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EDITED BY
Shalini Gaur Rudra,
Indian Agricultural Research Institute, India

REVIEWED BY
Digambar Kavitake,
National Institute of Nutrition (ICMR), India
V. Ajesh Kumar,
Central Institute of Agricultural Engineering (ICAR), India

*CORRESPONDENCE
Hansong Yu
✉ yuhansong@163.com
Bo Lyu
✉ michael_lvbo@163.com

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Possibility of immediate treatment to soybean processing by-products using screw extrusion: a mini review

Yue Shen[1], Xiaolong Huang[1,2], Yujia Nan[1], Hansong Yu[1,2]* and Bo Lyu[1,2]*

[1]College of Food Science and Engineering, Jilin Agricultural University, Changchun, China, [2]Division of Soybean Processing, Soybean Research and Development Center, Chinese Agricultural Research System, Changchun, China

Soybeans are an important oil and protein supply crop, but the utilization of by-products from its processing products has never been effectively resolved, while a large number of nutritional resources have been wasted and environmental pollution is serious, restricting the sustainable development of the industry. The critical problem of soybean processing by-products includes excessive levels of microorganisms, residual proteins, metal ions, and other substances. Because the screw extrusion process has potentially advantageous processing characteristics, it appears that it's just the right solution to the above problem of soybean processing by-products. We propose that this technology may be a potentially scalable technology for the immediate processing of soybean by-products. This paper reviews the theoretical foundations in existing research, briefly discusses the technological advantages, feasibility, and potential risks of this process, and hopes that researchers may pay attention to this technique and conduct feasibility studies.

KEYWORDS

soybean processing, soybean dregs, soybean whey, processing technology, texturized protein

1 Introduction

With customers' desire for healthier diets and the popularity of plant-based diets, soy has emerged as the primary source of plant-based lipids and protein for humans (Qin et al., 2022). Traditional soybean processing, like the processing of many primary agricultural products, generates a large number of by-products, most notably soybean dregs and soybean whey (Lyu et al., 2021; Yang et al., 2022), which are produced during the processing of traditional soy products (such as tofu) and new soy products (such as soybean protein isolate [SPI]), although the composition may differ (Chua and Liu, 2019). In traditional processing models, by-products are often used directly as waste or as animal feed. However, soybean by-products can no longer be used as waste and are not permitted to be used as such due to growing environmental consciousness and researchers' usage of useful components.

Soybean dregs, also known as okara, are the main solid by-product of the preparation of traditional soy products and SPI. Its primary components are water and fiber; upon drying, insoluble dietary fiber predominates (Wang et al., 2021), meanwhile also contains some residual proteins and peptides (Fang et al., 2021). Rich in nutrients, soybean dregs are extremely prone to spoiling during storage, while the special structure of soybean fibers leads to their extreme water absorption (Lyu et al., 2021), making it difficult to dry and transport. As the traditional soybean product manufacturing businesses are often small and dispersed, the huge production of soybean dregs has become an intractable problem.

Soybean whey, also named yellow slurry water, soybean whey, or soy wastewater, plays a role similar to that of soybean dregs. Unlike this, however, the consequences of residual metal ions and excessive protein residues in the soybean whey are more serious (Wang and Serventi, 2019; Chen et al., 2024). Also, as a liquid by-product of soybean processing, it is more productive than the solids. The extremely high Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) of the soybean whey prevented it from being discharged properly (Chua and Liu, 2019), and the processors had to merge it into industrial sewer lines, thus facing high treatment costs. Furthermore, extra coagulants added during the soy product manufacturing process may result in excess metal ions in soybean whey. In summary, from the perspective of food safety risks, the main risks of soybean by-products come from three aspects: microbial contamination, metal ion contamination, and residual proteins.

To address the issue of soybean by-products, researchers have devised multiple pathways for high-value use, such as the use of soybean dregs to prepare dietary fiber (Wang et al., 2021) and the use of soybean whey to obtain isoflavones (Wang and Serventi, 2019). These methods have generally remained at the experimental level and have not been generalized to actual production due to various problems, such as high treatment costs. Finding a processing technology that applies to the production line, that can address all three food risks at the same time, and at a lower input cost, is imperative.

Screw extrusion technology for soybean food processing is mainly used for the production of soybean texturized protein (STP) (Zhang et al., 2023). The basic principle is to use the screw to generate high pressure and high shear at a high temperature so that the material in the molten state produces directional texturization of the structure (Dahl and Villota, 1991). This feature coincides with the food risk problem of soybean by-products we propose to address. Complementary single screw extrusion technology can be used to process coarse materials (Lyu et al., 2022a), which makes it possible to use screw extrusion equipment to mimic the STP production model to process by-products. Additionally, the screw extruder is a type of low-cost processing machinery.

