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SOYBEAN ECONOMIC VALUES AND WASTE VALORIZATION THROUGH DIFFERENT APPROACHES

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ABSTRACT
Soybeans are a crop of extreme global importance, being one of the main sources of vegetable protein, oil and other by-products used in human and animal food, industry and biofuels. Its large-scale production, mainly in Brazil, positively impacts food security,

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economy and international trade. Proper management of soybeans biomass and waste is crucial for mitigating environmental impacts. Efficient management of waste, such as crop residues and bark, can reduce soil, water, and air pollution, as well as prevent environmental degradation. The recovery of this waste is equally important, as it can be reused in the production of animal feed, organic fertilizers, biomass for renewable energy, pharmaceuticals and others. An overview is presented in this work, focusing on the data available at Food and Agriculture Organization of the United Nations (FAO) database and other similar organizations, about economic aspects, production values, import and export aspects and others, in addition to the variety of possibilities to provide high added-value applications for soybeans waste and biomass. This work presents a complete investigation about several agricultural indexes available at different organizations alongside some perspectives of high impact literature, emphasizing the size of soy residue market and underlining the importance of investing in the recovery of soy residues by high-added value applications, which not only reduces the environmental impact, but also promotes the circular economy by increasing the sustainability of agricultural production and contributing to the conservation of natural resources on a global scale.

Keywords: Soybeans. Soy Products. Biomass. Residue. Applications.

INTRODUCTION

SOYBEAN ECONOMIC VALUES AND MARKET SIZE

Due to the great complexity of decomposition and the aggravating pollution from non-renewable materials to the environment, the interest in replacing materials with an innovative profile are emerging in today's science (Gong et al., 2017; Lima et al., 2015). According to the literature, the scientific development of new biodegradable materials has been a path to major technological applications, based on abundant renewable sources, which offer superior mechanical, thermal and chemical properties when compared to conventional materials, aiming to serve areas such as engineering, automation, biomedical, environmental and others (Soares et al., 2005).

In the last ten years, especially in Brazil, there has been high growth in the agricultural sector, due to being a country with a large agricultural export, in which it has also boosted its economic development. A promising source of high economic value is soybeans, which is one of the main agricultural products in the world. In Brazil, soybean production has contributed to the growth of the agricultural sector, where it has been one of the major sectors in expansion since 1994 (Flach et al., 2021). Since 2019, soybeans accounted for 49% of the agricultural area and 41% of agricultural revenues, according to *Instituto Brasileiro de Geografia e Estatística* (IBGE, 2023). That same year, 37% of all the soybeans produced in the world corresponded to the production of Brazil (Flach et al., 2021). Also, according to the Food and Agriculture Organization of the United Nations (FAO) (Food and Agriculture Organization of the United Nations, 2023), Brazil currently leads the first place as the world's largest soybean producer, surpassing the United States of America, as of 2021, with annual production of 134,934,935 tons and $51,607,792 million in gross production value. Among the world's main soybean producers, Table 1 shows the other countries that lead the soybean market, showing the values produced.

Table 1. Soybeans biggest producers worldwide according to FAO in 2021 and import quantity and value of soybeans products worldwide in 2021, based on the Top 20 highest commodities (Food and Agriculture Organization of the United Nations, 2023).

Countries	**Production, tons**	**Production value, 1000 US$**
Brazil	134,934,935	51,607,792
United States of America	120,707,230	46,166,204
Argentina	46,217,911	17,676,700
China	16,400,000	6,272,414
India	12,610,000	4,822,875
Paraguay	10,537,080	4,030,057
Canada	6,271,835	2,398,753
Russia	4,759,908	1,820,495
Ukraine	3,493,200	1,336,024
Bolivia	3,318,168	1,269,081
Soy-based product	**Import quantity, tons**	**Ranking worldwide**
Soybeans	163,360,904.81	3rd

Cake of soybeans	69,264,488.00	4th
Soybean oil	14,199,575.17	20th
	Import value, 1000 US$	**Ranking worldwide**
Soybeans	91,272,050	1st

Therefore, soybeans are demonstrably one of the most important sources of food for human consumption. Combined with that, an adequate management of its biomass and residues are needed in a society increasingly concerned about the environmental. This paper presents several added-value alternatives for soybeans biomass utilization and emphasizes the importance of its plant nowadays.

All data of the soybeans production values and quantities according to the Food and Agriculture Organization of the United Nations are available in FAO's website (Food and Agriculture Organization of the United Nations, 2023). Table 1 reports also the biggest producers of soybeans worldwide and presents also the ranking of different soy products. Brazil leads in the first place and in the last years presented a significant increase in soybeans numbers. It should be noted that the significant growth of this agricultural sector is due to the intense production, whose yield between 1990 and 2019 went from 1.7 to 3.2 tons per hectare, and the expanding area from 11.5 to 35.8 million hectares from 1990 to 2019, especially in new agricultural regions to the north and west, of the regions already established in the Brazilian biomes, Amazon and Cerrado (Dias et al., 2016; Flach et al., 2021).

In the soybean import sector, the country that leads the ranking is China, becoming the largest importer of soybeans in the world with 96,516,785 tons, which corresponds to $53,528,188 million, followed by other countries, which can be seen in Table 2 and 3, with their respective quantities in tons and import values (Food and Agriculture Organization of the United Nations, 2023).

Table 2. Soybeans biggest importers worldwide according to FAO in 2021 (Food and Agriculture Organization of the United Nations, 2023).

Countries	Import quantity, tons	Import value, 1000 US$
China	96,516,785	53,528,188
Argentina	4,866,019	2,623,687
Mexico	4,597,127	2,537,823
Netherlands	4,162,889	2,173,331
Thailand	3,996,771	2,266,639
Egypt	3,773,173	2,156,199
Spain	3,656,836	2,001,681
Germany	3,590,728	1,923,268
Japan	3,271,220	2,074,642

Taiwan	2,585,363	1,497,066

Table 3. Biggest importers of soybeans products worldwide in 2021, based on the reported by (Food and Agriculture Organization of the United Nations, 2023).

