Research Article

www.bombaytechnologist.in

BOMBAY TECHNOLOGIST

ISSN: 0067-9925

SOY PROTEIN-BASED FILTRATION MATERIALS

Yuvraj Patil

Department of Fibers and Textile processing technology, Institute of Chemical Technology

ABSTRACT:

Soy protein-based polymers (soy protein fiber- SPF) were first developed in 1940 by Japanese researchers, and further advancements were observed in the coming years. Nowadays, we can see a significant shift towards using natural polymers to replace synthetic ones citing the concern over the environment and health. Polymers from natural sources have become a focus for research and advancement. Soy protein fiber is an attractive alternative over synthetic material for filtration application; it is cheap, abundant, easily fabricated, and has many functional groups on its surface; therefore, it can be used in various applications. The current situation of many major cities of India is worsening day by day due to increasing pollution. With the current covid-19 pandemic, the need for efficient, durable, and environmentally friendly filters is highlighted. Soy protein filters can fill this gap as they can be easily manufactured on an industrial scale and have the same or more significant advantages over synthetic filters. We can easily alter their surface chemistry to suit a particular function, and they are biodegradable, thus with a low pollution footprint. This review focuses on Soy protein-based filter fabrics for highly efficient and multifunctional filters: their manufacturing techniques, selection criteria, filtration efficiency, and biodegradability.

Keywords: soy proteins, biodegradable, air filter, natural polymer.

