven fabrics. The highest value of the WCA (118 ± 1.4º) with the longest water absorption time (over 7 min) was obtained when laccase of 160 U/mL was used. To evaluate the fastness of treated BC nonwoven fabric, treated BC nonwoven fabrics were washed in distilled water for 0, 30, 60, and 180 min. After washing for 30 min, the WCA was decreased from 118 ± 1.4º to 91.5 ± 1.5º. However, treated BC nonwoven fabric kept its WCA value over 88º after washing for 180 min (Song et al., 2019).

In another study by Song et al. (2019) have conducted a study to improve the hydrophobicity and durability of bacterial cellulose (BC) nonwoven by functionalization with poly(fluorophenol). Laccase was first entrapped onto BC and then used to polymerize the fluorophenol {4-[4-(trifluoromethyl) phenoxy] phenol} in-situ. After treatment, BC nonwoven fabrics were washed for 0, 30, 60, and 180 min., then dried for 3 h at 25ºC. After drying, the WCA of treated BC nonwoven fabrics was evaluated. The authors related after BC functionalization with poly(fluorophenol) (20 mM) that the water contact angle (WCA) increased from 54.5 ± 1.2º to 120 ± 1.5º while the surface energy decreased (11.58 ± 1.4 mN/m).

The findings confirmed the polymerization of fluorophenol by laccase and its entrapment onto a BC nanofiber structure. The durability of the functionalization with poly(fluorophenol) was confirmed by evaluating the washing fastness, tensile strength after washing and dimensional stability. The results indicate that the functionalized BC nonwoven had higher tensile strength (×10 times), better dimensional stability (30%) and greater hydrophobicity than the non-functionalized BC nonwoven material (Song et al., 2019).

Leal et al. (2020) conducted a new strategy for the surface modification of bacterial cellulose (BC) through the combination of oxygen plasma deposition and silanization with trichloromethyl silane (TCMS). The combined use of the two techniques modifies both the surface roughness and energy and maximizes the obtained hydrophobic effect. The obtained dried membranes as ‘‘Non-treated’’ were processed by solvent exchange with ethanol, in order to accelerate drying. Membranes were compressed between two aluminum plates for 30 min, expelling the water entrapped in the BC network, until the thickness of the membrane was reduced by around 80%. The densified membranes were allowed to dry at 37 °C for 24 h.

Silanization was conducted in a reduced pressure chamber at a temperature set at 95 °C. The silanizing reagent, TCMS, was placed inside the chamber together with the plasma-treated BC membranes and set to react for 60 min, at - 50 kPa. Following that period, the beaker containing the remaining TCMS (in toluene) was removed from the oven and replaced with only toluene which was left for 10 min for the washing of some of unbound TCMS upon toluene condensation on BC surface. After this, the membranes in the chamber, were subject to vacuum (- 50 kPa) for 5 min to further remove the toluene and obtain the dried BC membranes (Leal et al., 2020).

The contact angle formed upon deposition of the water droplet (26.68º) does not significantly change, as compared with the non-treated material (24.98º). Differently, the treatment with TCMS on its own (Sil) is able to increase the static contact angle to 119.8º, due to the presence of the hydrophobic moieties of Si-CH3, as detected by XPS and FTIR. Surface O_2 plasma treatment previous to the TCMS silanization (PlasSil) further increases the contact angle to 132.6º (Leal et al., 2020).

According to authors, BC remained hydrophobic even after 6 months, in dry conditions or after being submerged in distilled water for about a month, enabling the production of a biodegradable and hydrophobic platform that can be applied to different areas of research and industry. The higher hydrophobicity is explained by the formation of a convex meniscus, due to high contact angle, leading to air entrapment in the rough surface, which contributes to a higher contact angle and lower wettability of the surface, a phenomena well documented in the literature (Leal et al., 2020).

Therefore, from the researched literature, a range of possibilities of hydrophobization of bacterial cellulose was found. As mentioned before, BC has a high hydrophilicity, so drying methods are extremely important in this process. Drying temperatures ranged from 25ºC to 120ºC, and drying time ranged from 1 min to 5 days. However, the most used drying method was the lowest temperatures (25ºC to 40ºC), with drying time above 12h. According to Domskiene et al. (2019), the best deformation properties retain when BC material is dried at low temperature (about 25°C). BC material becomes stiffer and ruptures at lower deformations due to rapid water evaporation at higher drying temperature.

Regarding the methods used, low-cost alternatives such as plant based products are highlighted. In the case of the Textile Industry and thinking of a large scale of production, using food waste could be considered a way to foster the Circular Economy. Because, according to Wilkes et al. (2015), with regard to waste management and circular economy, partnerships between sectors can be an excellent solution, since through interdisciplinarity one sector can provide a function for the waste generated in another. Reports of improvements in the properties of bacterial cellulose, in addition to hydrophobicity, such as elastic capacity (Bandyopadhyay et al., 2019) were also cited.

