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Techno-Economic Evaluation of Phosphorous Recovery in Soybean Biodiesel Process

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Abstract: The over-enrichment of phosphorus in waste streams can lead to eutrophication and oxygen limitations for aquatic life. To understand the release of phosphorus from a soybean processing facility, it is imperative to track the flow of phosphorus in different streams during the processing of soybeans. The objective of the study is to develop process simulation models to study the flow of phosphorus in the soy-biodiesel process and evaluate strategies to mitigate phosphorus release by recovering phosphorous from soapstock and wastewater. Since most of the P is found in soybean meal, the processing of which releases phosphorus, a third case of lecithin recovery was also studied to reduce the amount of phosphorous in soybean meal. It was observed that phosphorus can be economically recovered from the soapstock, as well as the wastewater stream, with an estimated operating cost of USD 1.65 and 3.62 per kg of phosphorous recovered, respectively. The phosphorus recovered from both streams can be potentially applied as fertilizer to more than 13,000 acres of corn or 96,000 acres of soybean, respectively. The lecithin recovery case was found to have the highest revenue, and it led to a 54% reduction in phosphorous during soybean meal processing.

Keywords: soybean processing; biodiesel; phosphorous recovery; techno-economic analysis; soybean meal; lecithin

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1. Introduction

Biodiesel is a renewable liquid biofuel which is known to offer a performance comparable to conventional diesel and reduce particulate, hydrocarbons, and carbon monoxide emissions in comparison to conventional diesel [1,2]. In the US, vegetable oils are major sources of biodiesel production [3,4]. The distillate fuel consumption in US is many times higher than biodiesel production [5], increasing the demand for alternative biofuel feedstocks. As a result, feedstocks such as oilcane [1,6,7], lipid-rich algae [8], and lipid-rich hemp [9] have been developed to meet these gaps. Novel approaches such as machine learning have been used in the industry to monitor and control biodiesel production processes [10]. Moreover, machine learning has also been used in research for modeling biomass pretreatment [11], the transesterification process [12–14], biodiesel characteristics, and internal combustion engines [10]. The Ukraine–Russia war has adversely impacted food production and supply and diverted grain use towards food production. As a result, there has been a recent interest in providing alternative biofuel sources due to the reduced feedstock availability for biofuel production and increasing fuel demand [15].

More than 50% of biodiesel in the US is produced using soybean oil [3,4]. Due to the high phosphorous (P) content (500 to 600 mg/dry kg) of soybeans [16], the soybean biodiesel process produces several phosphorous-rich streams including soybean hull, soybean meal, lecithin, wastewater, and soapstock waste [1,17]. Soybean meal and soybean hulls are used as an ingredients in animal diets [18]. Due to its high protein content and quality of protein [19], soybean meal can be used in non-ruminant diets (including poultry and swine), whereas the use of soybean hulls is restricted to ruminants. Although most of the soybean meal produced in the world is used for animal food operations, about 2% of soybean meal is used for human food applications [20]. Soybean meal is used as a raw material in production of protein-rich products such as texturized soy protein, soy protein concentrate (SPC), and soy protein isolate (SPI). SPC and SPI have a protein content (on a dry basis) of more than 65 and 90%, respectively, along with a high essential amino content [21]. Thus, their high nutritional value, along with their diverse functionality, make them a valuable ingredient in dairy, bakery, meat, and other food industries [21]. Lecithin contains a high concentration of phospholipids which contributes towards its diverse functionality. Thus, lecithin is used as an emulsifier, stabilizer, release agent, conditioning agent, and antioxidant in food, cosmetics, soap, pharmaceutical, paints, and other industries. Soapstock waste is a coproduct of the transesterification of soybean oil to biodiesel, and it can be used as a raw material in the biochemical industry [22].

The over-enrichment of water bodies with phosphorous can lead to eutrophication and oxygen limitations, resulting in adverse effects on aquatic life [23,24]. Industrial wastes and agricultural run-offs [25] are both responsible for excess phosphorous in water bodies. Thus, wastewater from biorefineries requires treatment for reduction in phosphorous content and biological oxygen demand [17]. More than 70% of the phosphorous in soybeans is present as phytic acid [16], which has less than 25% digestibility in animal diets [26]. Soybean meal has phosphorous contents (~6.7 g/kg) higher than animal diet requirements (~3 g/kg dry basis for ruminants) [18,27,28], with most of the phosphorous present as phytic acid. Phytic acid (or phytate) is also responsible for reduced bioavailability of essential nutrients such as minerals [29,30] and proteins and the inhibition of enzymes responsible for digestion in animals [31]. A high phosphorous content in animal feed and its indigestibility are directly correlated to the over-enrichment of phosphorous in animal manure [32]. With a total carcass production doubling over the span of fifty years (1970 to 2020) [33], manure production has also increased substantially [34]. Although manure can be used as a natural fertilizer in farms, the application of manure with a nutrient content in excess of crop requirements can lead to run-offs in water bodies. Thus, phosphorous management in manure is crucial to reduce phosphorous run-offs in water bodies. Phosphorous reduction in animal diets is the most efficient way to control phosphorous concentrations in manure.