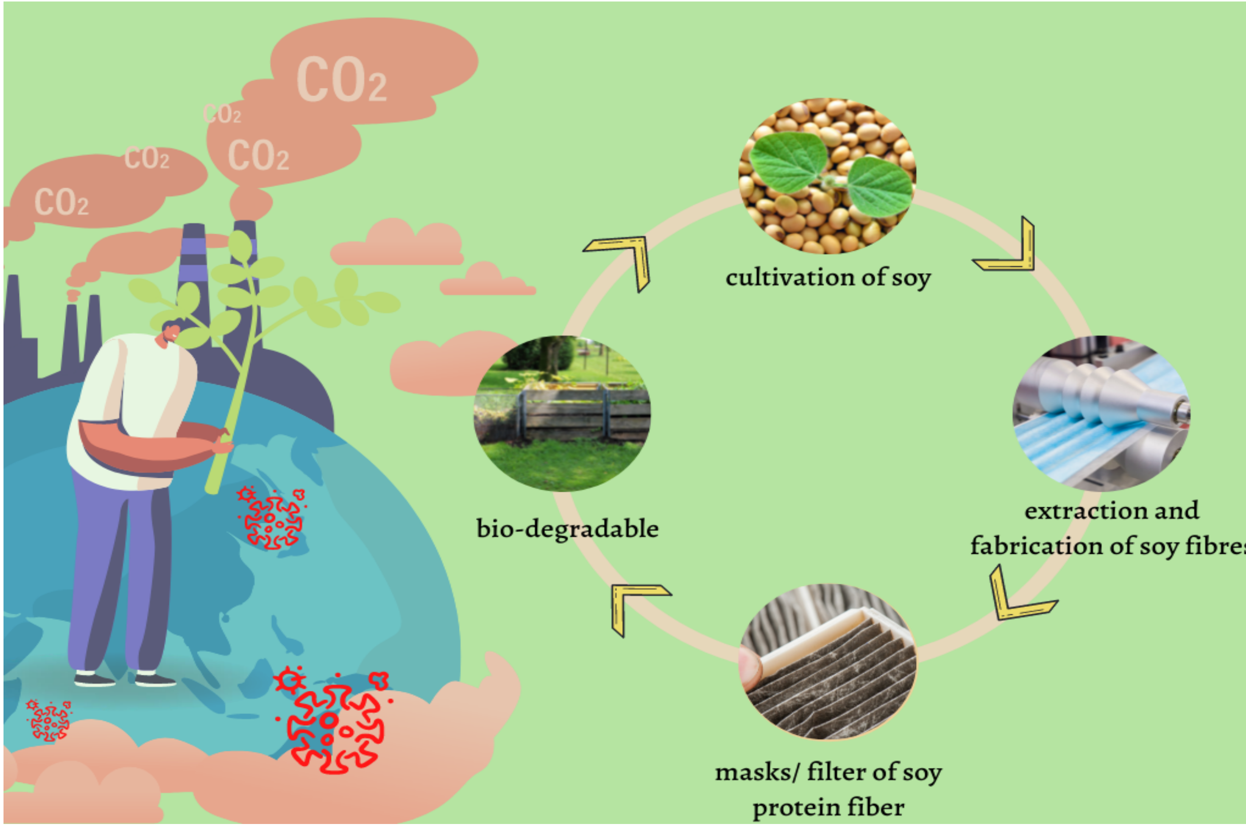


Fig 1: Illustrating the life cycle of a soy protein filter

1. INTRODUCTION

The word filter comes from the Latin word "filterum", which means the feeling of compressed wool. Since the early 1950s, textiles have been used for filtration based on fabrics made of cotton, wool, glass fibers, etc. Air filters are a relevant alternative in global efforts to reduce air pollution and provide adequate personal protection. The structural anisotropy of Soy protein-based filters can improve various physical properties of it over multilayer and nonwoven synthetic air filters.

Our major dependency on petroleum-based air filters in today's age creates immense pressure on the biosphere. Their extraction and manufacturing release toxic waste, and most of them being single-use, are thrown away without proper disposal. With time, they break down into smaller pieces releasing nano plastics and leaching chemicals into the surrounding, which have adverse effects.

Filters made of soy protein are the new alternative for these petroleum-based materials. They are easy to produce, environmentally friendly, sustainable, and biodegradable. The raw material for soy protein is the waste generated from oil extraction. We can turn this extracted waste into SPF with few inputs. Being biodegradable, Soy protein fibers can be composted and used in soy cultivation, forming a cyclic production system. Fig 1.

2. PROPERTIES OF SOY PROTEIN FIBERS

Soy proteins isolate (SPI) consist of 18 different amino acids[1]. Out of which about 23% are acidic amino acids such as aspartic amino acid and glutamic acid, about 25% are alkaline amino acids such as tryptophan, serine, lysine, threonine, arginine, tyrosine, and about 30% are neutral amino acids such as glycine, valine, alanine, phenylalanine, isoleucine, leucine, proline[1]. The vast spectrum of functional sites offered in proteins and polysaccharides permits various extremely meticulous filtration systems for particulate matter. The addition of different biopolymers with different properties and combining them through post-processing will improve their overall filtration talents and add to their physical properties, resulting in extensive filtration of material, chemical, and biotic molecules with wider and greater abilities[2].

3. FABRICATION OF SOY PROTEIN FILTERS

Soybeans have high-protein content (37-42% of dry bean)[3]. These Globular proteins are polypeptide bonds connected with hydrogen bonds, electrostatic The solution is then extruded in an acid bath forming new disulfide bonds, and the coagulated soy protein fiber (SPF) is precipitated out.

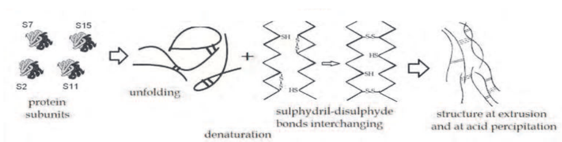


Fig 2. The conversion of globular proteins into fiber-forming proteins[1,5].

The petroleum-based filters are excellent in filtering particulate matter. Still, they cannot filter out toxic compounds by themselves unless paired with other fillers such as activated carbon, etc., increasing their price. This is where personal protective equipment and air filters can be made with biopolymer-based filtration materials such as soy protein fiber.

The strength and tenacity of just soy protein fiber are very low; thus, they cannot be used to make filters. We can overcome this by changing the spinning method and adding dope material. The dry spinning method is favored for fabricating soy protein fibers as they are highly dissolvable in water and glycerol[6]. To increase durability and reduce shrinkage, soluble polymers such as polyvinyl alcohol can be added[7]. Polyvinyl alcohol (PVA) inserts firmness and durable characteristics to soy protein blend[8]. One downside of increasing the amount of dope is that it decreases the amount of SPF, thus reducing the number of active functional sites resulting in reduced filtration performance. The best ratio of SPF to PVA for optimal filtration and good fiber properties is 1:1 [9]. Another way to increase fiber strength and not

forces, disulfide bonds, etc.[4] For drawing fibers and crystallization of proteins in fibers, it is essential to unfold these globular proteins. The process of unfolding these proteins is called denaturation. Denaturation alters the protein’s secondary, tertiary, and quaternary bonds. When soy proteins are exposed to strong alkali/acids, heat, organic solvents, detergents, and urea, it causes the native globular protein to denature, thus converting them into unfolded polypeptide chains[1], which are connected with the interchanging of disulfide bonds[4]. Fig 2.

