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A Simplified Techno-Economic Analysis for Sophorolipid Production in a Solid-State Fermentation Process

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Abstract: Sophorolipids (SLs) are microbial biosurfactants with an important role in industry and a continuously growing market. This research addresses the use of sustainable resources as feedstock for bioproducts. Winterization oil cake (WOC) and molasses are suitable substrates for SLs via solid-state fermentation (SSF). The model proposed herein was established for annually processing 750 t of WOC and comparing three support materials: wheat straw (WS), rice husk (RH), and coconut fiber (CF). Production capacity ranged 325–414 t of SLs per year. Unit Production Cost was 5.1, 5.7, and 6.9 USD/kg SL for WS, RH, and CF production models, respectively, and was slightly lower with other substrates. Financial parameters were CAPEX 6.7 MM USD and OPEX 1.9 MM USD/y, with a NPV, IRR and payback time of 6.4 MM USD, 31% and 3.2 y, respectively. SLs recovery from the solid matrix was the major contributor to operating costs, while fermentation equipment shaped capital costs. Results show that the physical properties (bulk density, WHC) of substrates and supports define process costs beyond substrate purchase costs and process yields in SSF systems. To our knowledge, this is the first attempt to model SLs production via SSF at full scale for the economic valuation of the SSF process.

Keywords: solid-state fermentation; sophorolipids; waste; biosurfactant; techno-economic analysis

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1. Introduction

New global trends point to the use of sustainable products and increasing circularity in production processes. In this way, circular economy and bioeconomy are being promoted by most governments. These two strategies overlap in a circular bioeconomy strategy when a product is bio-based and produced from organic waste or side streams [1]. Surfactants, usually organic compounds, amphiphilic and with properties to reduce the surface tension between two phases, are extensively used in household products and industrial applications. Surfactants are generally petrol-based and produced through synthetic chemical processes; they have a low biodegradability [2], and some of them, or their degradation products, are toxic [3]. The surfactants market size is projected to reach USD 52.4 billion by 2025, up from USD 42.1 billion in 2020, at a compound annual growth rate (CAGR) of 4.5% [4]. This makes surfactants a target product for circular bioeconomy practices; however, economic feasibility must be proved. Biological origin surfactants are known as biosurfactants (BS). The global BS market was estimated at USD 4.20 billion in 2017 and is projected to reach USD 5.52 billion by 2022, at a CAGR of 5.6% from 2017 to 2022 [5]. The BS market is boosted by the growing awareness that they are biodegradable compounds and, as such, are environmentally friendly and non-toxic, with antimicrobial and antifungal properties, among others [6].

BS also are amphiphilic molecules, but in this case, the hydrophilic head corresponds to a sugar, an ester, a hydroxyl, a phosphate, or a carboxylate group. The hydrophobic tail is constituted by proteins, peptides, or fatty acids of 10 to 18 carbons [7]. BS can be of low molecular weight (glycolipids, phospholipids, and lipopeptides) with high superficial tension reduction power; or high molecular weight (proteins, lipoproteins, polysaccharides, or lipopolysaccharides) with higher emulsifying properties [7], reporting similar emulsification properties to the non-ionic commercial surfactant Triton X-100 [8]. Sophorolipids (SLs), glycolipids produced by non-pathogenic yeast [9], are one of the most studied due to their characteristics and applications. These compounds have presented promising results for use as food emulsifiers [10], germicides [11], anticancer agents [12], in several environmental applications [13,14], as antimicrobial agents to formulate oral hygiene products [15] and cosmetics or pharmaceutics [11], as cleaning products [16], and in food formulation [17].

Specifically, the global SL market was valued at USD 375 million in 2019 and is projected to reach USD 547 million by 2027; it is expected to grow at a CAGR of 5.0% from 2020 to 2027 [18]. From this information, it can be assumed that the SL market only accounts for nearly 8.0% of the BS global market and is growing at a similar rate. The global BS production was estimated at 477 kilotons by 2018 [19], a higher value than the 462-kilotons by 2020 reported elsewhere [20]. In this report, household detergents and personal care applications were the larger application segments, with 154 and 51 kilotons, respectively. Europe was the largest regional market with a consumption of 179 kilotons.

Even though de novo sophorolipid synthesis is possible using the yeast *Starmerella bombicola*, SL production is performed by the addition to the fermentation process of a hydrophilic and a hydrophobic carbon source. Generally, SLs are produced by submerged fermentation (SmF), using the yeast *Starmerella bombicola* and pure substrates such as glucose [21], combining glucose with oleic acid [22], or using several different organic waste streams as carbon sources [13].

The cost of substrates dictates the minimum production costs. In addition, when first-generation substrates are used, the related environmental impacts greatly affect sustainability, so research is focused on using second to fourth-generation feedstock [23]. Recently, Solid-State Fermentation (SSF) has been noticed as a technology suitable for a circular bioeconomy, as the use of solid substrates allows the valorization of organic solid wastes and by-products [24], which are inexpensive solid substrates, such as oil cakes from an edible oil refinery [9] or mango kernel [25]. SSF is characterized as a process in which microorganisms grow in the near absence of free water, demanding less energy for sterilization; it is also less susceptible to microbial contamination and to substrate inhibition, and ultimately allows higher productivity for many enzymes [26], with the subsequently reduced operational costs, which arise mainly from mixing and heating. However, drawbacks related to instrumentation and control, poor homogeneity, and energy and mass transfer affect the process yield, and a more complex downstream process compared with SmF should be considered [27]. Moreover, the solids derived from SSF might be used as a soil amendment or for soil bioremediation [28].

Recently, we have demonstrated the feasibility of producing SLs from oil cake and molasses from the food industry by SSF at a representative scale [29]. Also, the system can admit different lignocellulosic materials as supports [30]. This is a significant advantage due to the low cost of the lignocellulosic materials, such as current agricultural residues, and provides a revalorization option. The surface and structure of the support materials are key parameters to favor the immobilization of microorganisms. On the one hand, the roughness of the surface facilitates the fixation of microorganisms on the support. On the other hand, the porosity increases contact surface, thus increasing the potential surface available for immobilization. Porosity is usually greater in inert and synthetic materials (e.g., polyurethane foam) than in biomass supports, their pore size being of a higher diameter; however these materials generally present smoother surfaces. Agricultural residues have the structure and roughness that favor the fixation of microorganisms into supports that, in combination with optimal conditions, will allow higher production yields compared with synthetic supports. Indeed, Kilonzo et al. [31] studied the immobilization of different strains of *Saccharomyces cerevisiae*, reporting that cotton showed the highest efficiency of cell absorption compared with synthetic materials (polyurethane foam, nylon, polyester). Similarly, Rodríguez et al. [30] obtained higher SLs production using lignocellulosic materials than with polyurethane foam. Because the availability of lignocellulosic materials is seasonal and depends on the geographical location, SLs production using different support materials has been assessed [30].

Several published studies analyze the cost of producing SLs under SmF. According to Van Bogaert et al. [32], production price strongly depends on the substrates used and the production scale, ranging between 2 and 5 USD/kg. Ashby et al. [33] simulated a high production volume (90.7 million kg production process) with a yield of 100 g/L using *S. bombicola*, with glucose and sunflower oil as substrates, achieving a production cost of 2.95 USD/kg. More recently, Wang et al. [34] have reported a techno-economic study for the production of SL in crystal and syrup presentation forms, from hydrolyzed food waste and comparing different sources of equipment costs, with the production cost ranging from 19.65 USD/kg to 16.45 USD/kg. The cost can be reduced to 10 USD/kg with an integrated bioprocess design [23]. However, no techno-economic studies have been reported to produce SLs through SSF.