Cake of soybeans	**Import quantity, tons**
Indonesia	5,343,415.00
Viet Nam	4,882,220.00
France	2,910,887.00
Spain	2,777,815.00
Thailand	2,754,738.00
Soybean oil	**Import quantity, tons**
India	3,522,865.46
Nepal	1,275,201.26
China	1,109,945.28
Bangladesh	797,340.74
Algeria	654,293.16

Regarding soybean exports, Brazil also leads the top 10 of the largest export countries, as the world's largest exporter, with 86,109,785 tons and US$ 38,638,731 in exports, as can be seen in Tables 4 and 5.

Table 4. Export quantity and value of soybeans products worldwide in 2021, based on the Top 20 highest commodities, reported by (Food and Agriculture Organization of the United Nations, 2023).

Soy-based product	**Export quantity, tons**	**Ranking worldwide**
Soybeans	161,212,557.18	3rd
Cake of soybeans	61,888,495.00	4th
	Export value, 1000 US$	Ranking worldwide
Soybeans	77,703,371.00	2nd
Cake of soybeans	27,894,251.00	13rd
Countries	**Export quantity, tons**	**Export value, 1000 US$**
Brazil	86,109,785	38,638,731
United States of America	53,050,523	27,522,855
Paraguay	6,329,541	2,975,124
Canada	4,504,522	2,449,989
Argentina	4,284,452	2,232,371
Uruguay	1,768,288	896,993
Ukraine	1,144,695	621,432
Netherlands	988,047	591,297
Russia	982,215	408,026
Croatia	186,429	130,948

Table 5. Biggest exporters of soybeans products worldwide in 2021, based on the reported by (Food and Agriculture Organization of the United Nations, 2023).

Cake of soybeans	**Export quantity, tons**
Argentina	17,396,491.00
Brazil	17,149,123.00
United States of America	9,833,559.00
Netherlands	2,857,498.00
Paraguay	1,880,322.00
Soybean oil	Export quantity, tons
Argentina	4,661,375.54
Brazil	1,650,954.52
United States of America	734,317.30
Netherlands	579,082.53
Paraguay	561,930.64

Notably, soybeans are one of the most consumed plants worldwide. Its numbers about production quantities and import and export values are massive. Brazil leads almost all statistics mentioned, followed by USA, China and Argentina, underlining the importance of expanding technical information and applications for soy biomass of all types. In the next section, impactful and varied works will be presented for potential and future research, aiming a more sustainable and valorized way of managing residues. A comprehensive and detailed description about several physical chemical properties of soy biomass can be found at (Bramorski et al., 2023).

SOY WASTE BIOMASS APPLICATIONS AS VALUE-ADDED MATERIALS

One of the first known use of soybean as a raw material for composite applications were performed by Henry Ford, in 1941, when soybeans were tested compressed for plastic-like components. Differently, at that time, petroleum-based materials were cheap and renewable resources was not economically attractive (Mohanty et al., 2002). Normally, soy waste biomass is often obtained after the oil extraction. The waste is often found in large quantities and does not have a specific use, so, it is cheap and largely available (Bulgariu & Bulgariu, 2018). One type of soy waste biomass is soy protein, a by-product of the soy oil production and commonly obtained by soy meal, which uses soybeans as source material. During the oil extraction, soy flour is obtained as a secondary product of the process, which can be further purified to obtain concentrate and isolate soy protein (Leceta et al., 2014). Another soy residue from the oil extraction is soy hulls, representing around 2% in weight of whole soy grain and extensively available commercially in high productors countries, such as Brazil (Cardoso et al., 2013). (Fung et al., 2010) described Okara biomass as a by-product of the soy milk and tofu manufacturing, mainly caused by the great increase in the soy food consumption over the last decades, attributed to the healthy characteristic of soy-based foods. Additionally, some different types of soy residues are available in the literature, such as soy peels (Rambo et al., 2015) and used soy oil (Melo et al., 2021) as potential raw materials. One of the great interests in reusing biomass as raw materials for manufacturing high value-added materials, is related to the high rate of greenhouse gases generated by today's society costumes and its great dependence on fossil energy. In this chapter, several different soy-based materials are mentioned. However, detailed information about specific processes or analysis performed are beyond the scope of this review article and could not be amply described in the subsequent discussion. Original articles are extremely encouraged to be pursued by enthusiasts.

(Leceta et al., 2014) used soy protein, a by-product of soy oil extraction, to produce biobased films and its life cycle assessment. The proposed work was to obtain biodegradable packages by different biomasses, including soy protein, as a source for short-terms or one-time use plastic products, and to analyze contaminant stages of its production. It was concluded that, for soy protein films, the most environmental setback was the land use, necessary to produce and extract soy protein to obtain bio-based films, with greater waste generation, alongside the necessity of additivities and energy consumed during the film processing. Nevertheless, all studied films presented the capability of composting, being the major benefit compared to synthetic polymer films.

(Kumar et al., 2009) prepared soy protein isolate (SPI) films using a novel plasticizer thiodiglycol (TDG) and compared mechanical properties to glycerol-plasticized samples. Results showed higher tensile strength and elastic modulus for TDG-plasticized samples and increased content of plasticizer also increased elongation at break for both plasticizers. The presence of TDG as a plasticizer decreased the water uptake of SPI films after immersed in distilled water for 26h, indicating that the TDG formed a strong interaction with native hydroxyls of SPI films, preventing it to form bonds with water, and due to the fewer hydroxyl groups when compared to glycerol as plasticizer. In this study, it was possible to confirm TDG as a good plasticizer for SPI films.