compromise the filtration efficiency is to use a dope with functional groups. The Soy Protein Isolate (SPI), with its functional structures and large surface area, when combined with the bacterial cellulose (BC), provides multi-level filtration functionality for the SPI/BC composite. BC is synthesized from *Acetobacter xylinum or* Gluconacetobacter xylinus bacteria, and it is a natural polymer that is soft and highly hydrated. It consists of a three-dimensional nanofibrous network structure with high mechanical strength and superior physical and biological properties[10].

The most common way to fabricate nanofibers is using the electrospinning process. The soy protein blend is loaded into a syringe. A high voltage is applied, and a pump injects the solution through the syringe, and nanofibers are collected on the other end. The needle position can be adjusted to achieve a uniform fiber web with controlled nanofiber diameter and densities[11].

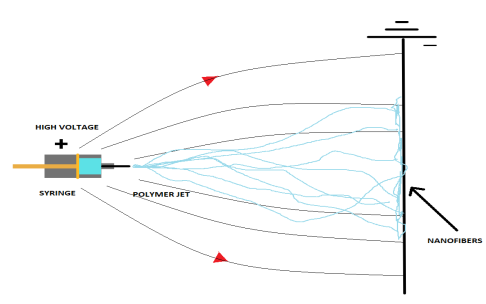
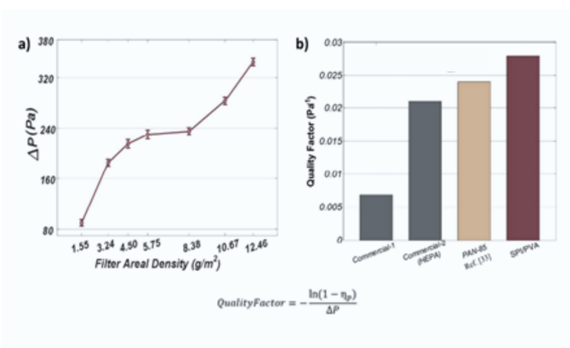


Fig 3. Schematic of Electrospinning process[12].

Various other methods are also available to make nanofibers, such as melt blowing, blow spinning, etc. Every method has its advantages and disadvantages, and one can choose the method which suits their end product best[11].

Filters made of nanofibers (fibers having a diameter smaller than 1 μm) are the best and the most efficient filters. They provide a greater surface area than microfibers, a smaller pressure drop, and better efficiency at the same pressure drop[13]. The quality factor (QF) is a parameter that represents a comprehensive analysis of the air filtering performance, meaning a good filter should have a high QF factor, i.e., achieve high removal efficiency with a low-pressure drop. PVA/SPI nano fabric possesses the highest QF (ca. 0.027 Pa-1)[9] Fig. 4. The areal density of SPI/BC composites is about $60 g/m^2$, much lower than commercial HEPA filters ($164 g/m^2$)[10], which have the highest filtration efficiency level in the market. These results show that the protein-based nanofiber filters can achieve the best filtration efficiency[14].



The soy protein fibers and filters manufacturing process does not pollute the environment. Most of the added auxiliaries used in the production process could be recovered from semi-fabricated fibers and used again[1]. This is an essential step in achieving a sustainable and environmentally friendly production method.

PHYSICAL PARAMETERS	SOY PROTEIN FIBER
Breaking strength	3.8 - 4.0 for dry (2.5-3.0 for wet) cN/tex
Density	1.29 g/cm^3
Diameter	100 to 200 nm
Shrinkage	Dry heat - 2.2 %, Boiling water - 2.3%
Moth/fungus resistance	RESISTANT

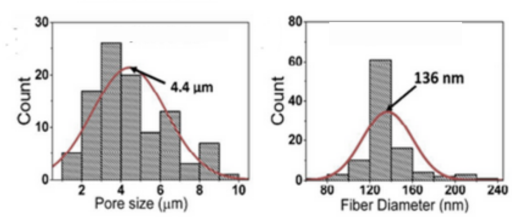


Fig 4. Physical parameters of SPF[15]; Pore size distribution, fiber diameter distribution, pressure drop, and quality factor of SPI/PVA 1:1 nano fabric filter[9].