Downstream processing for SL production at a commercial scale is based on SmF. Here, easy recovery of biosurfactants can be achieved by centrifugation and spray drying, thus removing the majority of the water and the remaining cells from the product [33]. Van Bogaert et al. [32] indicate that SL can be separated from the fermentation media by centrifugation or decantation, with further elimination of water and impurities by the addition of polyhydric alcohols followed by distillation. Also, different strategies have been suggested for integrated bioprocessing [35]. As has been pointed out above, SSF opens the production of SL to the use of organic solid wastes and by-products as substrates. However, in this case, downstream processing for SL is rather different, mainly due to the fermentation matrix (a solid).

Different methodologies can be used to optimize production at lab/pilot scale, such as experimental design [36], neural networks [37], and recently, machine learning [38]. Also, for SmF, several reports on the modeling of the economics of full-scale production and related environmental impact [39] are available. However, there are no reports dealing with the modeling of full-scale processing via SSF nor the environmental impact of the process. Therefore, modeling the industrial process is essential to study and estimate the costs and the environmental impacts of SL production through SSF on a small scale. In this way, it is possible to establish whether this process for SL production is an economical alternative to substitute the chemically synthesized surfactants by biosurfactants based on a circular bioeconomy strategy and whether its cost is competitive with SL produced by SmF.

The aim of this work is to perform techno-economic analysis of a small scale sophorolipid production plant through the valorization of by-products from the food industry (winterization oil cake, molasses) via solid-state fermentation, comparing three supporting biomaterials (wheat straw, rice husk, coconut fiber) and based on our previous research [30]. Plant size was set to process 750 t WOC/y. The production capacity was designed to be implemented related to the production of an existing edible oil processing facility intended to valorize its winterization oil cake waste. Obtained results were compared to the use of raw materials as substrates (soybean oil, oleic acid, and glucose) and to the use of other by-products (sunflower oil cake, frying oil, and mango-kernel fat). Techno-economic analysis also includes the comparison between a brand-new facility and implementing the process in an existing edible oil refinery (when WOC is used as substrate and in both cases with the same SSF process configuration), and the use of SmF instead of SSF

2. Materials and Methods

2.1. Base Scenario

The base scenario was based on previous work performed at different scales, with reactor volumes of 500 mL [9], and 22 and 100 L [29]. These studies demonstrated the feasibility of the production of SL through SSF at bench and pilot-scale, using winterization oil cake (WOC) and molasses (MOL) as substrates, wheat straw (WS) as the support material to provide porosity and resistance to compaction, and *S. bombicola* ATCC 22214 (American Type Culture Collection, Manassas, VA, USA) as the SL-producing yeast. Under these conditions, the productivity is 0.026 g SL/g dry matter d, and the obtained production yield is 0.72 g SL/g fat (corresponding to 0.26 g SL/g WOC). Based on the results obtained for 100 L reactors, we considered a scale-up factor and assumed to achieve 85% of the SL yield obtained in our previous works, as a conservative value in the simulation [29].

In this base model, SLs are extracted with ethyl acetate, the organic extract is filtrated, and the solvent is later recovered by evaporation. The crude extract is finally dried in a drum dryer. SL extract, the main product, was considered a combination of 80% SL and 20% impurities, as a conservative value, and took into account that a lower impurity content would require further downstream processing. Depending on the final application, this crude SL extract can be further processed to obtain purer SL forms, such as crystals.

The base scenario considers that the new SL production plant is dedicated to process WOC produced by a single oil refinery, according to data from local refineries in Spain. This capacity can be increased up to 5× times by including other WOC generating industries near the original facility location. Transportation distances should be considered due to the characteristics of the supporting material as organic biomass. However, they are not included in this preliminary model. In Table 1, raw material composition and the corresponding annual flows are presented.

Table 1. Raw material composition and annual flows used in the base model.

Material	% *w*/*w*	t/y
Winterization Oil Cake		750
Carbohydrates	0%	–
Fats	67.5%	506
Perlite	32.5%	244
Molasses		188
Carbohydrates	65%	122
Fats	0%	–
Others [1]	35%	66

[1] Insoluble carbohydrates, proteins, and ash.

2.2. SL Production Process

The SL production process was based on processing 750 t/y WOC at a ratio of WOC:MOL 4:1 (on a mass basis). Plant scale was selected based on WOC production in several facilities in Spain. The process includes five stages: (1) material sterilization, (2) fermentation, (3) SL extraction, (4) SL recovery, and (5) waste treatment. The flow diagram for SL production is presented in Figure 1. Inoculum preparation is not included in the diagram but is considered in the cost analyses.

2.2.1. Material Sterilization

Material sterilization was set on batch mode lasting one day. In the model, WOC (S-103), MOL (S-104), and WS (S-105) are stored in separate bins before being sterilized. To avoid contamination due to fungal spores potentially present in agro-industrial lignocellulosic wastes, the supporting material is sterilized twice before being mixed and sterilized a third time with the rest of the materials. Batch time comprises three sterilization cycles, each one including 45 min of heating at 121 °C giving a sterilization period of 17 h in total considering the loading and unloading of the mixture. Two sterilization lines and 1-cycle per day are proposed with 75% of usage for each piece of equipment.

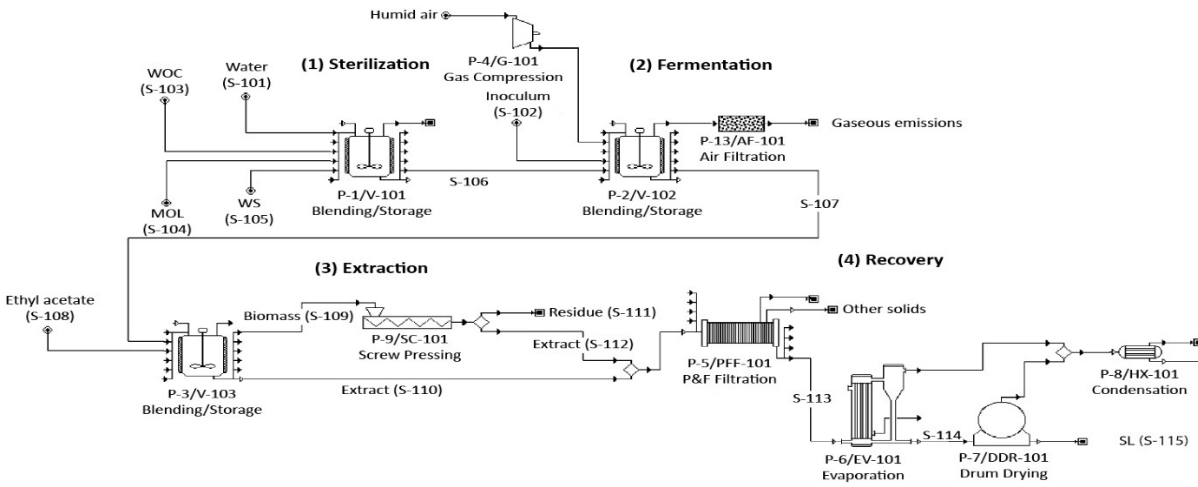

Figure 1. Flow diagram for SL production from WOC by solid-state fermentation and by organic solvent recovery. Nomenclature: WOC: winterization oil cake, MOL: molasses, WS: wheat straw, EA: Ethyl acetate, SL: sophorolipids.

2.2.2. Fermentation

SSF was set on batch mode lasting five days (time for maximum productivity). With an operational availability of 330 d/y (7920 h/y), two lines comprising five fermenters each (5 m^3) for treating 750 t/y of WOC were considered based on a setup time of 1 day between batches for loading and unloading the fermented biomass and cleaning the equipment. This gave 55 fermentation batches per year. The bioreactor system was set in the design by adapting the parameters indicated in [30] using a diameter/height ratio of 0.6 in SS304 and working at 75% of the total capacity for gas transfer and agitation procedures. After the sterilized material (S-106) was transferred to the fermentation tank, *S. bombicola* was added as the inoculum (S-102) at a ratio of 1:9 (w/w). Fermentation conditions were set at 30 °C, 27 kg/h of continuous supply of humidified air (45% HR), and with intermittent agitation (every two days, [9]).