Phosphorous recovery from soybean biodiesel processing would reduce phosphorous concentrations in animal feeds such as soybean meal. Phosphorous recovery from industrial processing would reduce the load on wastewater treatment facilities. Phosphorous (phytate) can be recovered as an alkaline metal salt precipitate using alkaline hydroxide [29,30,35]. Recovered phosphorous coproduct can also replace diammonium phosphate (DAP) as a fertilizer and make additional revenue [29] for the plant. Several studies related to phosphorous recovery from biomass ash and wastewater [29,30,36,37] have been previously performed. The focus of the study was P recovery from grain processing. P recovery of 70.7 and 31.9% of inlet P was observed in corn wet milling and a dry grind ethanol process. In corn processing operations, the costs required to recover P (USD 1.23 to 2.33/kg) were many times lower than the costs associated with treating wastewater [29,30]. To the best of our knowledge, this is the first manuscript evaluating P-recovery potential in a soybean facility. A detailed mass balance is required to determine phosphorous distribution and determine the streams most suitable for recovering phosphorous in a soybean processing plant. A techno-economic analysis would be required to estimate the costs involved in phosphorous coproduct recovery from various streams. Thus, the objective of our study was to (1) determine phosphorous distribution in various streams in a soybean biodiesel plant and (2) assess the technical and economic viability of phosphorous recovery as a coproduct in the process.

2. Materials and Methods

2.1. Process Description

A techno-economic analysis of conventional soybean biodiesel process and processes modified for phosphorous recovery was performed by developing process models using SuperPro designer (Intelligen, Inc., Scotch Plains, NJ, USA). In all the designs, the soybeans consisted of 4.56, 27.44, 18, 0.36, 36.64, and 13.00% *w/w* ash, carbohydrates, lipid, phosphorous, protein, and water, respectively [1]. The soybean processing capacity for all models was assumed as 1995.8 MT/d and the annual plant operating period was assumed as 330 d [1]. The phosphorous contents of various soybean processing streams were calculated using phosphorous concentrations in soybean meal, lecithin, soapstock waste, and soyhulls obtained from a commercial soybean facility. The phosphorous concentrations in these products were analyzed in a commercial analytical laboratory using ICP. In addition to the above-mentioned products, phosphorous concentrations were also measured for soy protein concentrate and soy protein isolate. The study was carried out in the US, and the statistics have been retrieved from the US Department of Agriculture (USDA) and Energy Information Agency (EIA) [3,4,38] for the time frame of the 2015/16 to 2019/20 marketing years.

2.1.1. Conventional Soybean Biodiesel Process

The process designs for the conventional soybean biodiesel process (CSB) were developed using previous studies [1,17]. The soybean biodiesel process consisted of four major sections: soybean receiving and preprocessing, oil extraction and refining, biodiesel production, and coproduct recovery. A schematic of the conventional biodiesel process, along with P flow and concentrations, is presented in Figure 1.