3.5 Bacterial cellulose applications for the textile industry

The textile industry, despite being an important global manufacturing sector, is directly related to negative environmental impacts resulting from the use of toxic chemicals, the consumption of huge amounts of energy and water and inadequate disposal (Luo et al., Wang, 2020; Singh et al., 2019). Therefore, to achieve a more sustainable consumption scenario, it is necessary to find solutions to reduce the negative environmental, social and economic impacts of this industry (Freudenreich and Schaltegger, 2019; Ingulfsvann, 2020).

One solution would be to invest in areas such as biotechnology and biofabrication that explore alternatives, such as the use of microorganisms, for the manufacture of textiles, both for clothing and in the footwear industry (Camere and Karana, 2018; Saraç et al., 2019). The biofabrication of bacterial cellulose is regarded as a major bioeconomy technology, meaning its sustainability and associated footprint in the downstream processing and finishing phases should be closely monitored (Hildebrandt et al., 2021).

Therefore, several tests have been carried out on bacterial cellulose (BC), to explore its exclusive properties, such as high purity, absence of lignin and hemicellulose, high crystallinity, high polymerization, good flexibility, tensile strength and nanofibril network structure (Chan et al., 2018; Fernandes et al. 2019). BC resources grown from bacteria have been developed mainly as fine materials to replace animal leather (Camere and Karana 2018; Chan et al. 2018; Fernandes et al. 2019), as can be seen in **Figure 5**.

Fig. 5 Bacterial cellulose (BC): a possibility for replacing animal leather. Project carried out at the University of Southern Santa Catarina (UNISUL).

Nowadays the fashion industry faces increasing pressures to reduce the environmental impacts associated to the production of leather-based fashion products, particularly considering issues regarding public acceptance due to animal welfare standards and due to the toxicity of tanning chemicals (Hildebrandt et al., 2020). The tannery industry faces several challenges associated with high environmental impact, scarcity of raw materials and increasing consumer demand for environmentally friendly products. Worldwide, for bovine skin, 370 billion liters of water are consumed annually, generating 6.5 million tons of solid waste (Fernandes et al., 2019).

Leather is a natural fabric material obtained from skins of animals, the treatment process of leather is highly complicated, especially the tanning process, because toxic chemicals such as metal salts and hexavalent chromium are used, and the decomposition of protein wastes causes serious odor. Furthermore, the supply of the leather is currently decreasing due to the animal protection movements (Kim et al., 2021). An alternative solution facilitated by the bio-textiles industry is the introduction of vegan and bio-based leather substitutes for the production of shoes, handbags, clothing and upholstery i.e. on the basis of natural fibres, bio-based polymers, microbial cellulose and fungal mycelium composite products (Hildebrandt et al., 2020).

The idea of BC as a potential leather substitute rests on the industrial production of cellulose fibres by members of the genera *Komagataeibacter* (also known as *Acetobacter xylinum*) (García and Prieto, 2018; Rathinamoorthy and Kiruba, 2020). This (bacteria ingested as part of Kombuchá tea and other fermentations, enjoys Generally Regarded As Safe (GRAS) status. These can be generated at desired thicknesses and when dried produce a resilient leather-like material with properties that resemble the type of animal leathers used in the footwear industry (García and Prieto, 2018). According to Hildebrandt et al. (2020) the choice of the feedstock for bacterial conversion is very important as it affects the environmental footprint of the entire production process, as well as the properties of the final products, e.g., flame retardancy and hydrophobic properties.

Some bacteria naturally produce cellulose (BC). If produced biotechnologically in large quantities, it might afford an alternative to plant cellulose. BC is already used commercially in high-end acoustic products, in medical wound dressings, and to make many other goods. At the laboratory scale, it has even been used to create artificial blood vessels and biodegradable tissue scaffolds, and has shown promise in organic light-emitting diode displays, flexible electrodes, sensors and other devices (García and Prieto, 2018). The application of bacterial cellulose in the fashion industry has been the focus of several studies, as shown in **Table 1.**

Table 1 - Compilation of 15 current studies on the use of bacterial cellulose with a focus on the textile industry.