2 Barriers to utilization of soybean processing by-products

To address the issue of soybean processing by-products, an overview of the barriers to their integrated use is necessary and can be summarized in the following three sections:

2.1 Poor processing suitability

Fresh soybean dregs can have a moisture content of between 80 and 85% (Chen et al., 2022), which affects the separation and purification of the dry matter in them directly. Based on the large amount of soybean dregs produced in practice, processors must dry the dregs as soon as possible to facilitate storage; otherwise, the high moisture content and unhygienic storage conditions would cause the dregs to quickly deteriorate. However, soybean dregs are different from ordinary food materials, their drying is extremely difficult, often accompanied by a large amount of energy consumption and long-time input (Lu et al., 2022). Even if the dregs are dried through higher processing costs, their rough palatability often makes them difficult for consumers to accept, which led to the frequent use of soybean dregs as animal feed (Jiang et al., 2019; Hu et al., 2023). To improve the processing performance of dreg as food, it is often modified using different methods, such as fermentation, chemical modification, etc., (Zhou et al., 2019; Wu et al., 2023), which undoubtedly diminishes the suitability of soybean dregs as a food ingredient for processing.

Soybean whey's unsuitability for food processing can be shown in its inability to be utilized in food preparation. It is challenging to link this effluent to food processing because of its bitter flavor (Huang et al., 2022) and high concentrations of several constituents, such as trypsin inhibitors and lectins. The conventional way of processing soybean whey into food is to ferment it with probiotics to improve its potential functionality and processing characteristics (Tian et al., 2021; Yang et al., 2021), which gives some special potential functionality to the soybean whey but does not enhance its suitability for processing from a practical production point of view. Instead, it raises the cost of processing.

2.2 High processing costs

As shown in Table 1, soybean processing by-products do contain a large number of potential processing resources (Li et al., 2012; Chua and Liu, 2019). However, obtaining these processing resources comes at a significant expense due to processing.

The most worthwhile potential processing resources to be obtained from soybean dregs are soybean dietary fiber and functional peptides (Fang et al., 2021; Wang et al., 2021). Insoluble dietary fiber from soybean dregs, for example, has been shown to regulate the body's glucose-lipid metabolism and intervene in the intestinal internal environment at high purity (Lyu et al., 2022b; Wang et al., 2023), which is considered a good resource for functional food. However, to obtain it, a combination of drying methods and the use of enzyme engineering techniques are required (Lyu et al., 2021), whose level of cost is unacceptable in industrial production.

Representative potential processing ingredients in soybean whey are oligosaccharides and isoflavones (Hu et al., 2024). As of today, the most efficient method recognized for separating these two components from soybean whey is membrane separation technology (Liu et al., 2015a,b). Complemented by larger yields than soybean dregs, it is more costly to achieve efficient separation of oligosaccharides and isoflavones from soybean whey in practical production. Again, no producers are doing this.

The process of extracting potential processing ingredients from soybean by-products is characterized by the fact that it is generally

TABLE 1 Main components and content of soybean by-products (Li et al., 2012; Chua and Liu, 2019).

Soybean dregs (fresh)*	Moisture (%)	Protein (g/100 g dry matter)	Fat (g/100 g dry matter)	Dietary fiber (g/100 g dry matter)	Ash (g/100 g dry matter)
	80.0–85.0	15.2–33.4	8.3–10.9	42.4–58.1	3.0–4.5
Soybean Whey (Tofu)*	Carbohydrates (g/L)	Proteins (g/L)	Fats (g/L)	Minerals (g/L)	Isoflavone (mg/L)
	8.50	1.33–8.20	3.9–10.0	3.9–4.6	About 50

*Refers to the dregs/whey produced during the production of traditional soy products, to differentiate them from the production of SPI.

easy to succeed in the laboratory but difficult to scale up and apply in actual production. High processing expenses should be held primarily responsible for this.

2.3 Contamination and food safety risks

Contamination and food safety risks of soybean by-products can be summarized in three categories: microorganisms, residual proteins, and metal ions.