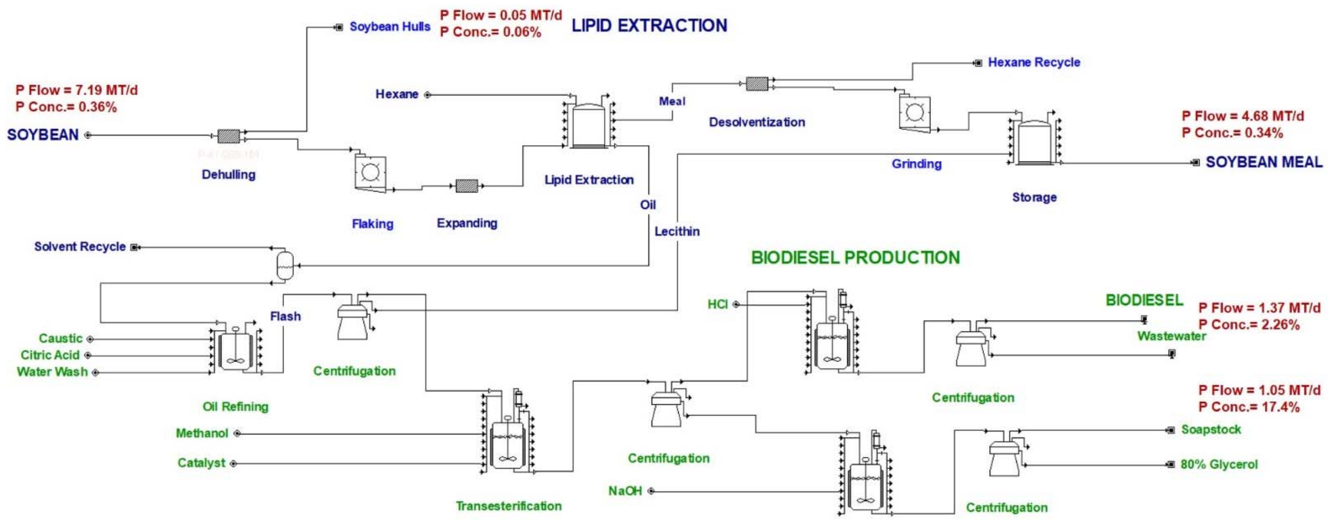

Figure 1. Schematic representation and P flows in the conventional soybean biodiesel (CSB) process.

In the receiving and preprocessing section, soybeans were received, cleaned (0.3% soybean impurities), and dehulled prior to oil recovery. Soybean hulls (7% of a soybean) were sold as a coproduct. The dehulled soybeans were conditioned, flaked, and expanded to improve efficiency of the oil extraction process.

Oil extraction was performed using hexane as a solvent, with 98% oil extraction efficiency [1]. The hexane in the oil and post-extraction flakes was evaporated and reused in the oil extraction process. The post-extraction flakes were dried and ground to produce soybean meal. The recovered soybean oil was refined through degumming using citric acid, a caustic soda treatment, a hot water wash, and subsequent separation using a disk-stack centrifuge. The refined oil and crude lecithin were the two streams produced after the refining process. The refined oil was processed for biodiesel production and the lecithin was mixed with soybean meal. In the biodiesel production section, the transesterification of lipids was performed using methanol as a reactant and sodium methoxide as a catalyst (60 °C, 1 h residence time, and 90% efficiency) to produce biodiesel from the lipids. The resulting stream was then centrifuged to produce biodiesel and glycerol-rich streams. Transesterification of the residual biodiesel stream was performed to achieve an overall 99% lipid conversion efficiency. The unreacted methanol was recycled in the process using vacuum evaporation and subsequent condensation.

The biodiesel-rich stream was further mixed with hydrochloric acid to neutralize sodium methoxide, washed with water, and centrifuged to recover the refined biodiesel and wastewater streams. The refined biodiesel was sold as the main product, and the resulting wastewater was sent to a wastewater treatment facility. The glycerol-rich stream was neutralized similar to the biodiesel-rich stream, centrifuged to remove soapstock waste, neutralized to reduce the residual acid content, and sold as a glycerol coproduct (80% purity).

2.1.2. Soybean Biodiesel Processes Modified for Phosphorous Recovery

Phosphorous recovery was performed using soapstock waste (PRSS) and wastewater (PRWW) from biodiesel processing as feedstock in separate cases (Figures 2 and 3). The process design and separation parameters for the phosphorous recovery section were similar to that of Juneja, Cusick, and Singh [29]. Briefly, sodium hydroxide was added to the feedstock to raise the stream pH and calcium chloride was added to maintain a Ca:P ratio of 1:1, and it was mixed for 5 min and centrifuged to separate phosphorous precipitate [29]. The phosphorous precipitate consisted of 90% phosphorous in the feedstock, and it was sold as a natural fertilizer.