Author / Year	Title	Advantages in the Textile Industry	Disadvantages in the Textile Industry
García and Prieto (2018)	Bacterial cellulose as a potential bioleather substitute for the footwear industry	- BC production should be much more bio-economically sustainable; -The use of plant-	- The inherent wettability and liquid-absorbing capacity of BC are crucial drawback in shoe

		derived water-soluble dyes should render BC-based footwear hypoallergenic; - BC can be to undergo rapid and eco-friendly biodegradation, with no leaching of toxic compounds to groundwater; - BC as a leather substitute could result in a reduced demand for animal hides, fewer greenhouse gas emissions and diminished tanning-associated toxicity; - Economic production of BC using food and industrial wastes as sources of nutrients.	manufacture; - The inherent incompatibility between hydrophilic cellulose and generally hydrophobic polymer matrices, as well as thermal stability issues, needs to be addressed; - Bacterial cellulose is currently very expensive, because the main factor contributing to its high production cost is the synthetic media required to culture the bacteria.
Camere and Karana (2018)	Fabricating materials from living organisms: An emerging design practice	- The production of bacterial cellulose can be handled by using almost no additional energy and by using sustainable resources; - Large potential in replacing animal- or plant-based material production systems.	- Bacterial cellulose needs more research and tests for its application and commercialization.
Chan et al. (2018)	Development of Tailor-Shaped Bacterial Cellulose Textile Cultivation Techniques for Zero-Waste Design	- Bacterial cellulose is a sustainable biomaterial; - This organic material is able to be cultivated in any desirable garment panel shape, with no cutting and less textile waste; - Self-synthesizing property; - Biodegradable bacterial cellulose can shed light on the development of new sus- tainable textile materials and manufacturing practices in the future.	- Mass produce specific cultivation containers in future bulk production; - Dispose of unused blockers and containers at the end of their life cycles; - Would be necessary to pay attention to the ongoing genetic and biochemical research works focused on bacterial cellulose production at the molecular/biological level in order to incorporate innovative applications into fashion and textile industries.

Domskiene et al. (2019)	Kombuchá bacterial cellulose for sustainable fashion	- BC is eco-friendly, safe to the human body, and renewable raw material; - Can be grown to the extent necessary; - Can be use food waste; - Worn BC clothes can easily biodegrade.	- The high hydrophilicity of bacterial cellulose; - Mechanical behaviour of BC film (when material is wet and when it is dried) shows that ability to apply direct 3D formation technique is limited and needs further studies; - It is difficult to get material with even structure and constant mechanical parameters even for small experimental sample; - BC film loses its elasticity over time and products produced from elastic and strong BC material are unlikely to be durable.
Fernandes et al. (2019)	Bacterial Cellulose and Emulsified AESO Biocomposites as an Ecological Alternative to Leather	- Reduction of the animal hide dependency by the development of composites from bacterial cellulose.	- The high hydrophilicity of bacterial cellulose.
Fernandes et al. (2019)	Development of novel bacterial cellulose composites for the textile and shoe industry	- BC is free of lignin, hemicellulose and pectin, therefore, no extra processing is required for purification; - BC features a unique porous interconnected structure, organized three-dimensional network of interconnected nanofibres, properties which are very advantageous for the production of composite materials; - BC exhibits high crystallinity, which results in a high Young's modulus; - It also has a high degree of polymerization and high moldability in situ (during	- The loss of flexibility upon drying is a disadvantage for several applications such as in the textile and shoe industry; - Due to the collapse of the 3D nanofibrillar BC network, a significant reduction in gas permeability also occurs, heavily reducing the material's breathability; - The hydrophilic nature of BC hinders the combination with hydrophobic polymer matrixes; - The bulk distribution of the particles within the BC is also

		fermentation) and ex situ (after fermentation).	heterogeneous, a feature further aggravated by the hydrophobic nature of certain polymer matrices.
Song et al. (2019)	Improvement of bacterial cellulose nonwoven fabrics by physical entrapment of lauryl gallate oligomers	- Bacterial cellulose (BC) is a renewable bio-nanomaterial, with unique characteristics, that include high purity, high degree of polymerization and high crystallinity; - Excellent biodegradability, biocompatibility, and moldability.	- Hydrophilicity; - When BC nonwoven fabric is exposed to moist or wet conditions, it loses its original shape and it is difficult to recover its shape and strength.
Naeem et al. (2019)	A preliminary study on the preparation of seamless tubular bacterial cellulose-electrospun nanofibers-based nanocomposite fabrics	- Bacterial cellulose (BC) is an outstanding nanofibrous extracellular biodegradable polymer produced by nature; - Possess high modulus and strength estimated to be 114 GPa and in excess of 1500 MPa, respectively; - It causes no harm to humans and the environment and does not contain any impurities that require intensive processes to be purified and isolated, such as lignin and hemicellulose; - Its unique physical characteristics and cultivation properties have demonstrated a great potential to achieve zero-waste design.	- BC alone lacks the durability required for daily usage in sustainable applications for textiles; - High hydrophilicity for use in the textile industry.
Song and Kim (2019)	Bacterial cellulose as promising biomaterial and its application	- BC is chemically pure (free of lignin and hemicellulose) and it does not require any extra processing to remove contaminants - Biodegradability and	- BC has several drawbacks such as lack of antibacterial, antioxidant, and conducting properties; - The high water holding capacity corresponded to its