2.2.3. SL Extraction

The extraction stage was designed in a semicontinuous mode. Three operation lines were considered for extraction and further recuperation due to processing volume, operational flexibility, and/or equipment capacity.

The model comprises a set of extractors coupled to screw and press filters working on a staggered mode in three shifts per day. In this stage, fermented biomass (S-107) is transferred to the extraction units after each fermentation batch is completed. SLs are recovered in ethyl acetate fed continuously to the process (S-108) by direct application and washing of the fermented biomass. Fermented biomass is extracted using ethyl acetate in a liquid-to-solid ratio of 5:1 (v/w) in a single-extraction process lasting 15 min at room temperature. After extraction, a decanting phase is used for gravity separation of the maximum amount of the extract (S-110) before the biomass enters the screw press. Through this process, 70% of the ethyl acetate is recovered initially while decanting the solids. The slurry (S-109) is further separated by screw pressing into the SL extract (S-112) and residual biomass (S-111). After extraction, the SL extract recovered by decanting and pressing is combined and passed through a press filter for suspended solids removal (4.0% in the extract). The clean extract is then derived to the SL recovery stage, and the residual biomass is sent for treatment. The models consider costs for spent solids managed through anaerobic digestion in an existing industrial facility in the region, since biomethane production potential has been confirmed in the range of biowaste [29].

2.2.4. SL Recovery

This process was designed in a continuous mode. The liquid fraction containing the SLs is evaporated, and the paste is dried to obtain SL crystals. For this, a single-stage evaporator is loaded with SL extract (S-113) at room temperature in which the solvent (ethyl acetate) is evaporated by heat transfer using vapor at 152 °C. The SL paste derived from the evaporator (43% solids) (S-114) is dried in a rotavapor at 70 °C to obtain the final product of SL (>99.0% of solids) (S-115) [40]. Recovery of the solvent from the evaporator and the drum dryer is carried out in a condenser at 20 °C using chilled water. Vapor fractions are condensed and 99.9% of the solvent is recovered (S-117), while the remainder is lost to the atmosphere (S-116). The recovered solvent (95% of total solvent used in S-108) is reused within the process.

Solid waste treatment: Solid residues after SL extraction are used as a material for biogas production in a co-digestion plant. Biogas production is estimated based on experimental results [29]. In this model, 5% of the solvent is lost, embedded in the solid matrix of the waste material, despite the support material. This assumption should be validated in further experiments.

2.3. Comparison Scenarios

2.3.1. Support Material Comparison

Having a seasonally produced material is a major inconvenience for an annual operating facility, mainly due to the costs of accumulating the biomass (and also sometimes pretreating it) before processing, and generally also involves oversizing the plant if biomass accumulation is limited because of material degradation. By combining different support materials throughout the year, the processing plant can be fitted properly to maintain a steady SL production on a year-round basis. This uncertainty of the seasonal and geographical production of agricultural wastes was assessed by evaluating two alternative supports to WS. Specifically, rice husk (RH) and coconut fiber (CF) were selected according to [30]. SL yields for RH and CF were 0.22 and 0.28 g SL/g WOC, respectively. In these scenarios, water-holding capacity (WHC) and bulk density were utilized to calculate water addition for each case to obtain the final processing volumes. Bulk density was experimentally determined in previous work, with a value of 35.2 kg/m^3 for WS, 117.6 kg/m^3 for RH, and 54.4 kg/m^3 for CF [30].

2.3.2. Facility Investment Comparison

To assess the effect of investment in a new brand facility, the base scenario will be compared to a scenario where the process plant is located inside the edible oil refinery, producing 750 t/y of WOC.

2.3.3. Substrate Comparison

Experimental data regarding SL production using frying oil, oleic acid, and glucose as substrates were gathered from previous studies [41] and adapted to the proposed scenario. Data for mango kernel, and sunflower oil cake and soybean oil were taken from [12,24], respectively. These authors also provided a comparison point for raw materials (oleic acid and glucose). All these processes were simulated under the SSF scenario as indicated in each article and most of the technical parameters described above were applied, with minor modifications due to the physical parameters of the substrates. For comparison, all scenarios were evaluated at the same capacity production of 384 t of SL per year, as this is the capacity value for our novel SL production model.

It should be mentioned that even when processes were simulated using the information proposed by the authors in each evaluated article, process conditions could not be optimized for industrial production and the results obtained here should only be taken as a reference.

2.3.4. SL Extraction Comparison

Although the base model SL extraction was based on a single-step ethyl acetate extraction, a different extraction method (a two-step extraction using methanol and ethyl acetate) was evaluated, as proposed in [12].

2.3.5. Fermentation Technology Comparison Scenario

For comparison purposes a scenario including an SmF process was included. In this case, data for SmF and equivalent SSF process were obtained from [12] using soybean oil (SO) and sunflower oil cake (SOC) and compared to our base scenario.

2.4. Technical Considerations

All technical considerations made were based on experimental results and the simulation parameters obtained by the SuperPro Designer software v10.2 (Intelligent Inc., Scotch Plains, NJ, USA, [42]). All the scenarios and the process flowsheet were carried out using SuperPro Designer with the objective of generating mass and energy balances from which the requirements for consumables, utilities, and energy needs were calculated. Moreover, this software uses an internal database of industrial equipment with its commercial costs and characteristics.

Through engineering parameters, previous bench (0.5 L [9] and pilot-scale (20 and 100 L [29,30]) results were upscaled in a Class 5 analysis, aiming as the first approach in terms of investment and operational costs. Moreover, sensitivity analysis was carried out to highlight critical variables for the future improvement of this preliminary model.

For plant sizing, SL production per added WOC (kg SL/kg WOC) was considered using data reported for the three supports used [30]. Because of bulk density and the WHC of the supports, yield in dry mass or in volume can be misleading so, to simplify sensitivity analysis, the SL yield was considered in terms of the fermented material.

Another point considered was that, even when productivity results were reported on the 7th day of fermentation, similar results were obtained on the 5th day [30], reducing the operational costs considerably (up to 20%) when initial simulations were made.

2.5. Cost–Benefit Analysis

Cost–benefit analysis (CBA) was carried out considering the scheme proposed as a completely new asset because there is no pre-existing infrastructure similar to that proposed. Equipment depreciation, price, and technical contingencies were also considered. Equipment and material inputs/outputs were scaled up, and cost estimation was performed using the same simulation software as indicated in Section 2.1.

2.5.1. Cost Estimations

Equipment costs were based on in-house data, information from equipment suppliers, and historical equipment costs. Prices were calculated using the Chemical Engineering Plant Cost Index (CEPCI), when needed, to convert equipment prices to the year 2021 by using Equation (1). In some cases, prices were determined using the SuperPro Designer software, which scales up equipment purchase costs by using a relationship for equipment capacities, as shown in Equation (2). The acquisition of land was not considered as part of the capital costs. An α value of 0.6 was considered, which has been indicated as the six-tenths rule giving an approximate cost within plus or minus 20% [43].

$$\mathrm{Cost}_2 = \mathrm{Cost}_1 \cdot \left(\frac{\mathrm{CEPCI}_2}{\mathrm{CEPCI}_1}\right) \tag{1}$$

$$\mathrm{Cost}_2 = \mathrm{Cost}_1 \cdot \left(\frac{\mathrm{Size}_2}{\mathrm{Size}_1}\right)^{\alpha} \tag{2}$$

Installation and maintenance factors were 30% and 10% of the equipment purchase cost, while unlisted equipment accounted for 25% of the total purchase cost. We also considered operational costs, such as raw materials, labor, consumables (equipment parts, replaced items, fungibles, and chemicals), laboratory (off-line analysis, quality control, and quality assurance), utilities (heating and cooling, as well as electricity) and equipment-dependent expenses (depreciation of the fixed capital investment, maintenance of equipment, insurance, taxes). Facility expenses and depreciation (linear) were 6 and 5% of direct fixed cost (DFC), respectively. Also, a miscellaneous item (insurance, local taxes, and factory expenses) was included, accounting for 8% DFC. The start-up and validation cost was 5% DFC. The product failure rate was considered 0%, while advertising, selling expenses, and royalties were not included at this point. All these considerations were taken from [43,44], relating to a plant with technology uncertainty at a large scale. The plant was estimated over a 10-year lifetime, including a one-year construction and start-up phase.