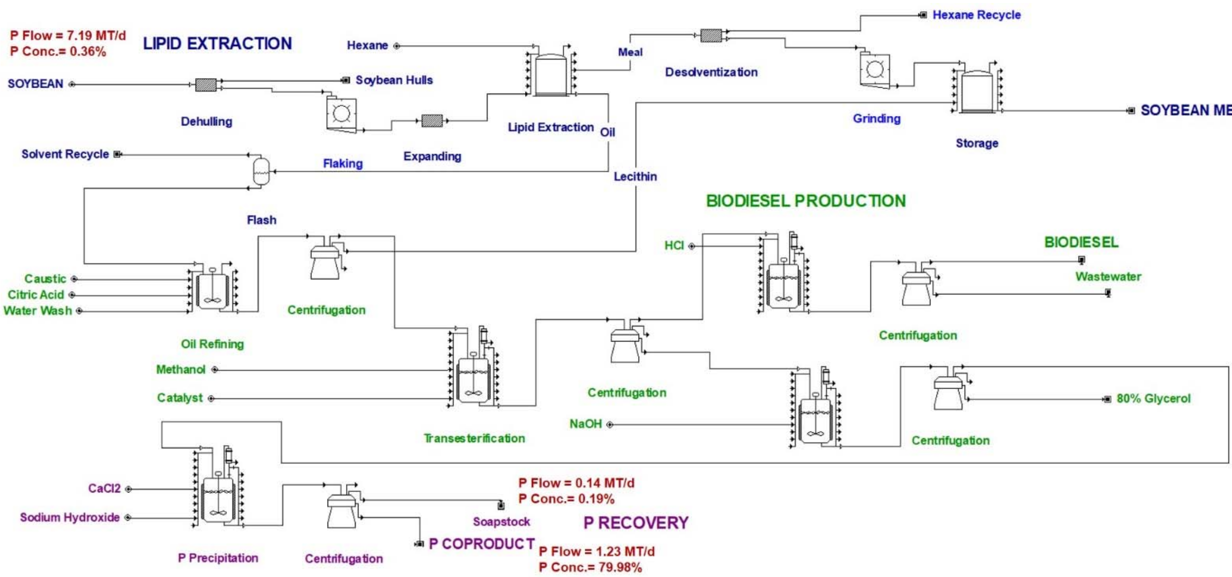

Figure 2. Schematic representation and P flows in the soybean biodiesel process with P recovery from soapstock (PRSS).

In some plants, lecithin is mixed with soybean meal. Lecithin has a high phosphorous content and contributes to the phosphorous content in soybean meal. In the lecithin stream, phosphorous is present as both a phospholipid and phytate, which does not allow for phosphorous recovery using the previously mentioned technology. The recovery of phospholipids from lecithin in a commercial soybean biodiesel process is cost intensive. Thus, selling lecithin as a coproduct would be an economical option. A process design was developed (SBL) where the lecithin and soybean meal streams were not combined (Figure 4). In this design (SBL), lecithin was flash-evaporated to remove the residual hexane and sold as a coproduct [39]. The lecithin coproduct would not be used as a fertilizer, but rather as an ingredient in the food and bioprocessing industries.

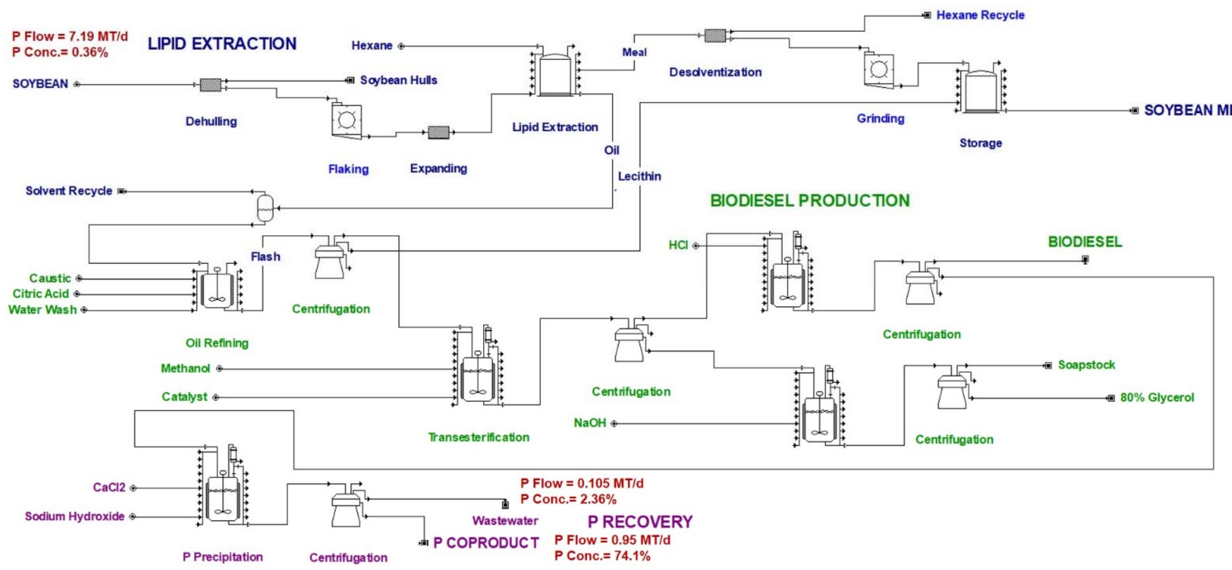

Figure 3. Schematic representation and P flows in the soybean biodiesel process with P recovery from wastewater (PRWW).