(Huang et al., 2020) extracted cellulose nanocrystals (CNC) from textile waste and reinforced soy protein isolate (SPI) films for mechanical and physical evaluation. TEM images showed successfully the obtention of cellulose nanocrystals from textile waste, presenting a typical rod-like shape. In this work, authors did not used any chemical pre-treatments for the obtention of CNC. Moreover, it was evaluated that CNC presented a crystalline structure I_{β} with high crystallinity index. Films maintained transparency with significantly higher mechanical properties of tensile strength and Young's modulus. The application of soy-based films as an alternative for common packaging applications are significantly well-grounded in the literature.

As an alternative of soy protein isolate (SPI), (Mekonnen et al., 2016) utilized a cheaper source of soy, called soymeal (SM), on the fabrication of soy-based films for packaging. For this, raw material needed to be treated by fermentation processes and then plasticized with glycerol and blended with poly(butylene adipate-co-terephthalate) (PBAT). Materials were conventionally extruded to obtain films and evaluated by several characterizations. The authors observed that the fermentation processes used can act as a destructuring process for carbohydrates, being applicable for several other biomasses. Also, a potential film was obtained by the saccharification and fermentation processes, which produced a sample with significantly higher tensile strength when compared to PBAT and to the other samples obtained by different processes.

(Soares et al., 2005) produced biodegradable films based on soy protein and corn starch to evaluate its thermal stability. The presence of corn starch in the structure seemed to produce films with decreased thermal stability, mainly when compared to pure films of starch and soy protein. Also, authors could evaluate through activation energy values that the presence of protein in starch films caused degradation via chain scission in strong bonds of the protein chain, normally expected in weak bonds (< 100 kJ/mol).

Additional work about soy protein isolate (SPI) films were done by (Gu et al., 2019) In this approach, authors prepared a blend with SPI, water-soluble hyperbranched polyester (HBPE) and a polyfunctional cardanol derivative. Some great performance in mechanical properties was observed by the authors, with values of tensile strength and elongation at break of 11.6 MPa and 123%, respectively. Authors mentioned that this performance is due to the structure alteration caused by the introduction of nanosized cavities into the matrix from HBPE. Moreover, increased crosslink also increased tensile strength, caused by the incorporation of bifunctional reagent within the processing. Several properties, including thermal, optical, UV-barrier, spectroscopy and structural were investigated to obtain a conclusive report of the material.

Hydrogels can also be produced by soy protein biomass, essentially described by (Hwang & Damodaran, 1996). By this approach, authors have used some residues from soy protein isolate (SPI) and performed modifications to obtain a crosslinked material, a hydrogel, with an absorption of 105g of water/g of dry gel. Biodegradable hydrogels based on proteins could be a potential replacement material for synthetic hydrogels, with a wide range of applications. Swelling properties of the obtained hydrogel are comprehensively discussed in the original article.

Soy protein could perform several roles in the engineering area. The work realized by (D. Liu et al., 2013) describes the production of soy protein microspheres (SPM) as bio-sorbents for heavy metal ions in aqueous solutions. Microspheres with a diameter range of 4-45µm showed higher capacity to absorb several metal ions, including Zn(II), Cr(III), Cd(II), Cu(II), Pb(II), and Ni(II), when compared to natural polymeric sorbents, according to the authors. Also, parameters that influenced in their sorption capacities, adsorption kinetics and isotherm models were evaluated in this work.

(J. Liu et al., 2017) also produced hydrogels from soy waste biomass. In this approach, authors used soy protein isolate (SPI) and polyethylenimine (PEI) as matrix and functional component, respectively, to obtain a blend hydrogel for wastewater treatment. As seen in this section, protein can be a low cost, abundant and sustainable raw material for several applications, also seen by carbohydrates. SPI seems to be one of the most used proteins to produce a biopolymer with biocomposite, hydrogels or packaging applications. Hydrogels composition with 50% of both components (SPI/PEI) presented an excellent selectivity of Cu(II) ions when combined with a second heavy metal ion, such as Zn(II), Cd(II), and Pb(II). Additionally, Cu(II) ions could be reduced to nanoparticles to form a uniformly dispersed composite with Cu NP-loaded-SPI/PEI material. Detailed evaluation performed by the authors made it possible to conclude that the produced hydrogel is efficient for wastewater treatment, in addition, it can be a possibility to protect the environment combined to metal recycling.

(de Souza et al., 2020) prepared soy protein isolate (SPI) films with *pinhão* seeds residue, an aqueous extract from the cooking process which has phenolic compounds with known antioxidant properties. *Pinhão* is a seed from a tree cultivated at South America countries, commonly ate boiled and peeled, resulting in a solid and aqueous residue. Aiming packaging applications, authors performed physical, structural and antioxidant properties of the obtained material. Authors analyzed that the presence of *pinhão* extracts did not negatively affect the mechanical properties of the film produced, combined with higher antioxidant capacities and oxidative stability, when tested as a package for several different oils.

SOY HULLS

Some physical properties of soy hulls were provided by (Cardoso et al., 2013) and the information are summarized the previous section. In this work, authors investigated density, particle size and shape distributions of several types of biomasses, including soy hull. Different results were observed as well as influence of different properties in the behavior of the material as a renewable energy. Properties obtained can serve as source for numerical simulations for pyrolysis, combustion and gasification processes, as well as optimal condition studies.