		chemical-modifying capacity; - The process of BC production requires simple, mild, semicontinuous static, and low-cost medium cultures and represents interesting alternatives for many developing industries.	OH-rich structure causes a low interfacial compatibility, resulting in inadequate mechanical performance; - The high moisture uptake results in the poor rehydration with loss of dimensional stability and fiber strength when BC is exposed in water.
Kamiński et al. (2020)	Hydrogel bacterial cellulose: a path to improved materials for new eco-friendly textiles	-Environmentally-friendly technology allowing for obtaining textiles based on bacterial cellulose; - Bacterial cellulose can be produced from completely renewable and reusable sources and according to the principles of waste-free technologies; - HydroGel Bacterial Cellulose fabric may be a viable alternative for the currently used synthetic materials; - BC is a very convenient material when it comes to modifications in view of its applicability since it can be manufactured/grown in different shapes, processed to achieve enhanced properties and functionalized to gain new applications.	- BC produced by Kombuchá has the disadvantage is the brown colour of the product which is a result of melanoidins from the Maillard reaction, and an unpleasant smell of the material due to the presence of difficult to remove fermentation products, mainly carboxylic acids; - The alkaline purification method with NaOH is commonly used in BC, however, it requires the use of significant amounts of water and neutralizers to obtain materials with neutral pH.
Hildebrandt et al. (2020)	The circularity of potential bio-textile production routes: Comparing life cycle impacts of bio-based materials used within the manufacturing of selected leather substitutes	- Bacterial cellulose (BC) is a bio-renewable nanomaterial with a high purity, high degree of polymerization and high crystallinity.	- Microbial cellulose sheet finishing requires additive materials for hydrophobic finishing, fire safety, and softening agents.
Rathinamoorthy and Kiruba (2020)	Bacterial cellulose-A potential material for sustainable eco-friendly fashion products	- Bacterial cellulose is one such biomaterial, sustainable, and environmental friendly and has a lot of potential in the fashion industry.	- The production cost and lower yield are the major issues in the bulk production of bacterial cellulose and hence.

Kim et al. (2021)	Comparative study on the physical entrapment of soy and mushroom proteins on the durability of bacterial cellulose bio-leather	- Animal protection, avoiding the use of leather; - BC is an eco-friendly cellulose material, making it environmentally friendly and biodegradable, thus helping reduce textile waste; - Altering the fermentation conditions can result in BC with excellent moldability and biocompatibility; - Unlike animal leather, additional processes such as tanning and graining are not necessary for BC bio-leather.	- The high water-holding capacity of BC has several drawbacks. Its hydrophilicity causes poor rehydration and durability of BC bio-leather, and when exposed to moist or wet conditions, BC loses its shape and strength.
Laavanya et al. (2021)	Current challenges, applications and future perspectives of SCOBY cellulose of Kombuchá fermentation	- High crystallinity, biocompatibility, non-toxicity and high porosity; - Purification of bacterial cellulose does not requires harsh chemical treatment like vegetable cellulose; - The growth of BC in various shapes and sizes gives rise to the idea of production of wastefree garments by the textile industry.	- Unpleasant smell; - One limitation that should be overcome is the regaining of moisture by the cellulose mat.

Source: the authors.

It is possible to observe through **Table 1** that the authors cite the main advantages of bacterial cellulose as its biodegradability properties, the possibility of being a substitute for animal leather, the reduction in the use of water and toxic products, among others. As well as, its disadvantages are due to its high hydrophilicity, heterogeneous production, among others. As well as the articles cited in Table 1, this review article highlights the numerous benefits of using BC, so it is necessary that tests be done to improve its properties for the commercial use of fashion products.

Researchers such as Chan et al. (2018) and collaborators developed an innovative technique for the production of bacterial cellulose textiles called “bespoke cultivation”, taking advantage of the fact that bacterial cellulose can be cultivated and grown in any format. This type of cultivation is suitable for producing basic fashion items, such as simple shirts, t-shirts and trousers, as these items do not require complicated shapes and their timeless styles are not restricted to trends (Chan et al. 2018).

According to Domskiene et al. (2019), investigating the unique features of BC film, researchers provided innovative ideas to grow seamless garments as direct 3D formation of BC sheets. Thus, scientists, working in the textile field, recently got interested in BC material, however, only a few studies are investigating this material as a new type of textile fabric for the fashion industry.