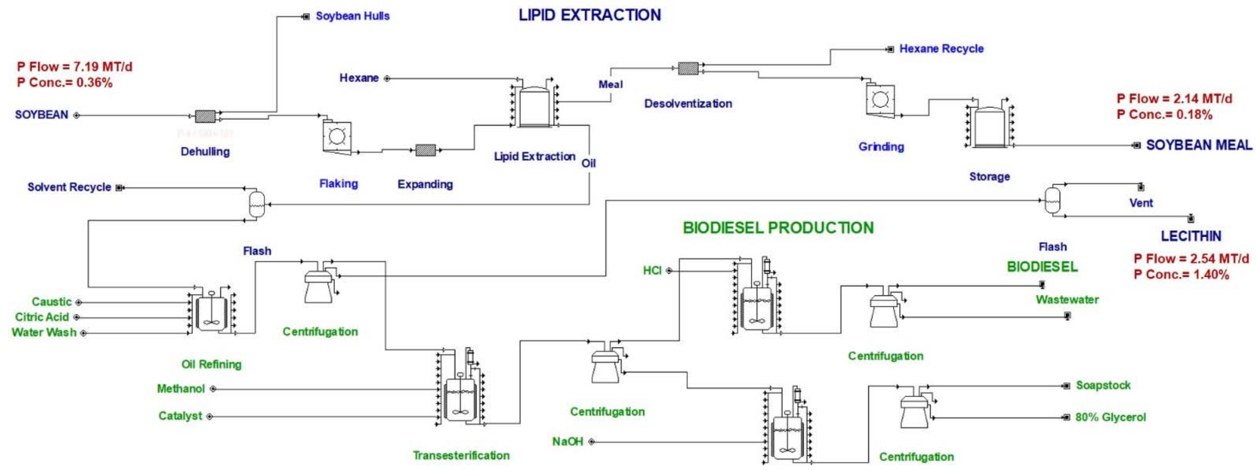

Figure 4. Schematic representation and P flows in the soybean biodiesel (SBL) process with a lecithin coproduct.

2.2. Economic Analysis

The specific equipment costs for the conventional and modified processes were derived from previous studies [1,17,29,30]. An exponential scaling model and equipment cost index were used to estimate the equipment purchase costs in the process models [40–45]. The direct fixed capital cost (DFC) consisted of the costs required for the process operations including equipment purchases, installation, piping, and instrumentation, and the costs of components not directly related to the process such as land, buildings, warehouses, and disposal [41]. The DFC was estimated by multiplying the total equipment cost with a Lang factor of 3.0. The total capital investment consisted of the direct fixed capital cost and start-up costs (5% of DFC).

The costs associated with day-to-day expenses including raw materials, utilities, labor, and facility-dependent costs are known as operating costs. The purchase costs of soybeans, methanol, sodium methoxide, sodium hydroxide, hexane, hydrochloric acid, and citric acid were USD 330/MT (average price for the 2015/16 to 2019/20 marketing years [3]), USD 0.547/kg, USD 2.93/kg, USD 0.41/kg, USD 0.9/kg, USD 0.205/kg [1], and USD 1.07/kg [46], respectively. The purchase cost of steam, electricity, chilled water, and cooling water were USD 12/MT, USD 0.1/kWh, USD 0.4/MT and USD 0.05/MT, respectively [46].

Miscellaneous operating costs such as labor-dependent costs, facility-dependent costs, and costs associated with laboratory/QC/QA were estimated using the modeling software [46]. The selling prices of biodiesel, soybean meal, soybean hulls, glycerol, and lecithin were USD 4.315/gal, USD 350.5 (average price for the 2015/16 to 2019/20 marketing years [3]), 180, 346.9, and 1635.5/MT, respectively [1,39]. As the recovered phosphorous coproduct has the potential to replace diammonium phosphate (DAP) as a fertilizer, it was assigned the selling price of USD 386.7/MT [29,30]. The biodiesel production cost (USD/gal) was determined as the ratio of the difference between operating cost and coproduct credits to the amount of biodiesel recovered. The operating costs for P recovery were determined as the ratio of the difference between the operating costs of the test and base cases to the amount of P recovered.