In other manner, (Alemdar & Sain, 2008) characterized soy hulls biomass to produce soy hulls nanofibers for bio-composites, summarized in the previous section. It is clear evident the effect of each chemical treatment performed on the lignocellulosic composition, reflecting at the structure of the fiber, being apparent the removal of phases such as hemicellulose, pectin and lignin, which acts as a cementing material around the fibers. Additionally, the average diameter of the fiber changed from 25-125 μm to 10-15 μm after treatments, i.e., the partial dissolution of the cell walls of the fibers. Also, crystallinity of soy hulls fibers was estimated by X-Ray Diffractometry (XRD) analysis. It is known that cellulose chains are ordered in a monoclinic lattice, which represents the wholesome fiber composed by ordered and disordered regions of cellulose chains, i.e., crystalline and amorphous regions in the same fiber, respectively. The length of crystallites is estimated to be 100-250 nm and one chain of cellulose can contain various crystallites (Fengel & Wegener, 1989). Integrated peak area of amorphous and crystalline regions was performed from XRD to obtain crystallinity index (CI) of soy hulls fibers, presented in the previous chapter. The removal of amorphous phases by the treatments increased the crystallinity index of the fibers, as expected, increasing the cellulose rigidity and, consequently, mechanical properties. Additionally, the authors obtained decomposition temperatures through Thermogravimetric analysis. The presence of a more crystalline structure, obtained by different chemi-mechanically treatments performed, reflected directly at the decomposition temperature during analysis, with nanofibers presenting higher thermal stability than untreated fibers.

(Herde et al., 2020) produced activated carbons (AC) with high specific surface area (SSA) from corn fibers and soy hulls. ACs are often desired by producers and users of batteries and supercapacitors and can be economically and environmentally produced when its source is from by-products of C5 biorefineries. In this work, authors detailed several chemical strategies to obtain the material, which consists in a selective hydrolysis of the grains to further obtain residual fibers and, consequently, activated carbon by chemical activation and carbonization. It was observed that these biomasses were very effective to produce high-SSA ACs. According to the authors observations, the surface area of the soy hulls post-treatment was almost 50% higher than that with no treatment. Also, potential source of graphene formation was observed through TEM images, where thin layers of non-amorphous carbon was detected. These potential results can lead to great value-added applications of some biomasses.

(Zheng et al., 2019) prepared an adhesive material based on soybean biomass of soy flour and soy hull. Authors performed a fermentation with a low-cost enzyme on the soybean biomass with further hot pressing to obtain bioadhesives and plywood. The resultant material showed to be crosslinked with soy protein, performing improved adhesive strength and water resistance compared to the non-hydrolyzed sample. According to the authors, this material demonstrated potential for being a replacement to synthetic wood-based adhesives.

SOYBEAN WASTE BIOCHAR

(Zhang et al., 2019) used soy residue as a precursor to obtain carbon for biochar dots (BCD) synthesis. In this work, it was mentioned the importance of using nitrogen-rich residue, such as soy, for synthesis of BCDs, which can be used as a sensitive detector for some metals, such as Hg^{2+} and Fe^{3+} ions. After a hydrothermal treatment, the authors could obtain

BCDs from soy residue, which was efficiently used to the detection of metal ions in aqueous solutions. Moreover, it was possible to detect metal ions also in a micromolar range, as a fluorescent probe, evidencing the importance of use cheap raw material as a source for eco-friendly materials.

Different biomasses were also used by (Lucaci et al., 2019), including soy waste, to produce biochar for the removal of Co(II) ion from aqueous solutions. Here, the produced biochar was obtained through pyrolysis at 600-650°C after oil removal with n-hexane in Soxhlet apparatus. It was observed in FTIR analysis the presence of some functional groups that works as binding sites for ion retention, such as amines, carbonyls, and oxygen compounds. Soy biochar showed sorption capacity of 19.61mg/g, under constant solution pH (5.0), sorbent dose (8.0 g/L) and room temperature during 60mins minimum, and the biochar samples could be used at least to three biosorption/desorption cycles, evidencing its capacity as a bio-sorbent material from waste biomass. Additionally, authors characterized the biochar sample of soy waste, which is summarized in the previous section.

Soybean derived biochar was evaluated by (Moon et al., 2017) as an improvement for an acidic soil quality. Authors compared soybean biochar with oak biochar and found that the former one presented higher capacity of soil treatment, through pH, exchangeable cations and maize growth results obtained, enabling biochar value-added applications for soy waste.

SOY-BASED BIOFUELS

(Choi et al., 2015) also studied okara, as a source material to produce bioethanol. According to the authors, okara represents 25% in weight as a by-product from the soy milk and tofu manufacturing. Considering soy beverage consumption worldwide, dozens of tons of okara are generated by year. In this work, authors performed a fermentation from a produced in-house enzyme called *Saccharomyces cerevisiae* to produce bioethanol from okara residue. It was concluded that okara can be used to produce bioethanol, with a fermentation yield of 96.2% and ethanol concentration of 59.1g per 1 kg of okara.

(Haas et al., 2001) produced a biodiesel fuel from soybean soap stock, a waste from soybean oil production. The developed small-scale method was used to produce the fuel, completely evaluated. According to the authors, several properties obtained were in accordance with the specifications of American Society for Testing and Materials (ASTM) for biodiesel, such as flash point, water and sediment, carbon residue, sulfated ash, density, kinematic viscosity, sulfur, cetane number, cloud point, copper corrosion, acid number, free glycerin, and total glycerin. Also, had density and iodine number values similar to those of commercial soy-based biodiesel. All results obtained by the authors fully indicate that the methyl ester obtained from soy soap stock are suitable for diesel fuel use, obtained by a simple and low-cost method, resulting in functionally identical fuel commercially produced.