The functionalization and modification of BC have been achieved through chemical or mechanical alteration of the polymer, and by making adjustments to the conditions of cultivation. By controlling the growth of the producing bacteria, the BC generated could be tailored to have properties desired by the footwear industry (sheets of BC measuring 40 x 40 cm – a size compatible with footwear manufacturing requirements). If the solubility limitations of BC can be overcome, a BC-based printable fluid might be produced and used to 3D print shoes (García and Prieto, 2018).

Ng and Wang (2015) performed tests related to the comfort and appearance of tissues obtained from bacterial cellulose. A total of 150 individuals participated in the test and the factors considered were comfort associated with touch, comfort associated with flexibility and comfort related to breathability. The result regarding the patterns analyzed was positive and it was possible to produce some prototypes of pieces of continuous 3D fashion.

According to Chan et al. (2018), the use of bacterial cellulose in the textile industry adheres to the concept of low to zero waste, but these materials are limited to patterns for specific types of clothing and are difficult to apply to the conventional manufacture of items of daily use. Zero waste patterns require a longer design process and more technical support for the execution of designs due to the special pattern allocation. Because it is not cost effective and is time consuming, zero waste design has not been widely used in the fashion industry.

Another relevant factor for the textile industry is the biodegradable nature of BC (Cazón et al., 2020; García and Prieto 2019) which could be successfully applied to obtain ecologically-friendly products (Cazón et al. 2020; Freudenreich and Schaltegger 2019). It should also be noted that for the manufacture of bacterial cellulose, only small amounts of water and energy are needed (Fernandes et al. 2019; Yim et al., 2017). Therefore, it can be considered an eco-friendly biomaterial and a mitigator of negative impacts within the textile chain.

Despite the various benefits of using bacterial cellulose, there are still many technical and practical problems associated with the manufacture of clothing that need to be resolved, such as mechanical durability, comfort, material contamination, organic acids (responsible for the characteristic unpleasant smell), and attack by microorganisms (Kamiński et al. 2020). This review addresses one such property of BC, its wettability, as can be seen in **Figure 6.**

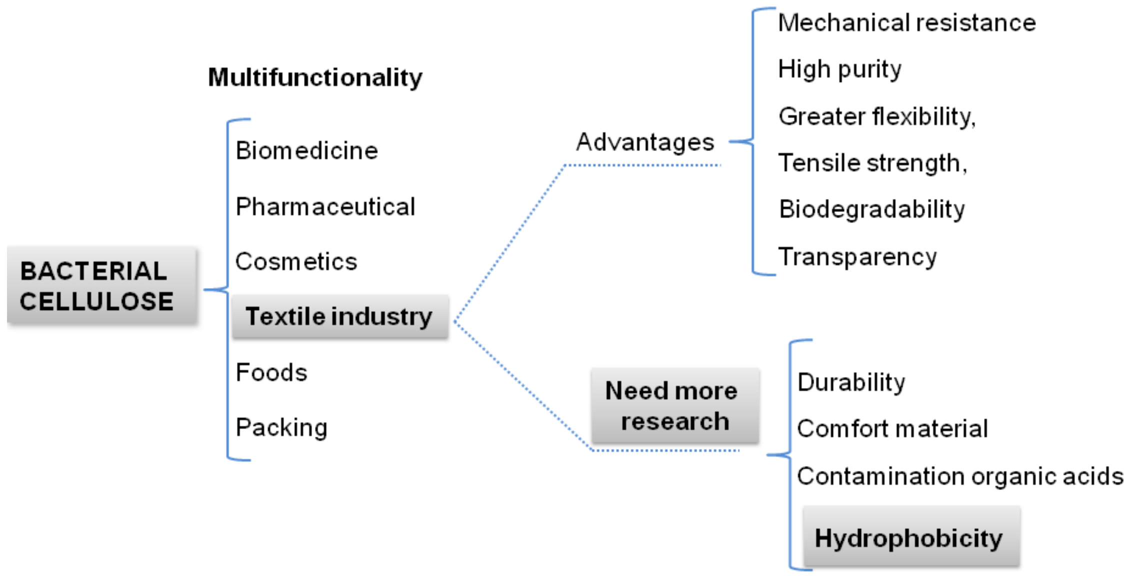

Fig. 6 The hydrophobicity of bacterial cellulose is an area of study that merits further scientific investigation for its use in the textile industry (source: the authors).