Labor costs were calculated based on a 24 h workday, 330 days per year (94% of the total time available per year to account for any downtime for repairs, etc., for a total of 7920 h/y). Plant processing lines included five operators (three operators for sterilization/fermentation, and two operators for SL extraction/recovery), two supervisors (availability 50% of the hours), and one plant manager (availability 25% of the hours) available for the processing operation execution, control, and administration. Salary for the operators was set at the minimum wage of 1238 USD/mo for Spain (BOE, 2018); supervisors and plant manager salaries were set at 1.25× and 1.5× times the minimum wage, respectively. Laboratory/Quality Control/Quality Assurance associated costs were set at 15% of the labor cost. Labor and Quality Assurance costs were assigned equally to the four processing stages.

The utilities electricity, steam, and process water were considered during plant processing. For electricity, electric power for unlisted equipment and general load accounted for 5 and 15% of the total consumption, respectively. Consumables were mainly replaceable parts (accounting for 10% of the respective equipment cost) and solvent replacement for that lost during the SL extraction and recovery stages. Table 2 presents prices for utilities and main raw materials used in the proposed plant (VAT on purchased material and consumable costs are included). For waste streams, solid residue treatment through anaerobic digestion was set at the cost of 55 USD/t [45].

Table 2. Prices for utilities, main raw materials, and products in the presented scenarios.

Parameter	Unit	Value Used in the Model
Utilities		
Standard power	USD/kWh	0.087 [1]
Steam	USD/t	12.0 [2]
Cooling water	USD/t	0.05 [2]
Chilled water	USD/t	0.4 [2]
Raw material		
WOC	USD/t	58 [3]
MOL	USD/t	167 [3]
Frying oil	USD/t	50 [3]
Sunflower oil cake	USD/t	58 [4]
Soybean oil	USD/t	1265 [3]
Oleic acid	USD/t	1390 [3]
Glucose	USD/t	80 [3]
Mango kernel	USD/t	60 [5]
WS	USD/t	84 [3]
RH	USD/t	100 [3]
CF	USD/t	250 [3]
Consumables		
Ethyl acetate	USD/t	1050 [6]
Methanol	USD/t	90 [6]
Inoculum	USD/t	40 [7]

Euro conversion to dollar 1.0 € = 1.09 USD (Banco de España, accessed on 4 May 2020); [1] https://tarifaluzhora.es/info/precio-kwh (accessed on 4 May 2020); [2] Cost given by default in the modeling software; [3] Price provided by the producing companies; [4] Estimated cost for a process similar to WOC production; [5] Estimated cost for imported mango kernel to Europe; [6] https://www.echemi.com/ (accessed on 4 May 2020); [7] Internal estimations at Fraunhofer Chile Research.

Cost estimation for this project is a Class 5 under the Cost Estimate Classification System provided by AACE International to evaluate, approve, and/or fund projects. Class 5 estimates a concept screening using methods, such as capacity factoring, parametric models, judgment, and analogies to estimate values in projects with a low definition (0–2%), for which ample accuracy values for low (−20–50%) and high (+30–+100%) ranges can be expected.

The unit production cost (UPC) was defined as the price derived in a zero net present value project using the method of capital and operating cost discounting, and it was calculated based on 1 kg of SL crystal produced. Key technical choices were evaluated through their impact on the UPC of the SL crystals as the final product.

2.5.2. Revenue

Revenue will be generated from the sales of products with an estimated price for commercial biobased sophorolipids of 10 USD/kg, as obtained by several online providers.

2.5.3. Profitability Analysis

The profitability was analyzed by evaluating net production cost, UPC, net present value (NPV), internal rate of return (IRR), and payback time as stated elsewhere [34]. Briefly, the net present value shows how profitable a project will be versus alternatives, the internal rate of return is the expected return on a project, while the payback period determines how long it would take a company to recover the original investment. By using these three parameters, a project can be evaluated on its feasibility.

The analysis will compare the base scenario, that accounts for the SL production in a brand-new facility, with a new scenario considering the plant located inside an existing edible oil refinery. In both cases the SSF process configuration (equipment, mass balance, etc.) is the same. This comparison intends to determine whether the construction of the plant inside the edible oil refinery has advantages, since requirements in infrastructure and maintenance would be lower and installed facilities and services could be used.

2.6. Equipment Selection

Table 3 presents the equipment selected to produce SL extract by SSF using WOC as the substrate and WS as the base scenario. Free on board (FOB) prices were corrected in the simulation by using a 1.25 factor. Equipment was overestimated at a maximum of 75% of usage for further plant expansion.

Table 3. Main equipment to produce SL crystals by using SSF, as modelled in Figure 1.

Equipment	Name	Comments	Purchase Cost (USD)	Capacity (Design Parameter)
Tank	V-101	Sterilization	11,100	6 m^3
Reactor tank	V-102	Fermentation	10,513	5 m^3
Reactor tank	V-103	Extraction Includes air filtration	3200	5 m^3
Compressor	G-101	–	10,900	10 L/h
P and F filter	PFF-101	–	41,000	350 kg/h
Screw press	SC-101	–	20,000	150 kg/h
Evaporator	EV-101	–	5500	550 kg/h
Drum dryer	DDR-102	–	5000	150 kg

2.7. Sensitivity Analysis

A sensitivity analysis was carried out using the @RISK software (Palisade), addressing uncertainty using the Monte Carlo risk assessment (MCRA). The following critical variables were addressed using a Beta Normal distribution. Summaries of the resulting distribution of effect estimates are then presented as within the 95% confidence limits. Moreover, a scale-up of the process for treating up to 3750 t of WOC (5× times the base scenario) was also assessed. Critical variables assessed, and their ranges, are indicated in Table 4.

Table 4. Variables used for the sensitivity analysis.

Variable	Range Evaluated	Value Used in the Base Model
Fat conversion into SL (%)	50–80	72
Solvent loss (%)	4.5–5.5	5.0
Scaling up factor (%)	76.5–93.5	85.0
Solvent consumption (v/w)	4.5–5.5	5.0
Residue treatment cost (USD/t)	49.1–60.0	54.5
Ethyl acetate price (USD/t)	855–1.045	950
Hydrophobic substrate cost (USD/t)	0–200	58
Hydrophilic substrate cost (USD/t)	0–250	167
Support cost (USD/t)	0–200	84

3. Results and Discussion

3.1. Mass Balance

Mass balances for the base scenario using WS as the support material are presented in Figure 2 including sterilization, fermentation, SL extraction, and recovery stages, and refer to the flows presented in Figure 1. For the base scenario, during the sterilization process, 2.8 t of material (a mixture of WOC, MOL, and WS) were processed per batch, stored daily, and sent to the SSF process (S-106). This balance gives approximately 2173 t/y of sterilized material, of which 506 t/y of WOC-derived fats are bioconverted into SL (S-107). After fermentation, the biomass is fed into the extraction process at rates of 2.6 t/d per module. Annually, the filtrate stream (S-113) after SL extraction is approximately 17,000 m^3, which is delivered to the SL recovery process. Residual biomass from the extraction process is further delivered to anaerobic digestion accounting for 2569 t/y (S-111). In the recovery process, 384 t of SL (S-115) are obtained from the processing of 750 t WOC on a year-round basis. According to this, the processing line, as proposed here, accounted for near 0.2% of the European market for biosurfactants.