SOY-BASED WASTE

In a recent work, (Bulgariu & Bulgariu, 2018) tested functionalized soy waste biomass as a cheaper biosorbent material for heavy metal removal from aqueous solution. The authors mentioned that choosing soy waste biomass were related to the broken cell walls of the soy, during the oil extraction process, which provides an increase in the surface area of the product. Also, it was mentioned that a washing step was not needed due to the oil extraction with organic solvents, so the functionalization proposed for the production of a biosorbent could be performed in a straightforward way. The obtained biosorbent from soy waste biomass showed efficiency on the removal of 0.40 $mmolL^{-1}$ Pb(II) ions from aqueous solution in an optimal experimental condition, it was used a 0.2 mLg^{-1} ratio of sulphur chelating agent solution and soy waste biomass, at 30°C of temperature. The functionalization increased 196% the biosorption capacity of the biosorbent for Pb(II) and 130% for Cu(II) and Ni(II). This efficiency was also noted at FTIR analysis, where spectra observations showed new functional groups containing Sulphur donor atoms at the surface of the biosorbent. Additionally, it was achieved a regeneration potential of the biosorbents used, which means a possibility to use the same biosorbent during five biosorption/desorption cycles for removal of Pb(II), Cu(II) and Ni(II) from aqueous solution.

(Zhu et al., 2019) used soybean curd residues as a renewable source to produce Pd-modified Porous *N-doped* Carbon Materials (Pd/PCNM), which is commonly prepared under harsh reactions conditions. This type of material is usually used as catalyst for hydrogenation of phenols to ciclohexanones, where its catalytic performance has proved to be great. In this work, authors determined that the prepared material presented high catalytic activity, even when compared to commercial materials, highlighting the novel strategy of production used as a promising and efficient nanocatalyst from a biomass source. In a different approach, (Suenaga et al., 2023) used a microorganism called *Aurantiochytrium* sp. L3W in several types of biomasses, including soy sauce, to produce docosahexaenoic and eicosapentaenoic acids (DHA and EPA), which is commonly found in fish oil. Proven benefits of DHA and EPA in cardiovascular health, visual and neurological functions are known by nowadays society and are concisely discussed by the article. Undesirably, fish oil resources are becoming a negative environmental concern, due to sustainability issues, related to constraints on aquaculture systems. Nevertheless, authors could confirm the use of solid food waste as a substrate for producing DHA and EPA by cultivation of *Aurantiochytrium* sp. L3W, proving again the wide range of commercial applications possible to several types of biomasses commonly present in the planet.

The importance of soy oil in nowadays society are clearly known, consequently having great production, it is expected that the incorrect disposal can cause severe water and soil pollution. Some strategies of reuse, such as soap, biodiesel or detergent fabrications has been delivered but seems to be insufficient. The effort dedicated by the academy in studying many possible applications and efficient reuse of biomass is of great value. (Melo et al., 2021) comprehensively described some strategies to produce a potential biomass for animal supplementation with favorable nutritional composition from used soybean oil residue and other biomasses. For that, the authors achieved a satisfactory result of hydrolysis by fermentation of soy oil from frying processes, using specific microorganisms. (Lim et al., 2011) studied the potential use of soybean husks as feedstocks for vermicomposting, a different disposal system, using rejected papaya as an amendment. The system elaborated by the authors showed that these materials have potential application at vermicomposting for 63 days, presenting great combination of nutrients for plants, being a sustainable way out to convert industrial solid waste into value-added materials, rather than decomposing in landfills or incinerating.

(Choct et al., 2010) detailed in a review article, several information about digestibility, nutritional and anti-nutritional effects of soy oligosaccharides in animal feed. In this work, authors explained summarized the nutritional composition of different soybean products Authors observed that some non-starch polysaccharides (NSP) present in the soybean composition were soluble and their extraction could improve the dietary quality of this food. Observations in the dietary of pigs and poultries were delivered and extraction processes of these NSPs were made, obtaining soy protein concentrate, which is a high-quality product for animal diet. (Luo et al., 2019) used an inexpensive soybean biomass, called defatted soy powder (DSP), to perform an enzymatic conversion in several different biomasses, in order to obtain biofuels from lignocellulosic masses, rather than high-costs and ineffective usual treatments. Authors observed that the addition of DSP could readily reduce synthetic additives loadings by 8 times in the conversion of biomasses, decreasing the process cost and significantly contributing to the entire biorefinery industry of cellulosic material, also, representing a reuse of biomass from soybean production.

Production of biocomposites reinforced with biomasses are extensively discussed by (Nagarajan et al., 2013). In this case, authors reuse several crop residues to reinforce a poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) and poly(butylene adipate-coterephthalate) (PBAT) biodegradable matrix, including soy stalk. Several properties of the specimens were evaluated. Regarding soy stalk biocomposites, it was found the highest thermal stability, evaluated by Thermogravimetric analysis (TG). Particular properties observed by each composition were assigned to be related to fiber nature composition and length distribution. The work of (Swain et al., 2004) provides a great review about soybean biomass. Authors detailed several information about oil importance in nowadays society, its production, yields and market value, focused on soybean oil, with included description of several products processing. Varieties and composition of soybean are also provided, regarding its amino acids and molecules with detailed discussion. Some applications of soybean were also delivered, including soybean bioplastics, film obtention processes and its additives and injection molded plastics based on soybean biomass, supporting that, at the beginning of the century, soy was already seen as a promising source of raw material for green technologies.

(Nyambo et al., 2010) prepared polylactide (PLA) composites reinforced with several types of biomasses, including soy stalks. The composite prepared with soy stalks presented fiber density of 1.424 g cm^{-3} with almost unaltered thermal events, when compared to pure PLA. However, crystallinity index of the blend with soy stalks were the highest amongst other fillers, with 56%. Complete mechanical properties of these specimens were obtained, and no significant effect were found, comparing each filler. Authors found that mixing different fillers from biomass resulted in similar physicochemical properties of each composite, indicating a possibility of utilization from different biomasses suppliers. (Xin et al., 2017) produced property enhanced soy adhesives with lignin amine, from a novel process developed. Primary lignin amine was produced by a free formaldehyde approach, commonly known oxidation and reductive amination reaction, comprehensively described in the original article. The presence of lignin amine in the soy adhesive produced higher water resistance and adhesion strength, aiming at plywood production. Utilization of biomasses from different sources can generate great commercial and environmental interest in the resulting material, due to its low-cost, renewable source and eco-friendly processes involved.