It was observed that despite its natural characteristic of being hydrophilic, which is advantageous for many applications, for instance, in the area of health, a more hydrophobic biomaterial would be of great interest for the textile industry. According to Araújo et al. (2015) and Fernandes et al. (2019), the hydrophilic nature of BC prevents the combination with hydrophobic polymeric matrices, presenting a challenge for the development of textiles (Araújo et al. 2015; Fernandes et al 2019).

In the textile industry, a hydrophobic cellulose material would have a wide range of applications, for instance, for clothing and impervious stain-resistant textiles, among others. Cellulose fabrics with hydrophobic fiber surfaces are suitable for producing water repellent items, as they resist water but have some porosity, which allows the transport of moisture for user comfort. Studies to reduce the hydrophilicity of the modified cellulose surface have involved different technologies with broken effects and diameters (Araújo et al. 2015).

Although bacterial cellulose is biodegradable, renewable and biocompatible, its inherent properties, such as low strength, stiffness, high fragility and a hydrophilic nature, make it a poor biomaterial for application in commercial products (Dhar et al., 2019). However, currently, one of the main ecological problems, with regard to the textile industry and the use of clothing, is the issue of the disposal of textile waste. Since most of this waste is not biodegradable, being synthetic and derived from oil, further studies on bacterial cellulose would be of great interest (Kamiński et al. 2020)

Research seeking to improve or modify the BC properties, to address, for example, the issue of hydrophobicity, could lead to more alternative biodegradable materials being inserted in the textile market. This issue merits increased investment, as the textile sector needs to identify new sustainable materials and, therefore, offering hydrophobicity must be aligned with proposal to increase sustainability in this sector. It should be noted, however, that other relevant properties, such as durability and biodegradability, must remain unchanged (Kamiński et al. 2020).

The Textile Industry, as well as other sectors that are related to serious environmental problems, need a quick change to contribute to the pillars of sustainability, likewise, in relation to achievement of the Sustainable Development Goals (SDGs). Therefore, investments in solutions such as new and more ecological materials are important, and bacterial cellulose is a good example.

However, when it comes to the textile market, some properties are necessary for BC to be commercialized with quality. Hydrophobia is an essential property for this area, according to research reported in this review article. Thus, it is important to look for effective changes in BC properties, without eliminating its main characteristic, which is that it is an eco-friendly biomaterial. Finally, future research on improvements in the general properties of bacterial cellulose is extremely important, as it is an eco-friendly, innovative material with great potential as a substitute for products from petroleum or animal origin.

5. Trends, future perspectives and conclusions

Studies on bacterial cellulose as a sustainable alternative for use as a fabric have been promising. Reduced water consumption, decreased use of insecticides and pesticides, and reduced waste, are among the advantages of using this biomaterial in the textile industry. The possibility of using bacterial cellulose as a substitute for animal leather was mentioned by several researchers.

Several properties of bacterial cellulose, such as mechanical strength, high crystallinity and three-dimensional structure, favor the use of this material in the textile industry, but its hydrophilicity poses a challenge for its application as a textile fiber. Based on the studies considered in this review, methods to make BC hydrophobic could be used to reduce the water absorption capacity such as: a) Acrylated epoxidized soybean oil (AESO) and Polyethylene glycol (PEG); b) Beeswax; c) Electrospinning; d) EVO Wet Fest; e) Glycerol and Plant-based proteins; f) Lauryl gallate; g) Oxygen plasma and trichloromethyl silane; h) Persoftal MS (polydimethylsiloxane) and Baygard EFN (perfluorocarbon); i) Poly (fluorophenol); j) Polyaniline (PANi); k) Polyvinylpyrrolidone - carboxymethylcellulose; and l) Poly (lactic acid) (PLA).

The continuation of studies and tests is indispensable; so that biodegradable materials can be inserted in the textile market and that they can be commercialized. The main issues that could be addressed in future studies are obtaining hydrophobic biomaterials, which are durable, comfortable and which remain with their ecofriendly characteristics. Therefore, bacterial cellulose treatment processes must find environmentally friendly means.

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CAPÍTULO 6

USE OF BACTERIAL CELLULOSE PRODUCED BY KOMBUCHÁ DRINK FOR THE MANUFACTURE OF BIOTEXTILES FOR THE BENEFIT OF SUSTAINABILITY

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Abstract: Textile industry is one of the most complex sectors in relation to environmental degradation, both with regard to the materials used and the manufacturing and disposal processes. One way to mitigate negative environmental impacts is the use of microorganisms such as bacterial cellulose (BC) in the formation of biomaterials considered biodegradable. One of the ways to obtain bacterial cellulose is through the production of the probiotic drink Kombuchá. Thus, BC production was carried out through the fermentation of teas belonging to the Camellia sinensis family and a sweetener, with the addition of a culture based on the symbiosis of bacteria and yeasts. Then, two methods of purification were used, the traditional method using NaOH solution (BC_NaOH) and the sterilization method using a non-thermal plasma reactor (BC_NTP). A control sample was also maintained, BC_Untreated was left in the medium without any treatment. Thus, the characterization of the surface was carried out to investigate the purification of the membranes and the possibility of using NTP in the Textile Industry. Finally, a discussion is also presented relating biotechnology production to the UN Sustainable Development Goals, in order to understand what goals can be achieved with this approach.