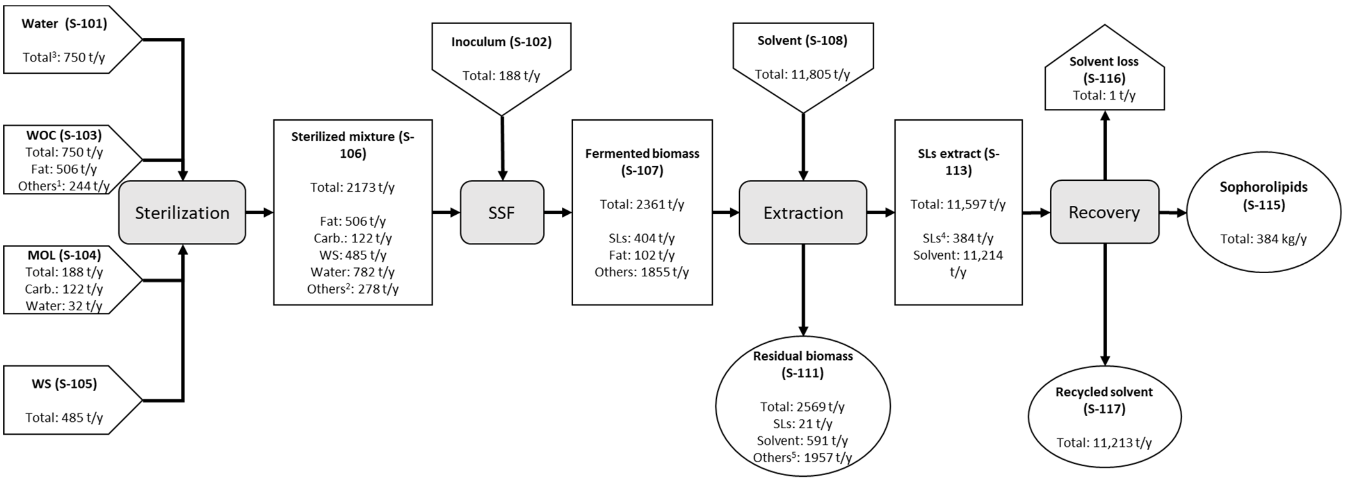

Figure 2. Major flows of the mass balance for the production of sophorolipids through Solid-State Fermentation. [1] Inert materials, not used in the bioconversion; [2] Material not considered as soluble carbohydrates and fats from MOL or WOC (proteins, fiber, and ash). [3] Water added to the solid mixture to reach water content suitable for yeast growth; [4] SL includes sophorolipids and impurities; [5] Includes reactive and non-reactive materials apart from fats entering the fermentation stage and cell proliferation during fermentation.

3.2. Overall Financial Performance

Simulation results were used to calculate the capital costs (CAPEX) and operating costs (OPEX) of the most relevant equipment (sterilization tank, fermentation vessel, extraction equipment, filters, evaporator, and dryer), in addition to the annual operating costs (labor, facility maintenance, consumables, etc.).

The investment was similar for the three scenarios, with an average value of 1303 +/− 68 USD per ton of WOC to be processed. The highest contribution to the investment was the fermentation stage (72%) due to the volume restriction (5 m^3) that prevents using larger tanks, as utilized in SmF. The extraction and sterilization stages accounted for 17 and 10%, respectively, while investment for solvent recovery was less than 1%. For SL production by SSF, CAPEX was 6.7, 7.7, and 7.5 MM USD for WS, RH, and FC scenarios, respectively.

Jiménez-Peñalver et al. [46] pointed out some disadvantages of using SSF, some of which can be difficult for scaling up, such as few commercially available bioreactors (increasing the investment costs) and the difficulty of product recovery. This last constraint is major for downstream technologies because there is a conflict between environmental impacts and costs for suitable process implementation. It is desirable that a large-scale facility does not work with organic solvents. Further research is needed to provide data on the performance of more environmentally friendly DSP technologies in SSF systems, such as aqueous two-phase systems or supercritical CO_2 extraction. This is also a drawback in terms of scaling up the plant, which should be addressed. An option for this is the implementation of large, conditioned chambers as utilized for cheese ripening. The adaptation of this type of chamber as a SSF facility is currently under evaluation because the fermentation of biomass in trays promotes better gas transfer, and temperature and humidity maintenance [47]. This may also represent an easier manipulation, lower the investment and operational costs, and allow for an easier scaling up.

Operational expenditure (OPEX) for SL production from WOC by solid-state fermentation was 1.9, 2.4, and 6.8 MM USD/y for WS, RH, and FC scenarios, respectively. Cost distribution was similar for the three scenarios, with facility as the major contributor with approximately 60% of the OPEX (1274 ± 67 M USD/y), followed by utilities (13% of OPEX, 290 ± 10 M USD/y), consumables (9% of OPEX, 196 ± 40 M USD/y) and residue treatment (7% of OPEX, 148 ± 35 M USD/y). Electricity consumption accounted for more than 75% of the total cost for the utility item. This was expected because of aeration and intermittent agitation required during fermentation and the solvent evaporation and condensation processes during the recovery of the ethyl acetate, both known as energy-intensive processes. The recovery stage accounted for almost 50% of the electricity consumption due to solvent evaporation, while the extraction stage was not relevant in the electricity consumption, mainly because extraction is carried out at room temperature in this model. These results are in agreement with those indicated by Krieger et al. [48] in that downstream processes using solvent extraction will probably have high importance in costs and environmental impact when organic solvents are used. This provides a major critical point to analyze in future work on extraction technologies or conditions, specifically in the solvent/biomass ratio or in its complete replacement.

Consumables changed mainly because of the solvent consumption rather than equipment replacement parts or other chemicals, with slightly higher values for the RH scenario as discussed above. Labor was similar for the three scenarios because even when equipment size was enlarged, especially for the RH scenario, it was considered that the same number of operators would be required to run the plant. Raw materials corresponded to less than 10% of the processing cost ranging from 78 to 210 M USD/y for WS and WHC scenarios, respectively, as they are extremely cheap as by-products from other processes, and producing companies are even paying for biomass transportation for its disposal. This result agrees with the 10 to 30% indicated by Mukherjee et al. [49] for raw material costs in a biotechnological process. However, it must be considered in a future scenario when WOC suppliers outside the original facility will charge for the raw material. Maintaining a low raw material cost is critical for the viability of the system. Comparing SSF to SmF, Ashby et al. [33] reported that the cost of the raw materials account for almost 90% of the total costs when glucose and oleic acid are used as the carbon source. From this, we could infer that the processing cost is considerably lower for SmF, probably due to (i) the more scalable equipment for fermentation and (ii) the recovery of the SL. These compounds are separated directly from the broth by centrifugation and filtration without needing an extraction step because no solid matrix was involved. Some authors have reported that downstream processes contribute up to 60% of the total production costs of biosurfactants [19,50], lower than the results obtained here (the extraction and recovery stages contributing to 80% of the OPEX). However, most of the research regarding SL has been carried out using SmF, in which higher operational costs can be observed during the fermentation stage, lowering the relative impact of the downstream stages on the cost.

In terms of the final product, UPC values were calculated at 5.1, 5.7, and 6.9 USD/kg SL crystals for WS, RH, and CF scenarios, respectively. When we compare the UPC values for the three scenarios, WS is the best support material choice to produce SL using SSF in terms of the economy of the process. Even when the SL yield is slightly higher using rice husk [30], bulk density and acquisition costs increase the UPC: the equipment needs to be larger, solvent consumption increases along with the recovery energy involved, and the residue treatment cost is also greater than those of the other two scenarios.