Microorganism overload is a common problem in the treatment of soybean dregs and soybean whey. Among plant-based food wastes, microbiologically contaminated soybean dregs have the highest acidity (Wahab et al., 2022). Although fewer microbial species spoil soybean dregs in the natural environment, food microbial contamination is high in acidophilic microorganisms (Rawat, 2015), which are highly susceptible to risks such as *Pseudomonas putida* (Cunha et al., 2022). The microbial spoilage pattern of soybean whey is similar to that of soybean dregs, which will spoil within a day under conventional storage conditions (Chua and Liu, 2019). Conventional processing methods make it difficult to process soybean whey in 1 day. In addition, the odor of soybean whey is hard to receive after rotting and remains even after sterilization (Hao et al., 2023), which makes it no longer suitable for food processing.

Residual proteins in by-products are closely related to microbial contamination. Insoluble dietary fiber and soluble sugars provide a rich source of carbon for microbial reproduction, while, residual proteins provide an amount of nitrogen. Residual protein in soybean dregs comes from proteins that are not fully soluble in water, and conversely, the residual protein in the soybean whey stems from incomplete cross-linking or reactions during the production of soy protein products. More seriously, the removal of certain residual proteins is not achieved by changes in processing methods, such as certain acid-soluble proteins found in soybean whey (Liu et al., 2016). In short, residual protein increases the risk of microbial contamination of by-products.

Contamination by metal ions, on the other hand, occurs mainly in soybean whey, which mainly comes from excessive coagulants added during the processing of tofu. Common tofu coagulants include gypsum (main ingredient: $CaSO_4$), salt brine (main ingredient: $MgCl_2$, etc.), and glucono-δ-lactone (Li et al., 2022), the first two of which cause metal ion contamination. The root cause of metal ion residues is the excessive use of coagulants to ensure the yield of tofu, and the salt ions that are not bound to proteins in this process are present in the soybean whey. Again, this problem cannot be solved at this stage by adjusting the production process.

3 Technical advantages of screw extrusion

Technologies commonly used include single-screw extrusion and twin-screw extrusion. Either technology provides a high-temperature, high-pressure, high-shear process that is just right for solving the problem of utilizing soybean by-products.

3.1 Addressing food risks

As mentioned above, the food safety risks of by-products include microorganisms, residual proteins, and metal ions, which can be avoided in the raw material processing environment provided by screw extrusion technology.

Any type of screw extruder can easily provide a processing environment above 120°C, especially during the production of STP using screw extrusion, where temperatures often exceed 200°C (Lyu et al., 2022a). This environment, coupled with the minutes-long processing time, is such that no microorganisms can survive, at least not at the moment the material leaves the extruder. The risk of microbial contamination is also non-existent.

Residual proteins are no longer considered by-products in the screw extrusion process but as raw materials. The central idea presented in this paper is to use by-products to replace some of the key raw materials in the STP production process, e.g., using soybean dregs to replace a portion of water and soybean meal, meanwhile using soybean whey to completely replace pure water. According to estimates, soybean dregs can replace at least 20% of the total amount of raw materials, and more for soybean whey. Therefore, in this substitution process, the residual protein is involved in the texturization process of the raw protein, which, together with the absence of microbiological risks, does not pose additional food safety risks.

As the by-products undergo the texturization process with the protein, the risk of metal ion residues is not present. Studies have shown that although some coagulants are toxic, they are rendered harmless when they bind or react with proteins (Ali et al., 2021). The violent reaction environment of the screw extrusion process causes the metal ions to fully cross-link with the proteins, and with a high content of proteins and a low content of metal ions, this reaction should be regarded as complete for the metal ions.

3.2 Low equipment and operating costs

In addition to the feasibility of the basic principles, the most limiting factor for the high-value utilization of by-products is the high cost of treatment. As a technology that has long been used in food processing and soybean product processing (Shelar and Gaikwad, 2019), screw extruders are not high-end processing equipment and have very low acquisition and operating costs. Especially single-screw extruders, which are more suitable for processing rough materials, such as soybean dregs (Lyu et al., 2022a), whose running cost is lower than others. This means that manufacturers can upgrade their inherent production lines at a very low cost and realize the utilization of by-products without affecting the production of the original products.

3.3 High value-added end-products

As mentioned previously, screw extrusion technology is mainly used in soybean processing for the production of STP. Compared to SPI, STP is a high-value product in its own right. As long as the by-product can be successfully turned into one of the feedstocks for STP production, its economic value is already very high because there are no more by-product treatment costs. On this basis, the inclusion of by-products will increase the content of dietary fiber, oligosaccharides, and isoflavones in STP, which will result in a significant increase in the value of the end product. This will help to realize the upgrading of ordinary food ingredients into potentially functional foods and get more market attention. The hidden value is very significant.

3.4 Sustainability of the soybean industry and environment

From the perspective of sustainable food processing, the use of screw extrusion technology to treat soybean by-products has longer-term significance.