CHARACTERIZATION OF SOY-BASED MATERIALS

In a different approach, (Fung et al., 2010) characterized various biomass from palm and soy oil industry, namely oil palm trunk, oil palm frond and okara. Okara is rich in protein and dietary fiber but is commonly disposed in landfills or energetically recycled, and its main source is soy milk and tofu manufacturing. The authors fully characterized various fibrous residues, in order to evaluate their capacity to perform nanofibers development. Additionally, authors mentioned that the chemical (alkaline, autoclave) and physical (grinding) treatments realized in the FM okara, promoted a more rough and flaky structure, seen in FR sample, due to the removal of waxes and non-cellulosic materials from its surface. Okara exhibits high protein content, which is significantly reduce after the alkaline treatment to the obtention of FR. Protein content also affects the emulsifying activity of the biomass. Fat content is also great, which reflects alongside protein content, the interest in soy oil and milk production from this source. Also, carbohydrate content was significantly increased by treatment, mainly composed by insoluble fibers discussed further. Also, soluble and insoluble fibers were also obtained as Total Dietary Fiber (TDF) content for okara residue and consists in pectins and gums, as soluble fibers, and lignin, cellulose and hemicellulose as insoluble fibers. High insoluble fibers content present in okara suggests potential application as dietetic products for dietary fiber supplements. Moreover, the presence of cellulose and lignin as the insoluble fraction, could promote okara application for nanofibers source in biomaterials applications. Conclusively, mineral content (Fe, Zn, Cu, Mn, Ca, K, Mg, Na, Si and P), reflectance values (Hunter L*, a* and b*) and functional properties (water-holding capacity, oil-holding capacity, emulsifying activity and stability and antioxidant activity) were comprehensively summarized and discussed in the original article, alongside the production of nanofibers.

(Rambo et al., 2015) characterized many Brazilian biomasses, including soy peels. Some of its properties were described in the previous chapter. Also, the composition of sugar was obtained. Among several analysis, it was possible to conclude by the authors that biomass with high calorific value and low ash content can be a promising source for bioenergy production. High moisture contents (>~10%) makes the biomass not suitable for energy feedstock but every residue showed some promising property as a source for value-added materials. (Silva et al., 2006) comprehensively summarized several chemical composition and protein value of soybean and soybean residue commonly used as animal food. Both materials were tested on a diet for weaning male Wistar rats. The soybean residue showed high protein content and lower energetic value than the soybean grain, with higher amino acid score values. The protein quality of soybean residue showed to be similar to the soybean grain in this work, potentially being a great source of animal food rather than common disposal or recycling.

APPLICATION EVALUATION OF SOY-BASED MATERIALS

In the last chapter, some perspectives of the literature were provided by pointing several possible applications of different soy-based residues. Now, this literature will be analyzed according to each type of soy residue used, the application mentioned and the different types of characterizations. The objective of this chapter is to summarize all the previous literature findings.

Figure 1 summarizes the source of soy-based residues cited in this work.

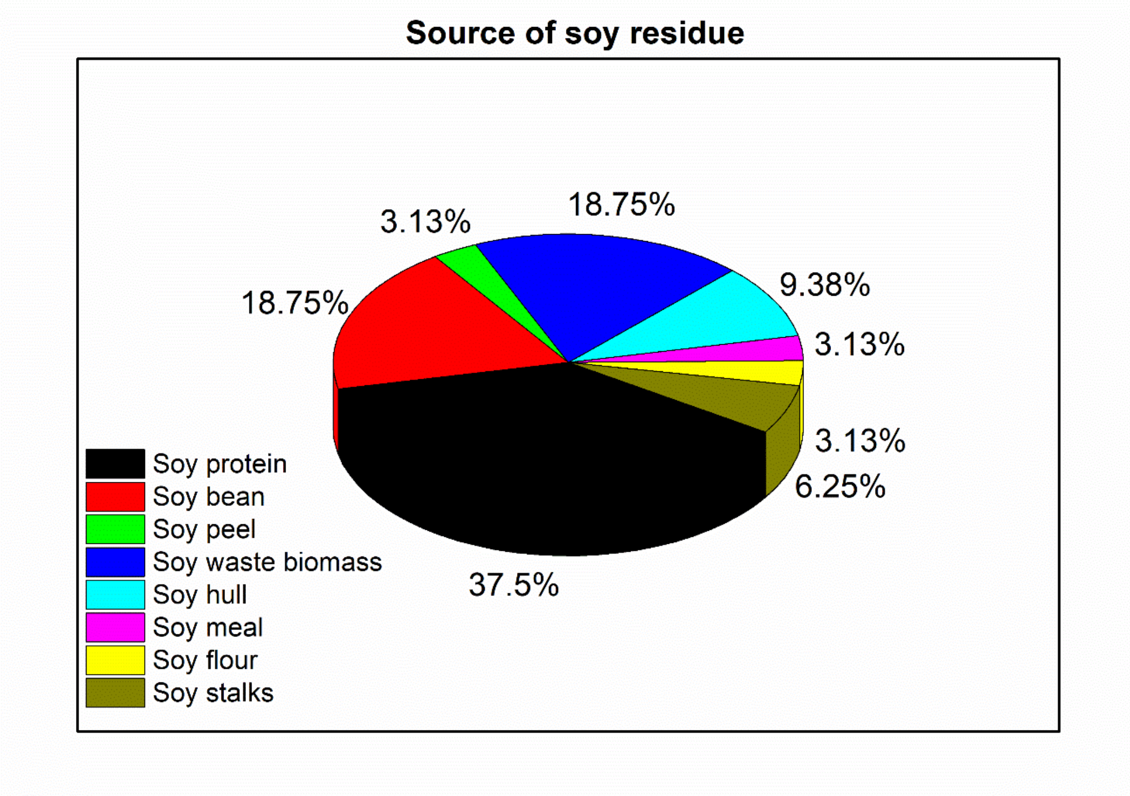


Figure 1. Source of the soy residue in the literature cited in this work.