As stated above, UPCs for SL for the three scenarios are higher than the commonly used petroleum-based surfactants, 1 to 4 USD/kg for synthetic surfactants, such as sodium dodecyl sulphate [51]. However, is it necessary to compare the cost for a product obtained in a bioeconomy framework to its petroleum-based analogue? From a systemic point of view, the answer to this question should be “no”. Indeed, besides cost, the answer should integrate environmental impact, land use, water consumption, labor qualification, etc. [52] to account fairly for the advantages of the bioeconomy. On the contrary, it is fair to compare the proposed process to the production of SL through submerged fermentation.

3.3. Financial Comparison for SL Production with Different Support Materials

For scenario comparison, the flow diagram and process lines for the three support materials are equivalent. In terms of infrastructure, no major changes were made when supports varied, rather than re-sizing equipment capacity due to the bulk density and WHC of the lignocellulosic biomass. These variables impacted the amount of solids and water in the slurry, and changed solvent consumption during SL extraction and the quantity of biomass residues to be disposed of. The most intensive was the RH scenario, with a daily consumption of 49 t/d, while the CF and WS scenarios consumed 37 and 33 t/d, respectively. Consequently, the RH scenario showed a higher impact in terms of residue production, with 10 t/d, while the CF and WS scenarios produced 8 and 6.6 t/d, respectively. Due to the remaining solvent imbibed in the solid matrix, if more solid residues are produced, more solvent is lost on a daily basis.

In Figure 3, financial parameters for the three supports (wheat straw, rice husk and coconut fiber) for a process in an existing edible oil plant and in a new facility (base scenario) are presented. Specifically, Figure 3 presents the following parameters: unit production cost (UPC); capital costs (CAPEX); operational costs (OPEX); payback time; internal rate of return (IRR); and net present value (NPV) as defined in the materials and methods section.

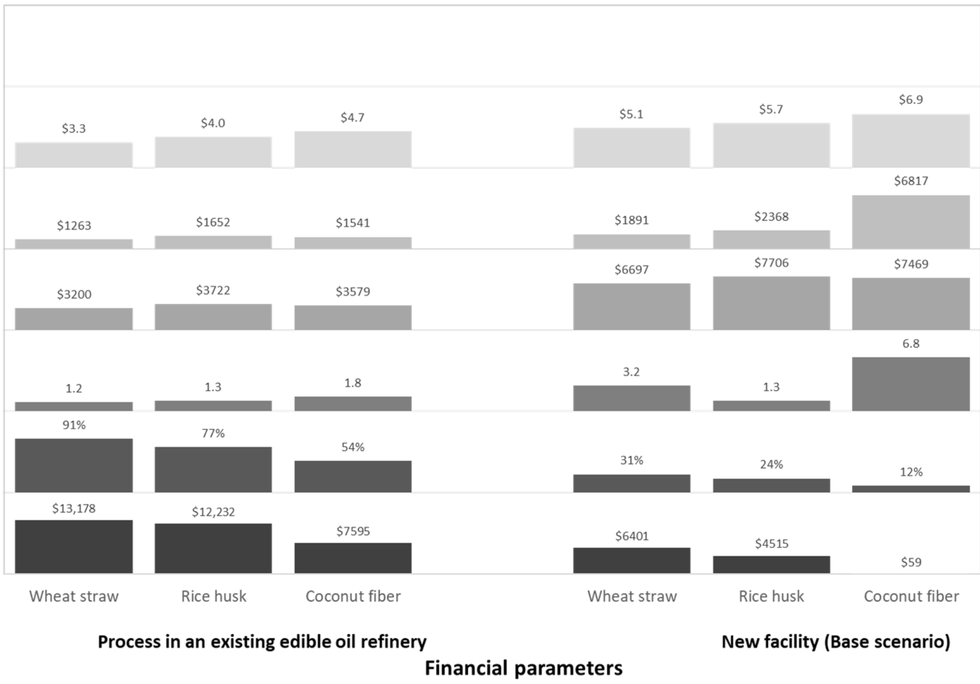

Figure 3. Financial parameters for the three supports (wheat straw, rice husk and coconut fiber) for a process in an existing edible oil plant and in a new facility (base scenario).

UPC values are in the range of other reported values for biobased sophorolipids, with prices up to 10 USD/kg being obtained from several commercial providers. Ashby et al. [33] reported between 2.0 and 3.7 USD/kg SL in a glucose/oleic acid-SmF system, which are at least 40% lower compared with the 5.1 USD/kg SL for the WS scenario selected as the best case for SL production by SSF. However, ref. [33] simulated a larger quantity of product (90,000 t of SL per year), while in this model, only 384 t of SL per year are produced. In another work, Van Bogaert et al. [32] indicate that the price for SL production by SmF depends on substrates and production scale, ranging from 2.4 to 5.9 USD/kg. Moreover, Wang et al. [34], in a waste biorefinery approach, reported a net production cost from 16.45

to 19.65 USD/kg, higher than the UPC values obtained here, while Soares da Silva et al. [53] indicated a production cost of 20 USD/kg for a system using 2% canola waste frying oil and 3% corn steep liquor in a volume of 50 L. Still, the economy of scale does not apply the same for SSF systems since fermenter volumes are limited due to solids handling and heat transfer limitations.

When we assumed that the SL production scheme would be implemented in the existing facility where WOC is produced, some costs were lowered. In terms of income, if we target a selling price of 10 USD/kg SL, annual revenues will be maximized by the WS scenario (1892 MUSD/y), followed by the RH and CF scenarios with revenues of 1768 and 1011 MUSD, respectively. Under the assumptions made in this study, the return of the inversion can be achieved during the second year of the plant operation (1.3, 1.2, and 1.8 years for WS, RH, and CF scenarios, respectively). Because no SSF industrial facility for SL production is currently ongoing, it is necessary to validate these results in further studies. Moreover, to reduce costs, some aspects of our proposal can be further addressed, as mentioned above, by re-defining the fermentation system or the DSP technology.

In the base scenario of a newly constructed plant, NPV values of 6401, 4515 and 59 M USD with IRR of 31, 24, and 12% can be expected for the WS, RH, and CF scenarios, respectively. For the WS scenario, payback time was 3.2 years. As an alternative scenario, the plant can be located inside the same edible oil refinery where the WOC is produced, thus lowering infrastructure requirements and maintenance, and using already installed facilities and services. This way, NPV is calculated as 13,178, 12,231 and 7595 USD for WS, RH, and CF. Payback time was calculated close to a year for WS, giving a good margin for the next iterations of the model. In this comparison, the difficulty of expansion when the process is located inside an established company with a different business core should be considered. This way, a newly installed facility for SL production may be the most attractive option even if the costs are almost double.

Up to this point, all scenarios have been compared against each other; however, one of the reasons for studying three lignocellulosic supports relates to seasonality. Therefore, even when the CF scenario is not economically feasible on its own, the complementarity of these three supports options should give a suitable scenario for SL production at a larger scale. For this, it is important to evaluate the annual periodicity and availability of these materials for further economic analysis. Nevertheless, a 12% of interest rate was used in this evaluation as the superior margin for rather new technology. However, lower interest rates should be considered for more robust technology.

In terms of the product itself, Wang et al. [34] evaluated two potential outputs: SL crystals (about 97% active) and SL syrup (about 78% active) using food waste and raw materials as glucose and oleic acid. The authors indicate the feasibility of this kind of industrial plant for treating domiciliary wastes for SL production; however, their SL recovery process is different from the one proposed here. The crude SLs were obtained by sequential clarifying processes with the removal of the impurities by a few washing steps with a final step of ultrafiltration. This way, the solid residues are free of solvents, and they can be sold for feed. Moreover, they indicate a higher selling price for the SL crystals (38,460 USD/t) than that proposed here and point out that the profitability of producing SL is also significantly higher than other biobased products. This gives us a wide range of opportunities to evaluate the best way to produce SL by adapting the technologies, the operational conditions, or the product presentation. Nevertheless, the commercialization of sophorolipids includes low- (detergents) and high- (pharmaceutics) value markets. Therefore, the quality of the SL should be taken into account when the selling price is set.