3. Results and Discussion

3.1. Phosphorus Flow

The flow of phosphorus in the streams was decided based on the ICP analysis of various products obtained from a soybean processing facility. The amount of phosphorus in soybeans is 0.36% (ICP analysis), and based on a soybean processing facility with a grind rate of 1995.8 MT/d, the inflow of P is 7.19 MT/d. Although most of the P from soybeans ends up in soybean meal, some part is also transferred to soapstock from glycerol recovery and to wastewater from biodiesel washing. The flow of P in a conventional soybean processing plant is shown in Figures 1–4. The values shown in the figures are the mass percentage of phosphorus and total mass flow per day in a stream with soybean processing of 1995.8 MT/d. The lecithin produced after oil refining contained 1.40% P, contributing to 2.54 MT/d P, which, in the conventional process, is mixed with soybean meal, leading to a final concentration of 0.34% P in the meal. The rest of the P flows to the transesterification process to produce biodiesel and glycerol. The wastewater produced during the washing of biodiesel contained 2.27% P, contributing 1.38 MT of P per day to the wastewater treatment plants. Soapstock, on the other hand, is produced during recovery of the 80% glycerol, and it contains 20.9% P. Since the soapstock and wastewater both had high concentrations of P, with no use downstream, it is beneficial to recover P from these streams to ease the wastewater treatment load and generate profits by selling the P coproduct.

In the case of P recovery from soapstock (Figure 2), the front end operations remain the same, but a phosphorus recovery unit, similar to our previous work [29], was applied to the soapstock stream. With two previous studies showing a recovery of 90% of the phosphorus as phytate [29,30], the simulation estimated a recovery of 0.95 MT/d, and the concentration of P in soapstock was reduced from 20.9% to 2.30%. Similarly, when the phosphorus recovery unit was applied to the wastewater (Figure 3), the concentration of P was reduced from 2.27% to 0.19%, with a recovery of 1.23 MT/d P as a coproduct. Since the maximum amount of P is present in lecithin, which is mixed with soybean meal in a conventional process, the maximum amount of P is available in soybean meal. As discussed before, some phosphorus in lecithin is present in the form of phospholipids, in addition to being bound to phytate, and, therefore, it cannot be recovered using the P recovery methods stated above. However, if lecithin is recovered as a coproduct, the amount of P in the soybean meal can be reduced from 0.34% to 0.18% (a reduction of more than 50%) (Figure 4), reducing the amount of P bound to indigestible phytate. In addition to being unavailable to monogastric animals, P bound to phytate also limits the availability of other minerals [47].

3.2. Process Economics

In the conventional process, the processing of soybeans leads to the production of biodiesel as the main product and soybean hulls, soybean meal, and 80% glycerol as co-products. For the PRSS and PRWW cases, phosphorus is produced as an additional coproduct, and for the SBL case, lecithin is an additional coproduct. Table 1 provides the amount of main product and coproducts produced in all four cases, with a grind rate of 1995.8 MT/d soybean. The amount of main product (biodiesel), soybean hull, and glycerol in all four cases remained unchanged; however, the removal of lecithin in SBL led to a reduction of soybean meal by 13%. The phosphorus in PRSS and PRWW was recovered from under-utilized streams and, therefore, had no impact on the production of conventional products, and instead provided an additional coproduct for increased revenue. The processing of 1995.8 MT/d soybean corresponds to an annual processing of 658616 MT of soybean.

Table 1. Main product and coproduct production in the four cases of soybean processing.

Coproducts	CSB	PRSS	PRWW	SBL
Biodiesel (million gal/yr)	34.54	34.54	34.54	34.54
Soybean hulls (MT/yr)	25,081	25,081	25,081	25,081
Soybean meal (MT/yr)	459,451	459,451	459,451	399,571
80% Glycerol (MT/yr)	29,354	29,354	29,354	29,354
P coproduct (MT/yr)	-	424	510	-
Crude lecithin (MT/yr)	-	-	-	59,880

3.2.1. Base Case (CSB)

The total capital cost of a soybean processing plant was estimated at USD 90.56 million, with a total biodiesel production capacity of 34.5 million gallons annually. The operating costs, including facility-dependent costs and the cost of raw material, labor, utilities, and waste disposal of the plant, were USD 268 million/yr, of which the costs of raw materials contributed about 83.9%. Soybean is the major input in soybean processing, contributing to more than 96% of the total raw material costs, followed by methanol (2.93%) and sodium hydroxide (0.54%). Utilities contributed to 1.64% of the total operating cost per year, whereas facility-dependent costs and labor costs added 6.78% and 6.7% to the operating costs, respectively. The revenue generated from biodiesel production was calculated as USD 149 million/yr. Including the coproducts (soybean hull, meal, and glycerol), the total revenue generated from the process was estimated as USD 324.8 million/yr. The overview of the process economics for the four cases is presented in Table 2.