As observed, the most common source is soy protein, one of the most abundant protein source on earth. This type of residue is normally a result from the industry of soy oil, which uses soybean as raw material. The most common process is the extraction of soy protein from soybeans after the oil extraction. Also, another by-product is produced, called soy flour, which can be purified to obtain soy protein powder (de Souza et al., 2020; Leceta et al., 2014; J. Liu et al., 2017).

In general, soybean waste can be defined as the byproduct formed by several types of soy-based industries, such as milk and tofu, and presents very a very interesting composition of protein and cellulose, being an important source for several applications, as emphasized earlier (Zhu et al., 2019), being the second most used source mentioned here. Soybean waste can also be called as “okara”, a byproduct of the same tofu and milk processes, representing a greater residue mass (Choi et al., 2015; Fung et al., 2010), which is different from the defined as soy waste biomass, being a byproduct normally obtained after oil extraction (Bulgariu & Bulgariu, 2018; Lucaci et al., 2019).

Soy hulls are also a byproduct of soybean oil extraction, but with a significant lower mass, approximately 2% of the whole grain (Cardoso et al., 2013), very similar to the soy peels (Rambo et al., 2015). To obtain purified isolate proteins of soy, soy meal urges as an alternative, being normally used as feedstock for animals. This residue is a byproduct from the oil industries also (Mekonnen et al., 2016), a similar approach to the soy flour (Zheng et al., 2019) and soy stalks (Nyambo et al., 2010). In general, soy-based residues are mostly obtained from the industries of food, such as tofu and milk, or oil extraction.

Figure 2 summarizes the applications observed in this work for each type of soy-based residues.

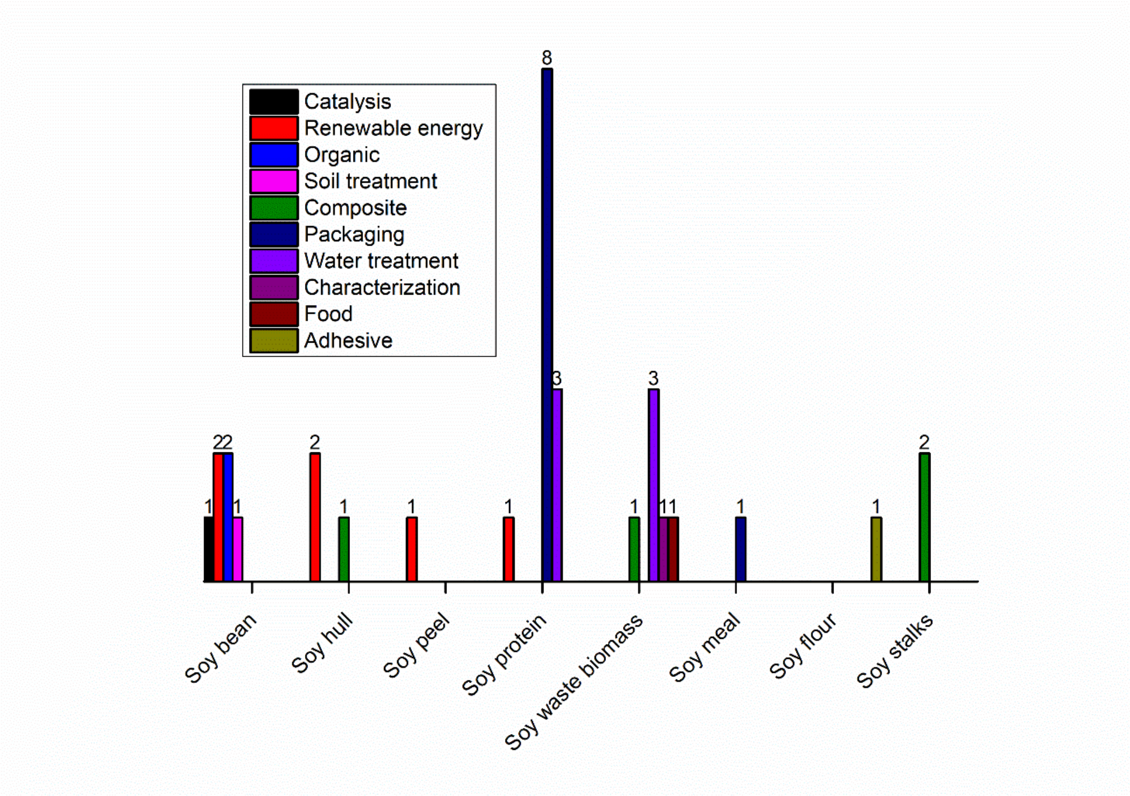
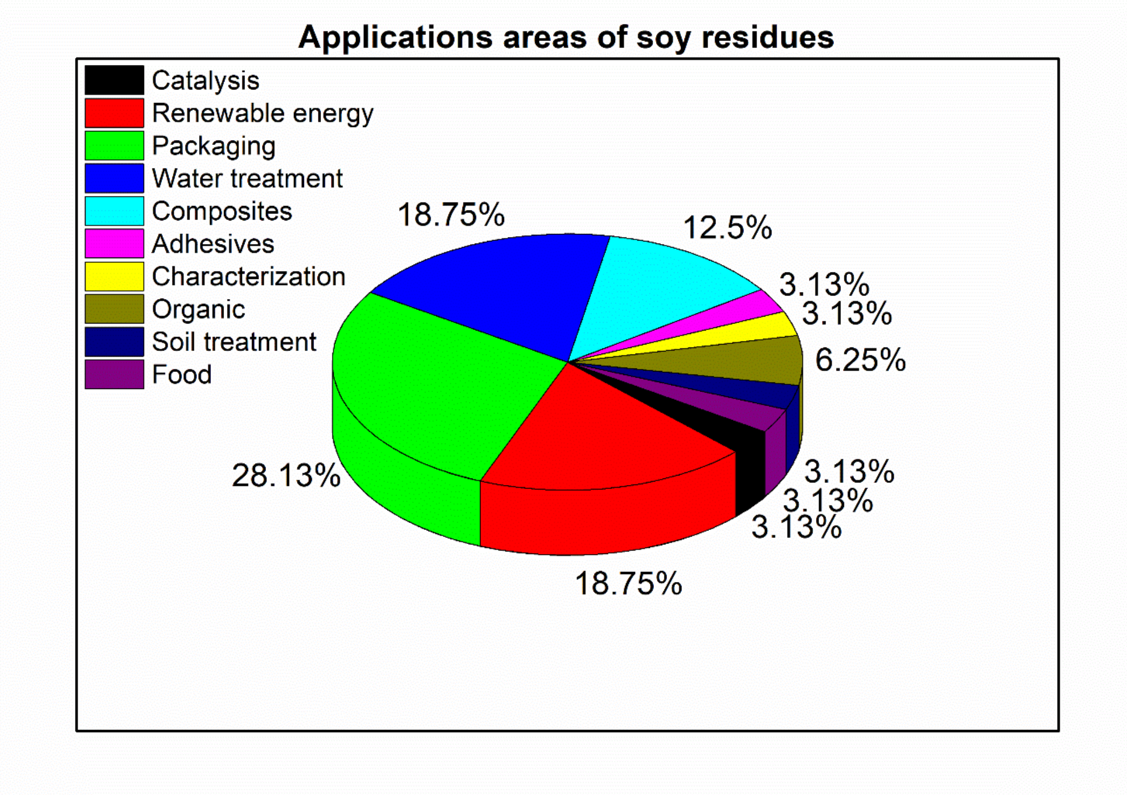