3.4. Financial Comparison for SL Production from Different Substrates

In Figure 4, financial parameters obtained for the different substrates reported by [41] (frying oil-MOL, oleic acid-MOL, WOC-glucose, frying oil-glucose, and oleic acid-glucose), and by [25] (mango kernel-glucose), are presented. Results indicate that UPC values are in the range of 3.7 to 4.3 USD/kg SL, up to 16% lower than those obtained in our model with WOC and MOL. These authors indicated higher yields for all the conditions tested compared with those obtained in this work, in which SL production yields using frying oil and glucose as the substrates were nearly 30% higher, while using oleic acid and glucose gave almost twice the yield obtained by fermenting WOC and MOL. Even when the conditions presented by the authors were not optimized for industrial or semi-industrial processes, they gave us a preliminary vision of the financial impact of changing substrates from residues (WOC, frying oil, and MOL) to raw materials (oleic acid and glucose). Using pure substrates implies higher yields and also higher substrates costs that affect UPC in opposite ways.

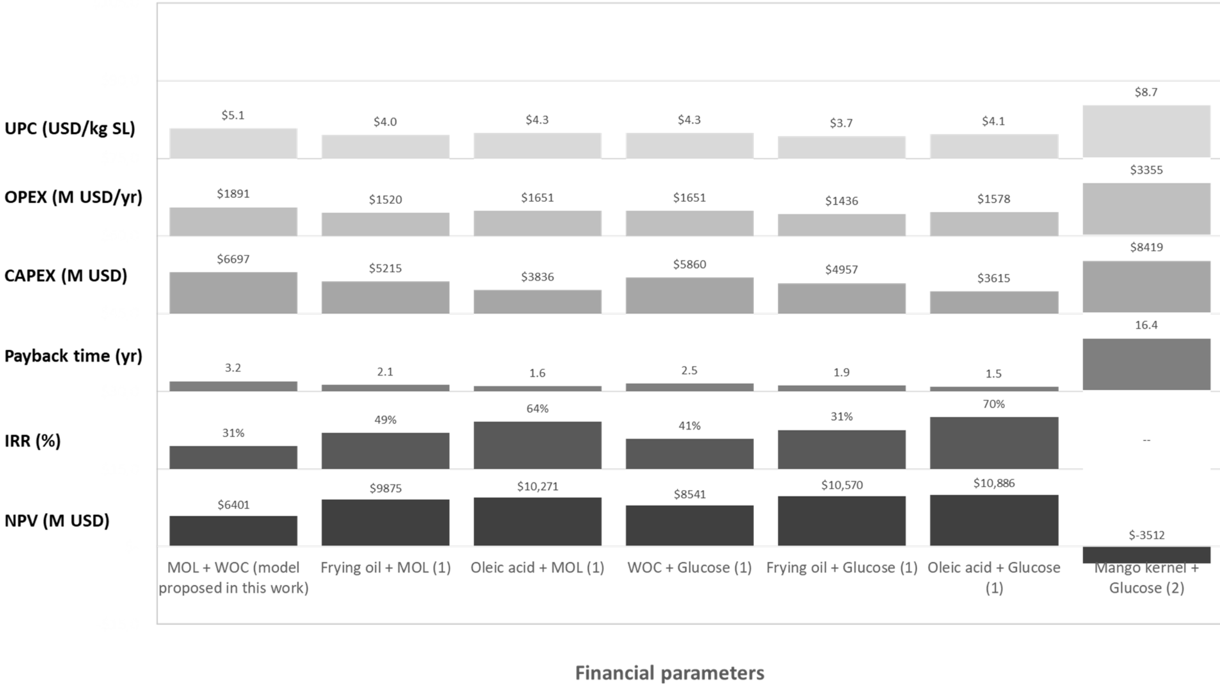

Figure 4. Financial parameters for the SLs production scenarios using different substrates. Nomenclature: WOC: Winterization oil cake; MOL: sugar molasse. (1) Jiménez-Peñalver et al., [41] (2); Parekh et al. [25].

In the SSF process modelled here, the best financial performance could be obtained by using oleic acid and glucose as substrates, with an UPC value of 4.1 USD/kg, but with an IRR of 70% and payback time of 1.5 y. Nevertheless, when frying oil and MOL were used as substrates, UPC was 3.95 USD/kg SL and payback time was 2.1 y, with an IRR of 49%, an up to 20% better performance than using WOC and MOL as proposed in this work. These differences were mainly because of the physical characteristics of the different substrates, which modified the processing volumes, thereby lowering costs associated with the equipment and the overall plant (infrastructure and maintenance). This is a relevant result, highlighting that in SSF systems the physical properties (bulk density, WHC) define process costs beyond substrate purchase costs and process yields. Besides, these results indicate that it is feasible to work with other residues in terms of investment and process conditions for SSF.

When the results using the information indicated in [25] are compared, the UPC of SL production using mango-kernel fat (MKF) was considerably higher compared with the WOC and MOL scenarios (8.7 and 5.1 USD/kg SL, respectively), mainly because of the equipment needed to process the mango kernel to obtain the fat and its physical characteristics. In this scenario, financial performance is very poor if the minimum selling price (MSP) is set at 10 USD/kg SL. For this MKF case, MSP should be 11.5 and 14.3 USD/kg for a NPV equal to 0 or for having a similar NPV as the model proposed here, respectively. Even when this MSP is not considerably higher (43% compared to the proposed value), it will affect the process feasibility, as mango kernel is not a common substrate in Europe and its obtention, maintenance, and processing will be more expensive than WOC or other oily residues easily obtained in this geographic area.

3.5. Financial Comparison for SL Production from Different Fermentation Technologies

In Figure 5, financial results using soybean oil (SO) and sunflower oil cake (SOC) by SmF and SSF are presented. In this case, SL production using SOC and SO as substrates also produced better results than using WOC and MOL. The UPC value was 4.2 kg/SL (18% lower than the base scenario), but similar to that obtained by using experimental data from [41], also giving better financial performance. Again, this probably means that, across all scenarios studied for substrates, co-substrates and conditions in SSF, yield improvements are not as important as the physical properties and material cost. As discussed above for substrates and support materials, density directly determines equipment volume and operation time. This affects investment costs and operating costs for manipulation and downstream processing. In addition, the material cost effect is due to the abysmal difference between a pure substrate (1265 and 1390 USD/t for soybean oil and oleic acid, respectively) compared with residues (60 USD/t for WOC and SOC), up to 23 times more expensive. For instance, if we consider the best yield obtained by [41] using oleic acid and glucose, but maintaining the WOC and MOL acquisition costs, the UPC decreases 45% to 2.8 USD/t SL. There is a potentially large field for investigating operational conditions on SSF economics; also, better technology needs to be developed due to the operational restrictions of the current SSF fermenters, which add costs that industrial SmF do not present (i.e., maximum reactor volume, flow air restrictions, multiple sterilizations of the solid substrate, and intensive labor).