Soy protein fibers are an attractive option for filtration material as they can be easily molded through various fabrication processes, influencing the porosity and mechanical property of the fibers produced and, ultimately, the filtration properties of the product[16].

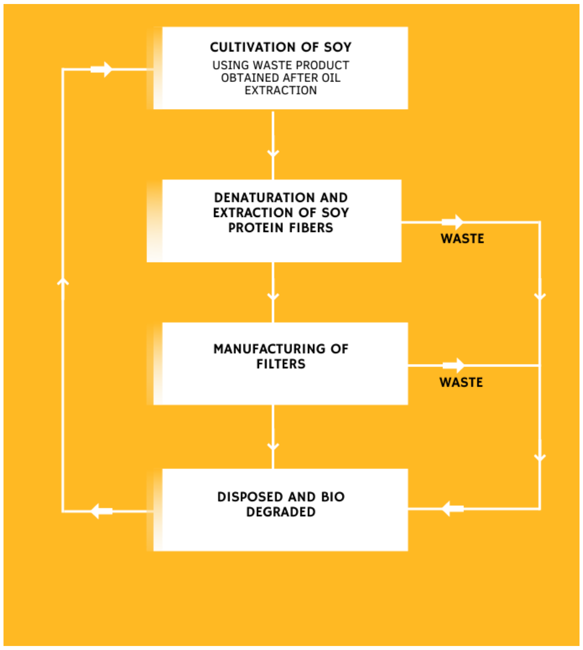


Fig 5. Flow chart depicting the life cycle of soy protein filter.

4. FILTRATION PERFORMANCE OF SOY PROTEIN FIBERS

According to the WHO, 2 million premature deaths

A filter works on two principles: physical adsorption, where particulate matter binds itself to the filter by impaction, interception, diffusion, and electrostatic interaction, and the other is by chemical interaction, where the active sites on the filters react with the pollutants or gasses entrapping them or rendering them inert. Fig 6.

The removal efficiency of SPI/PVA composite for PM10-2.5 is 99.90-99.99%, indicating that physical and mechanical mechanisms of filtration mainly capture large particles. For PM2.5, removal efficiency is 99.80%, which is an improvement of 0.4% over synthetic filters (99.45%)[9] Fig. 9. SPI/BC

occur due to air pollution. More than half of this disease burden is borne by developing countries[17]. Indian cities account for 13 of the 15 most polluted cities globally[18]. Polluted air consists of particulate matter and a mixture of gases such as CO, NOx, volatile organic compounds (VOC), sulfides, etc.[17].

The short-term and long-term effects of pollution have been studied extensively. Short-term pollution exposure, which is temporary, causes discomfort such as irritation to the nose, throat, eyes, or skin; sometimes, it can cause severe illnesses such as pneumonia or bronchitis. The long-term effects of air pollution can last for years or have lifetime effects and sometimes can even be fatal. Long-term exposure can cause severe illnesses and damage nerves, brain, kidneys, liver, and other organs[19]. Heart disease, lung cancer, and respiratory diseases such as emphysema are also causes of air pollution. With the covid-19 cases rising, the need for personal protective clothing and filters have skyrocketed, and most of the personal protective masks being single-use is an environmental catastrophe[20].

composite also showed the removal efficiency of PM10 at 99.95% and PM2.5 at 99.94%[10]. These results are comparable to commercial filters and masks. The most common filter found in the market is HEPA filters. They are mechanical air filters that trap particulate matter through physical means, and they also require pre-filters to assist with catching airborne particulate. They cannot filter out gases or other volatile compounds being a mechanical filter. However, the soy protein filter result indicates that small particles were removed due to interaction with the multiple functional groups present on the structure of SPI.

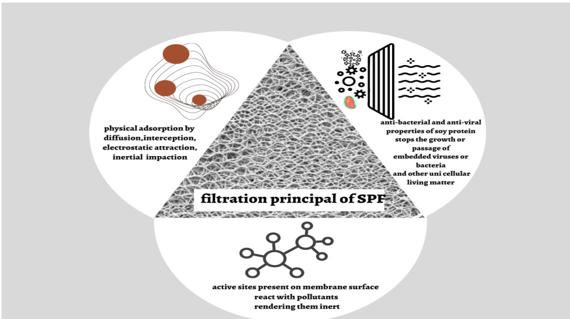


Fig 6. Illustrating the filtration principle of soy protein fiber.