Table 2. Process economics for the four cases of soybean processing.

Process	CSB	PRSS	PRWW	SBL	Reference
Capital Cost (×USD 1000)	90,561	91,285	91,452	90,668	[1]
Operating Cost (×USD 1000/yr)	268,166	268,865	270,017	268,484	
Raw materials	224,923	225,023	226,122	224,923	[1,3]
Labor-dependent	18,151	18,541	18,541	18,541	[46]
Facility-dependent	17,968	18,112	18,145	17,912	[46]
Laboratory/QC/QA	2723	2781	2781	2781	[46]
Utilities	4401	4407	4427	4327	[46]
Revenue (×USD 1000/yr)	324,765	324,932	324,966	401,710	
Soybean hulls	4515	4515	4515	4515	[1]
Soybean meal	161,038	161,038	161,038	140,050	[48]
Biodiesel	149,032	149,032	149,032	149,032	[1]
80% Glycerol	10,180	10,182	10,182	10,180	[1]
P coproduct	-	165	199	-	[29,30]
Crude lecithin	-	-	-	97,933	[39]
Biodiesel Production Cost (×USD/gal)	2.68	2.69	2.72	0.46	

3.2.2. P Recovery Case (PRSS and PRWW)

With the addition of the P recovery unit on the soapstock and wastewater streams, the capital cost increased by 0.8% to USD 91.29 million, and 0.98% to USD 91.45 million, respectively. The operating costs for both cases increased by 0.26% and 0.69% to USD 268.9 and 270 million/yr, respectively. Although biodiesel revenues stayed the same as the CSB in the P recovery cases (the same amount of biodiesel produced in both cases), the coproduct revenues increased in both the PRSS and PRWW cases. The total revenue generated for the PRSS case was USD 324.9 million/yr, which was USD 0.17 million higher than the CSB case, whereas the PRWW case generated a total revenue of USD 325.0 million/yr, which was USD 0.20 million higher than the SCB case. Since the phosphorus was not received from any coproduct, the coproduct revenues (excluding phosphorus) remained unchanged. Additional revenues of USD 165,371 and USD 198,603 could be generated annually with phosphorus as a coproduct from the PRSS and PRWW cases, respectively. The process economics related to phosphorus recovery are tabulated separately in Table 3.

Table 3. Changes in process economics with the addition of the P recovery unit.

Process	PRSS	PRWW
Capital cost (USD)	724,000	891,000
Operating cost (USD/yr)	699,000	1,851,000
Raw materials	100,000	1,199,000
Utilities	6000	26,000
Revenue (USD/yr)	165,371	198,603
Reduction of P in mainstream product (MT/d)	0.95	1.24

3.2.3. Lecithin Recovery Case (SBL)

Recovering lecithin from a conventional soybean processing plant is the most profitable process estimated. The capital cost for SBL was USD 90.28 million, which was USD 107,000 higher than the CSB case, which can be attributed to the equipment for the flash recovery of lecithin. The operating cost for SBL was USD 268.5 million/yr, which was USD 318,000 higher than the CSB. The total revenue generated in the SBL case was USD 401.71 million/yr, which was 23.7% higher than the CSB case. The biodiesel revenue remained unchanged; however, the coproduct revenue from the soybean meal was reduced by 13%, since, in the conventional process, lecithin was added back to the soybean, increasing its production. The additional revenue generated from the lecithin sold as a coproduct was USD 97.93 million/yr.