Keywords: bacterial cellulose; Kombuchá; biotextile; eco-fashon; Sustainable Development Goals.

1. Introduction

The textile industry is a complex sector, due to its intense participation in activities that cause major negative environmental impacts such as the use of pesticides, huge amounts of energy and water, chemicals used in processes and inappropriate discharges (Luo et al., 2020; Singh et al., 2019). Areas such as biotechnology and biofabrication (Camere and Karana, 2018; Scarlat et al., 2015), explore alternatives such as the use of microorganisms for the manufacture of textiles, both for clothing and for the footwear industry (Camere and Karana, 2018; Saraç et al., 2019). One of the forms of BC production is through the fermentation process of the ancient probiotic drink Kombuchá, of Chinese origin (Cardoso et al., 2020; Kamiński et al., 2020). Tea is produced as a nitrogen source for its culture medium, produced by dry leaves of Camellia sinensis and, for its fermentation, sugars with a symbiotic association of lactic acid bacteria are used as a carbon source (Ben Taheur et al., 2020; Sederavičiūtė et al., 2019; Velásquez-Riaño and Bojacá, 2017). Therefore, the main objective of this work was to produce a biotextile using Kombuchá, to analyze the purification processes through the use of NaOH and non-thermal plasma, and to carry out a discussion about the Sustainable Development Goals (SDGs).

2. Experimental conditions

For BC production, the culture medium prepared from 1 L water, 5 g green tea, 100 g of sucrose and 100 mL of 6% yeast extract was incubated with Kombuchá fungus and fermentation was being carried out under standard room conditions (24 ± 2 °C temperature and 65 ± 5% relative air humidity) for 35 days in static cultivation conditions. On the surface of liquid medium grown membrane was removed for the treatment and drying procedures. As the control sample the BC_Untreated was left in the medium without any treatment. Two purification methods were used, the traditional method using in 0.5% NaOH solution (BC_NaOH) and the sterilization method using a non-thermal plasma reactor (BC_NTP) high voltage AC source (± 17 kV) and current of 30 mA for maximum output power of 510 W and flow of Argon gas and air mixture of 3, 0 L min-1. Samples were subjected to drying procedure in the laboratory oven at 25 ± 1 °C until specimen gained a constant weight. Finally, microstructural characterization was performed using the Scanning Electron Microscope (SEM).

3. Results

Microstructural characterization (see Figure 1) using the Scanning Electron Microscope (SEM), showed BC_untreated with a less homogeneous surface compared to BC_NaOH and BC_NTP. The differences between the treated membranes also emerged. BC_NaOH showed several white spots due to the NaOH reaction, transforming its porous structure. BC_NTP showed some stains, probably due to the electrical discharge of the non-thermal plasma. However, both treated celluloses did not present the presence of microorganisms.

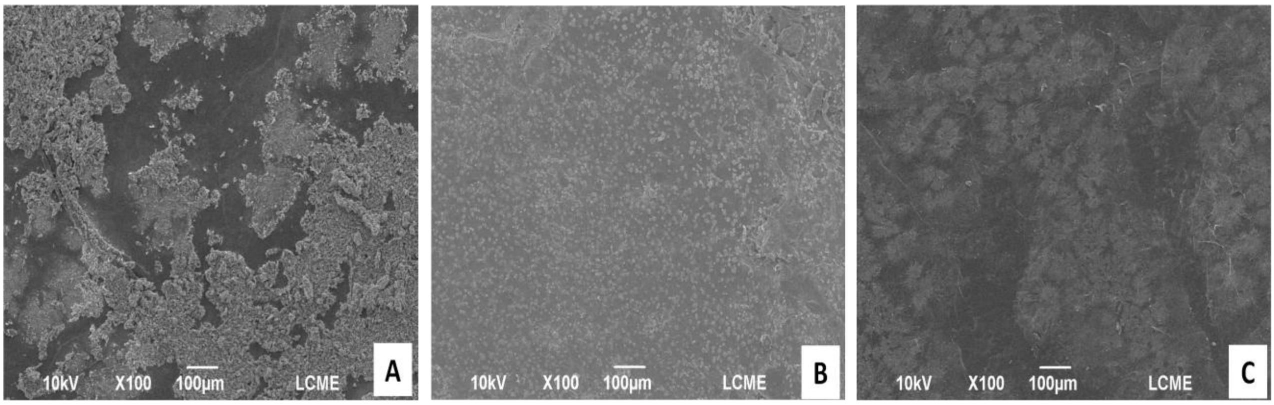

Figure 1. Microstructural characterization using the Scanning Electron Microscope (SEM). A) BC_untreated surface structure. B) BC_NaOH surface structure. C) BC_NTP surface structure.