With high efficiency for removing particulate matter, soy protein-based filters also filter toxic chemicals and other biomaterials such as bacteria and viruses.

SPI/PVA composite filter showed adsorption of toxic chemicals such as formaldehyde (HCHO) and carbon monoxide (CO) molecules. The HCHO removal efficiency was around 62.50% (SPI/PVA 1:1), and for CO removal efficiency, SPI/PVA showed much better performance efficiency, ranging from 76.90% to 90.90%. As a comparison, the removal efficiency for HCHO and CO by commercial HEPA filters was less than 5% and 3%, respectively, even though they have a much higher areal density[9] Fig. 9. Since gasses and toxic molecules are smaller than particulate matter, the removal of these molecules is due to the presence of active sites on the protein fibers.

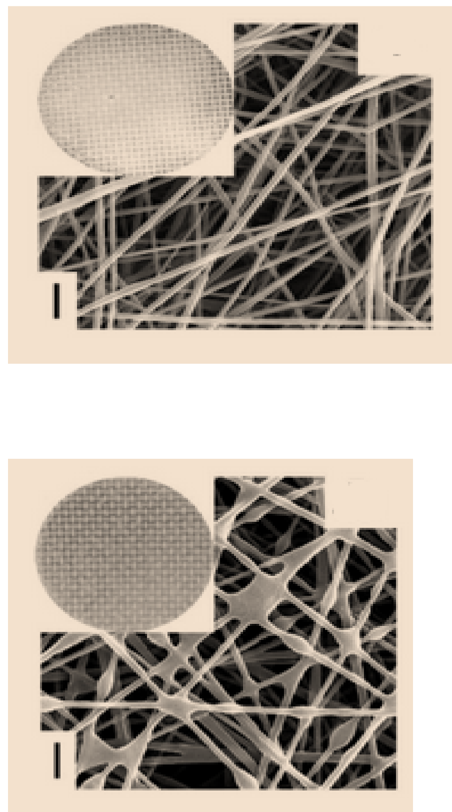


Fig 7. SEM images of before and after air filtration test on SPI/PVA 1:1 ratio composition[9].

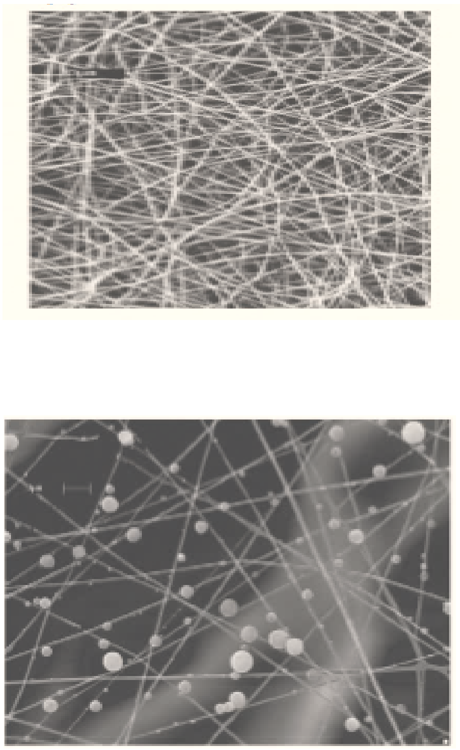


Fig 8. SEM images of before and after BFE test on SPI/PEO with fiber weight of 5 g/m^2 [21].

The bacterial filtration test conducted on soy proteins blended with poly-ethylene-oxide (PEO) showed the high capturing ability of gram-negative E. coli bacteria. Just the addition of a protein on-base filter significantly increases its filtration efficiency. 3 g/m^2 of the SPI/PEO is sufficient to capture 100% of the airborne bacteria. The test showed that bacteria via mechanical and charged-based interaction were filtered. The positive electrical charge on proteins attracted electronegative particles such as the aerosolized E. coli bacteria, and the nano filter provided a large surface area for these interactions. The ones not attached via charge attraction were trapped mechanically as the bacteria were too large to pass through the small pore size of the soy protein nano filter[21]. The size of the covid 19 virus is ≈0.1 µm in diameter, but the virus is transmitted via respiratory droplets, which are smaller or greater than 5 µm in diameter[22]. Soy protein nano filters can filter these droplets by a sieving mechanism.