3.3. Phosphorous Recovered

The total amount of P recovered as Ca phytate from the PRSS and PRWW cases with soybean processing of 1995.8 MT soybean/d was estimated to be 1285 kg/d and 1546 kg/d, respectively, corresponding to an annual production of 0.43 MT and 0.51 MT of fertilizer substitute each year. Based on the applicability of recovered phosphorus on agricultural lands, the phosphorus recovered from the PRSS case could be applied as a fertilizer on more than 13,000 acres of corn (considering a yield of 200 bushel/acre and an applicability of 0.34 lb P/bushel corn) or 93,000 acres of soybean (considering a yield of 50 bushels/acre and an applicability of 0.20 lb P/bushel soybean) per year. With the same assumptions, the P recovered from the PRWW case could be applied to more than 16,000 acres of corn or 112,000 acres of soybean annually. The operating cost for P recovery from wastewater in the PRWW case was estimated as USD 3.62/kg of P removed, which is many times lower than the actual price incurred by wastewater treatment plants for P removal [49]. The P recovery has a two-fold advantage of (1) increasing the coproduct revenue for the processing facility, and (2) reducing the load of phosphorus recovery on the wastewater treatment plants (in this case).

3.4. Implications and Challenges of P Recovery in Soybean Biodiesel Process

A 17.1 and 13.2% of P in soybeans was recovered in the PRSS and PRWW cases, respectively. In previous studies a high proportion of inlet P was recovered in corn processing operations using similar technology, with 31.9 and 70.7% recovery rates of inlet P in corn dry grind and corn wet milling processes, respectively [29,30]. A high proportion (65.1% of soybean P) of P present in the soybean meal reduces P concentrations in the downstream process, resulting and low P recovery. Low P recovery also resulted in higher operating costs (USD 3.62/kg P) of P recovery in comparison to the corn dry grind (USD 2.33/kg P) and wet milling (USD 1.23/kg P) processes [29,30].

Biodiesel production costs in the PRSS (USD 2.69/gal) and PRWW (USD 2.72/gal) cases were higher than in the CSB case (USD 2.68/gal), indicating a low profitability of the P recovery processes. Thus, incentivizing P recovery in soybean biodiesel plants would encourage processors to adopt the technology. A reduction in the costs associated wastewater treatment plant operation would be another benefit of recovering P coproduct. The biodiesel process with lecithin recovery had the lowest biodiesel production cost among all the cases due to the high revenue from the lecithin stream (Table 2). Thus, lecithin recovery would reduce P content in soybean meal and improve the economic performance of the process. The selling prices for gasoline and biodiesel are USD 2.51 and 4.315/gal, respectively, suggesting that the production cost of gasoline would be lower than that of biodiesel [3,50].

3.5. Phosphorous Release in Soybean Meal Processing Operations

As discussed in the mass balance section, most of the phosphorous in soybeans is present in soybean meal in a soybean biodiesel process. Soybean meal is processed to produce high protein products such as SPC and SPI for human food applications. Our objective in this section was to estimate the net phosphorous loss in these processes. SPC and SPI yields of between 60 to 70% and 30 to 40% of soybean meal weight, respectively, are typically observed in these facilities [20]. The P concentrations measured in SBM, SPC, and SPI were 5660 $\pm$ 104, 6603 $\pm$ 172, and 6776 $\pm$ 172 mg/kg, respectively. Considering a minimum yield of 60 and 30% for SPC and SPI, respectively, it was observed that up to 40.0 and 64.1% of phosphorous in soybean meal is potentially lost in these operations. Due to the increasing demand for plant-based substitutes for meat products, the production of protein-rich products such as SPC and SPI may potentially increase in the future [51–55]. This increase would also potentially increase the release of phosphorous through soybean meal processing facilities. Thus, a detailed study of phosphorous distribution and phosphorous recovery production would be integral in mitigating the phosphorous releases from these facilities.

4. Conclusions and Prospects

The phosphorus released in the waste streams from a soybean processing facility is a contributor to the increased nutrient concentration in wastewater inflows. The excess P is released from the wastewater produced after washing biodiesel, as well after the production of SPI and SPC from soybean meal. To mitigate the phosphorus release, it is essential to understand the flow of phosphorus in a soybean processing facility. Most of the phosphorus from soybeans is transferred to soybean meal, which cannot be recovered using the conventional P recovery unit. With an additional operating cost of USD 0.7 and 1.81 million/yr, 424,000 kg and 510,013 kg of phosphorus can be recovered annually with the PRSS and PRWW cases, respectively. Along with increasing the revenues from recovering P as a coproduct, the process also reduces the load of P removal on wastewater treatment facilities. It was calculated that the phosphorus recovered from both cases could be applied to more than 13,000 acres of corn or more than 93,000 acres of soybean. A future research prospect is needed to evaluate the P recovery processes using advanced sustainability tools such as life cycle assessment and exergy, combined with techno-economic analysis, i.e., exergoenvironmental and exergoeconomic analyses, respectively [56,57].

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