Figure 2. Application areas of each type of soy-based residues.

It is possible to observe that the soy protein is mainly used as a material for the fabrication of films with packaging purposes. This is mainly due to the good barrier properties, resistance to oils and biodegradability that natural proteins can have (de Souza et al., 2020; J. Liu et al., 2017), which was well described in a previous chapter.

The following applications most discussed in this work is water treatment and renewable energy, as shown in Figure 3.

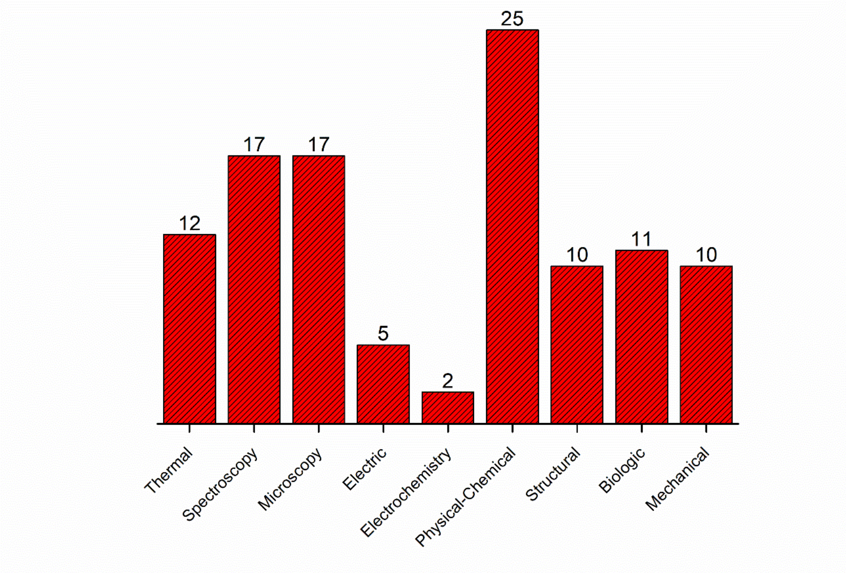
Figure 3. Application areas of soy residues of this work.



These observations emphasize that soy-based residues can have several possible applications. Water treatment purpose also utilizes soy protein as a source, discussed by (J. Liu et al., 2017). The same occurs with soy waste (Bulgariu & Bulgariu, 2018; Lucaci et al., 2019), which is normally used to overcome the high cost of synthetic biosorbents, being easily modified to this specific application.

Figure 4 shows the main characterizations performed in soy-based residues.

Figure 4. Types of analysis carried out in the several types of soy-based residues presented.



The most common characterization is the physical chemical, normally carried out to characterize the residue composition and properties, well described (Fung et al., 2010). Following analysis, such as thermal, spectroscopy and microscopy are commonly found in different types of applications and residue, as discussed earlier, and are mainly performed to renewable energy applications (Rambo et al., 2015), composites (Alemdar & Sain, 2008) and packaging (Gu et al., 2019), respectively.

Soybean biomass and some of its products revealed a multifaceted and promising scenario regarding the application of its residues and derived products for environmentally sustainable purposes. The mentioned studies highlighted numerous possibilities for the use of soybean biomass and waste, as well as their by-products, in different applications, evidencing their potential to contribute significantly to environmentally friendly practices. The objective of this paper was to emphasizes the feasibility of employing soybean residues in the production of biofuels, biochars, lignocellulosic source and a general biomass for clean energy generation, as well as in the manufacture of biodegradable and compostable materials. In addition, soybean by-products have been identified as valuable sources of bioactive compounds with potential application in the pharmaceutical, food and cosmetic industries, highlighting their added value and multiple possibilities of use. This overview reinforces the importance of exploring and valuing soy residues and their derivatives as renewable resources, promoting sustainable practices and mitigating environmental impacts, encouraging the development of innovative and sustainable strategies for the management of these materials in the search for an eco-friendlier future.

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