Filters made from soy protein can be installed in hospitals, schools, and other indoor conditions to protect from air pollution, toxic gases, bacterial and viral infections.

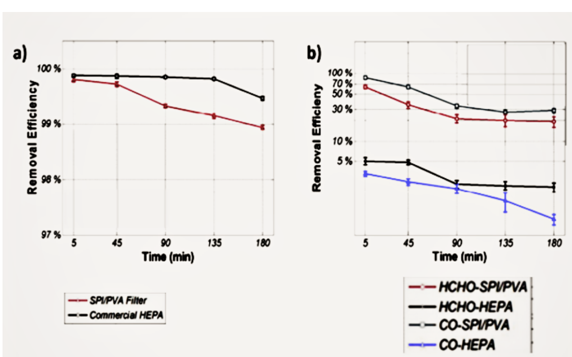


Fig 9. Filtration performance of SPI/PVA: a) TIME vs. filtration efficiency of PM2.5, b) Comparison of filtration efficiency for toxic gases with HEPA[9].

5.BIODEGRADABILITY AND DISPOSABILITY

In the last couple of years, an increase in personal protective equipment and indoor air filters has been observed due to ongoing pandemic and all-time high air pollution levels. This has generated up to 7,200 tons of medical and plastic waste every day[23], much of which is disposable masks. Face masks and other filters are made of non-biodegradable non-renewable plastics which are hazardous to their surroundings[24], this is where soy protein filters and other materials made from biopolymers are effective, as they are derived from natural materials, they are biodegradable and do not pose much threat to the environment, as far as soy protein and its composites are concerned, surprisingly, there are not any life cycle assessment (LCA) experiments conducted, available ones are not conclusive about the result. Composts made from it can act as an excellent soil stabilizer[25], but enough data is not available about byproducts released such as methane and other GHG during its decomposition[26]. More studies that include every aspect of the life of soy protein need to be conducted for effective comparison with synthetic polymers.

6. CONCLUSION

Soy protein filters fit all three pillars of sustainable development; they are environmentally friendly, economically viable[26], and socially compatible. Filters from soy protein show great filtration properties in standards with synthetic ones available in the market, and with their unique structure, they can be modified to fit the objective. Also, with many active sites present on the surface, they have been shown to filter out toxic gasses, particulate matter, other volatile materials, and even biological components, which could not be done with conventional filters. Soy protein as a filtration material is still in its infancy and many aspects from its production to decomposition have not been studied extensively. There are some areas where more data need to be collected, but Soy proteins can be the next green material to replace petroleum-based products.

7. REFERENCES

[1] Rijavec, T.; Zupi, Z. Soybean Protein Fibres (SPF). In *Recent Trends for Enhancing the Diversity and Quality of Soybean Products*; InTech, **2011**.

[2] Mathur, M.; Hira, M. Speciality Fibers - I: Soybean Protein Fiber, Man-Made Textiles in India. **2004**, *32*, 365–369.

[3] Hari, K. B.; Savithiry, N. S.; Ahmed, M. A.; Randall, N. L. Identification of Glycinin and Beta-Conglycinin Subunits That Contribute to Increased Protein Content of High-Protein Soybean Lines. *J. Agric. Food Chem* **2007**, *55*, 1839–1845,.

[4] Zhang, L.; Zeng, M. Proteins as Sources of Materials. In *Monomers, Polymers and Composites from Renewable Resources*; Elsevier, **2008**; pp 479–493.

[5] Pressley, K. J. J. R. Studies with Soybean Protein and Fiber Formatio. *Cereal Chem* **1966**, *43*, 195–206.

[6] Huang, H. C.; Hammond, E. G.; Reitmeier, C. A.; Myers, D. J. Properties of Fibers Produced from Soy Protein Isolate by Extrusion and Wet-Spinning. *J. Am. Oil Chem. Soc.* **1995**, *72*, 1453–1460. https://doi.org/10.1007/bf02577837.

[7] Zhang, Y.; Ghasemzadeh, S.; Kotliar, A. M.; Kumar, S.; Presnell, S.; Williams, L. D. Fibers from Soybean Protein and Poly (Vinyl Alcohol). *J. Appl. Polym. Sci* **1999**, *71*, 11–19.