For the soybean industry, this will be an attempt to utilize soybeans for laddering and whole-seed processing. This will achieve high-value utilization of more than 20% of the dry matter in soybeans, an amount that cannot be ignored in countries and regions where there is a scarcity of high-quality plant-based food resources, which will also further reduce pressure on the planting side regarding increased soybean production.

As far as the environment is concerned, in addition to the basic advantages mentioned above, zero-emission processing technology represented by screw extrusion has long-term significance for soybean processing and even for the food processing industry. Due to emissions and pollution issues, in most countries and regions, food processing companies must be located in suburban areas and cannot produce in urban or densely populated areas, which undoubtedly increases the cost of food production, especially transportation and storage. With the promotion of zero-emission processing technology, the urbanization of food processing will be promoted, which will bring many advantages, such as reduction of production costs, alleviation of labor problems, application of new technology, improvement of consumer acceptance, and so on.

4 Concluding discussion

In summary, the use of soybean processing by-products to replace some of the traditional raw materials in the screw extrusion process is a feasible way to utilize the by-products in a high-value way. However, there may be some constraints on the realization of this process.

4.1 Promotion of screw extrusion in the traditional soybean processing industry

Primary soybean processing is a traditional and stereotypical industry, but screw extrusion technology is currently only used in soy protein producers. Getting traditional primary soy producers to recognize and embrace screw extrusion technology is a long process, especially since the industry is highly fragmented. At the same time, compared to other new processing technologies, screw extrusion technology has a smaller overall investment. However, it is not easy to get producers to voluntarily bear the added costs in the actual production process. In addition to economic costs, there is an increase in hidden inputs to producers, such as labor and policy inputs.

4.2 Imbalance in throughput capacity

While the use of screw extrusion to process by-products has proven theoretically feasible (Wang et al., 2020, 2024), there is an imbalance in raw material and product throughput capacity for soybean processors. On the one hand, there is an imbalance between the amount of by-product output and the processing capacity of the screw extruder. The current capacity of large screw extruders is only a few tons per day (in STP or SPI), but conventional soybean producers produce much more than that as by-products. This means that producers need to introduce several screw extruders to solve the by-product handling problem, which undoubtedly raises production costs. On the other hand, the by-products are only co-materials of the STP production process. To realize the treatment of by-products, producers also need to purchase or produce SPI, gluten (wheat protein), soybean meal, pea protein, etc. as the main raw materials, which are exactly what the traditional soybean processing enterprises do not have. The above process again raises the cost of running it.

4.3 Enrichment and evaluation of functional components

While the addition of soybean dregs and soybean whey to the STP production process certainly enhances the content of functional substances in the product, this process brings up many unresolved scientific questions, for example: reactions of proteins and functional substances in extrusion processes, the change of functional components in the extrusion process, conversion of dietary fiber from insoluble to soluble, conversion of isoflavones from aggregated to free state, evaluation of processing and flavor characteristics of end products, etc. Precise analysis of these issues is the key to scaling up the technology, which in turn provides a potential research direction for researchers.

TABLE 2 The advantages, limitations, and further scopes of screw extrusion technology in soybean by-product processing.

Materials	Advantages	Limitations	Further scopes
Soybean dregs	• Improvement of processing applicability • Improvement of palatability • Reducing the risk of microbial contamination • Full utilization of residual proteins • High added value of end products • Reducing environmental pollution	• Technology promotion in industry • Additional raw material costs to produce the end product • Consumer acceptability	• Production of new soybean tissue proteins • Quality evaluation and promotion of new products • Processing and utilization of other by-products • Enrichment and change pattern of functional components • Research on other terraforming and whole-seed processing technologies
Soybean whey	• Reducing the risk of metal ions • Reducing the risk of microbial contamination • Enrichment of potential functional ingredients • Reducing environmental pollution • Reducing treatment costs	• Technology promotion in industry • Imbalance in throughput capacity • Food safety evaluation	

4.4 The summary of advantages, limitations, and further scopes

The advantages, limitations, and further scopes of screw extrusion technology in soybean by-product processing are summarized in Table 2.

Author contributions

YS: Conceptualization, Data curation, Writing – original draft. XH: Resources, Writing – original draft. YN: Investigation, Resources, Writing – original draft. HY: Funding acquisition, Supervision, Writing – original draft. BL: Funding acquisition, Supervision, Writing – original draft.

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Conflict of interest

The authors declared that they have no conflicts of interest and no commercial or associative interest that could be a conflict of interest with the work submitted.

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