Despite the sterilization of microorganisms through treatment of NaOH solution, the practice is not considered eco-friendly. Thus, the purification results also obtained through NTP, shows us a future possibility of greater investments in research using this cleaner and more environmentally friendly technology. Although the mechanism of action of plasma in different microorganisms inactivation, is still not well understood, it has been successfully applied and its efficacy differs due to differences in membrane structure (Cubas et al., 2019). Also it was observed that biotechnology, with the use of microorganisms for the production of biodegradable clothing, are consistent with cleaner technology without the need to exploit natural resources such as oil (Camere and Karana, 2018;García and Prieto, 2019). Therefore, thinking about biomaterials such as the use of bacterial cellulose, which is a biodegradable material, and treatments using cleaner technologies such as non-thermal plasma, is a form of mitigation and complies with the SDGs. Especially regarding SDG 12, which aims to ensure sustainable consumption and production patterns.

4. Conclusions

Despite the importance of the Textile Industry as a generator of jobs and entrepreneurial opportunities for countless families, in summary, needs to be thoroughly reviewed and analyzed. It has a system with several negative environmental and social impacts that do not match the Sustainable Development Goals. Thus, investment in environmentally friendly technologies and materials is the way. Through this research, the possibility of using biotechnology to manufacture biomaterials, such as bacterial cellulose through the probiotic Kombuchá drink, was observed. As well as, the positive results of purification by non-thermal plasma treatment.

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CONCLUSÃO

Os têxteis fazem parte da nossa sociedade há milênios, perpassaram pela história da evolução humana, protegeram nossos ancestrais (e ainda nos protegem) das intempéries climáticas e foram por muitos séculos distintores de classes sociais. Junto à Revolução Indústrial, o setor têxtil se concretizou e até hoje é um dos setores que possuem uma margem significativa nos lucros mundiais e uma das indústrias que mais gera empregos em âmbito global.

No entanto, a Indústria Têxtil e da Moda, ao longo dos anos, trouxeram complexidades como: i) O encaminhamento dos seus processos produtivos; ii) A exploração de pessoas em condições precárias, inclusive alguns são considerados análogos a escravidão; iii) Extração exacerbada de recursos naturais (vegetais e animais); iv) Produção de fibras artificiais e sintéticas que demoram muitos anos para se degradar, poluem recursos hídricos e contaminam o solo; e v) Descuido e falta de gestão adequada com o descarte de resíduos têxteis (pré-consumo e pós-consumo). Enfim, uma grande problemática para o contexto da sustentabilidade e seus pilares (social, ambiental e econômico).

Assim, muitos pesquisadores e profissionais da área não medem esforços para encontrar soluções adequadas, tanto pensando em novos materiais quanto preocupados na não geração de resíduos ou na gestão destes da melhor maneira. Desta forma, se tratando de novos materiais, os estudos de microrganismos como a celulose bacteriana (CB), obtiveram os holofotes. A CB pode ser considerada um biomaterial biodegradável, eco-friendly, potencial substituto de tecidos como o couro e, devido a sua moldabilidade, considera-se a CB um biopolímero promissor também para a fabricação de vários produtos sem a geração de resíduos.

Através da presente dissertação e do estudo aprofundado do estado da arte do uso de celulose bacteriana para a fabricação de biotêxteis, foi possível observar as inúmeras características favoráveis deste biomaterial, mas também analisar as propriedades que devem ser estudadas e melhoradas para que possa ser comercializado. O odor, a molhabilidade, os tratamentos utilizados de purificação, rendimento e a durabilidade, entre outras questões, devem ser foco de pesquisas futuras por ser um material inovador e importante para as causas ambientais.

Por fim, além de suas propriedades, a sua forma de produção deve ser alvo de estudo também, pois a celulose bacteriana pode ser produzida por meio de fontes economicamente viáveis e utilizando resíduos de outro setor como da Indústria Agroalimentar. Desta forma, incentiva-se a Economia Circular, a interdisciplinaridade entre setores e contribui-se para o cumprimento dos Objetivos de Desenvolvimento Sustentável (ODS), principalmente com o ODS 12 *"Consumo e Produção Responsáveis"*.