[8] Li, G. *Phytoprotein Synthetic Fiber and Method of Manufacture Thereof". United States of America Patent 7,271*; **2007**.

[9] Hamid, S.; Kyle, S. J.; Yu, W.; Keshava, B.; Wei-Hong, Z. Soy-Protein-Based Nanofabrics for Highly Efficient and Multifunctional Air Filtration. *ACS Appl. Mater. Interfaces* **2016**, *8*, p. 20023−20031.

[10] Liu, X.; Souzandeh, H.; Zheng, Y.; Xie, Y.; Zhong, W.-H.; Wang, C. Soy Protein Isolate/Bacterial Cellulose Composite Membranes for High Efficiency Particulate Air Filtration, " Compos. *Compos. Sci. Technol* **2016.**

[11] Tipper, M.; Guillemois, E. Developments in the Use of Nanofiber in Nonwovens. In *Advances in Technical Nonwovens, leeds, west yorkshier: matthew deans*; **2016**; pp 115–132.

[12] G. R., "Production of nanostructured nonwovens containing self-assembling peptides for hard tissue regeneration," Leeds, **2016**.

[13] Christopher, R. G.; Kayla, C.; Everett, S.; Kilian, L.; Guoxiang, J.; Shu, Y.; Xiao, H. Biopolymer-Based Filtration Materials. *ACS Omega* **2021**, *6*, 11804–11812.

[14] Washington State University. Environmentally-Friendly Soy Air Filter Developed: Soy-Based Filter Can Capture Toxic Chemicals That Other Filters Can't. *Science Daily*. January 13, **2017**. [Online]. Available: www.sciencedaily.com/releases/2017/01/170113155352.htm . [Accessed 15 december 2021].

[15] Swicofil AG, "Swicofil AG," Swicofil AG, 27 April **2011**. [Online]. Available: http://www.swicofil.com/soybeanproteinfiber.html. [Accessed 20 december 2021].

[16] S. blog, "Capturing Toxic Chemicals with a Soy Protein based Air Filter," [Online]. Available: https://blog.spotchemi.com/capturing-toxic-chemicals-with-a-soy-protein-based-air-filter/. [Accessed 15 December 2021].

[17] World Health Organization, "WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide: global update 2005 : summary of risk assessment," World Health Organization, Occupational and Environmental Health Team, **2006**.

[18] IQAir, "2020 World air quality report (2020)," IQAir, **2020**.

[19] N. G. society, "air pollution," nat geo, [Online]. Available: https://www.nationalgeographic.org/encyclopedia/air-pollution/. [Accessed 16 december 2021].

[20] Yuan, X.; Wang, X.; Sarkar, B.; Ok, Y. S. The COVID-19 Pandemic Necessitates a Shift to a Plastic Circular Economy. *Nat Rev Earth Environ* **2021**, *2*, 659–660. https://doi.org/10.1038/s43017-021-00223-2

[21] Lubasova, D.; Netravali, A.; Parker, J. Bacterial Filtration Efficiency of Green Soyenviron Nanofiber Air Filter. *J Nanosci Nanotechnol* **2014**, *14*, 4891–4898..

[22] -O. Yinon, M. B.; Avi, F.; Rob, P.; Ron, M. SARS-CoV-2 (COVID-19) by the Numbers. *eLife* **2020**, *9.*

[23] A. Trafton, "The environmental toll of disposable masks.A new study calculates the waste generated by N95 usage and suggests possible ways to reduce it.," MIT News Office Publication, 20 July 2021. [Online]. Available: https://news.mit.edu/2021/covid-masks-environment-0720. [Accessed 5 december 2021].

[24] Selvakumar, D.; Veeramuthu, A.; Sneha, H.; Akila, M.; Pau, L. S.; Cheng, T. C.; Chawalit, N. The COVID-19 Pandemic Face Mask Waste: A Blooming Threat to the Marine Environment. *Chemosphere,* **2021**, 272, p. 129601.

[25] Lingamoorthy, S. K. "development of soy-based biodegradable fibers and resins for soil stabilization and crop protection," **2010**.

[26] P. Dr. Martin, B. Dr. Catia, M. Dr. Luigi, Dipl.-Geoökol and W.-i. Eduard, "Environmental assessment of bio-based polymers and natural fibres".