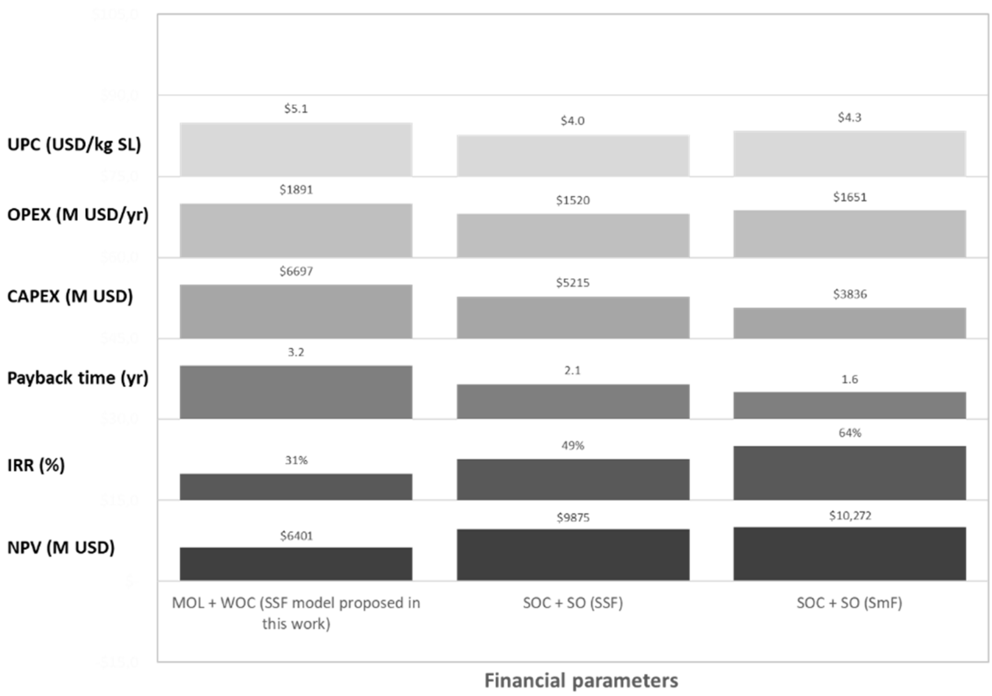

Figure 5. Financial parameters for the SLs production scenarios using sunflower oil cake (SOC) and soybean oil (SO) as substrates. SSF: Solid State Fermentation. SmF: Submerged fermentation.

SmF produced a higher UPC than that obtained for SSF under the conditions proposed by [12] and similar to our base case. However, financial indicators were better for SmF considering the total investment, NPV and payback time. When compared with the results from [33], it is noteworthy that even when UPCs for the latter were almost half of those obtained in this simulation, processing volumes are still considerably lower than those previously reported by [33] (2.95 USD/kg SL for a production capacity of 17.1 t SL/y compared with 5.2 USD/kg SL for a production of 384 t SL/y). Under this consideration, SmF values obtained in this simulation are according to those expected for a techno-economic analysis of a small processing plant, considering that [12] reported that SSF had better yields (in g SL/g substrate) by using a methanol/ethyl acetate double extraction compared with an SmF with a single methanol extraction. The combination of these factors affected the UPC for SmF. Therefore, when comparing SmF to SSF, not only should the yield be taken into account, but also the processing volume and the operational differences. In this sense, increasing the facility scale would be more advantageous for the SmF scenario since current commercial technologies for SmF allow for higher fermenter volumes than for SSF. Thus, the limitation by the maximum fermenter volume would be less restrictive, affecting UPC and other financial parameters.

3.6. General Scenarios Comparison

In Figure 6, a comparison of the investment for SL production by different substrates, supports, and technology is presented. In this work, several factors were considered in terms of costs, equipment, yields, and materials, among others, which were obtained from our own experiments and from other authors. However, as the SL production proposal in this study is still under evaluation and more pilot studies are currently being carried out, we developed an indicator to give the estimation of the equipment acquisition costs, which is the most relevant aspect for the feasibility of implementing this SSF technology. When all the evaluated cases including different supports and substrates are compared, an investment between 0.6 and 3.1 USD per kilogram of SL produced should be considered. It is worth noticing that changing the supports impacts less (1.9 ± 0.5 USD/kg SL) than changing the substrates (2.6 ± 0.4 USD/kg SL), mainly because of the physical properties (especially oil density) of the substrates and co-substrates that impact the average size of the fermentation and extraction equipment. These values should be considered when the scaling up of the process is being assessed for having an early estimation of the investment costs, at least on the major equipment needed. It was expected that lower values for SmF than for SSF would be obtained; however, under the conditions used to simulate SmF and SSF by using data from [12], this was not observed at this time, with values of 0.6 and 0.9 USD/kg SL for SSF and SmF, respectively, and considerably lower (−83%) than those obtained for the SSF as proposed here (2.3 USD/kg SL).

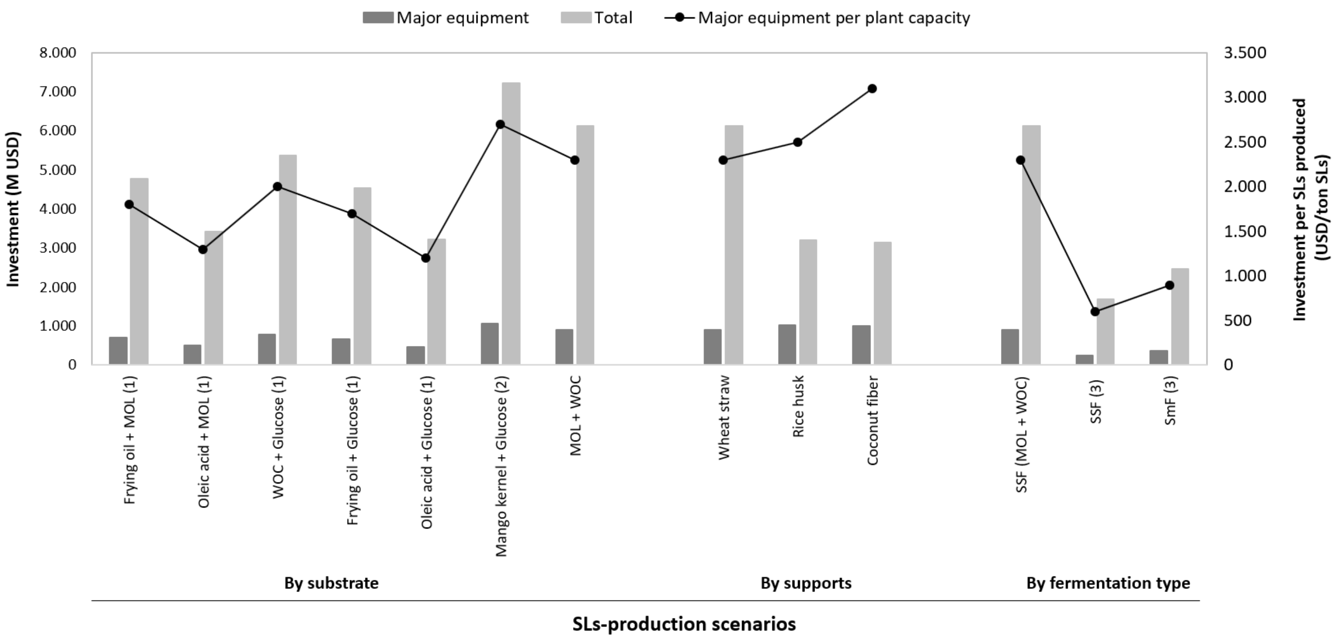

Figure 6. Investment of the studied cases for SL production by different substrates, supports and technology. (1) Jiménez-Peñalver et al. [41]; (2) Parekh et al. [25]; (3) Rashad et al., [12].

3.7. Sensitivity Analysis

Sensitivity analysis is commonly used in financial modeling to determine how critical, independent variables affect a dependent variable under certain specific conditions. In practical terms, sensitivity analysis using Monte Carlo indicates in which range of values the UPC will vary 90% of the time if all the variables change randomly in multiple potential scenarios.

Figures 7 and 8 present the results for the sensitivity analysis on the net present value (NPV) and unit production cost (UPC), respectively. Under the assumptions made in this study (Table 4), NPV could range between −2.1 and 10.9 MM USD, with an average value of 4 MM USD. The combined effect of multiple variables in a worst-case scenario would eventually lead to a negative NPV value. However, positive values in the range of 1 to 8 MM USD are expected with 90% of probability. UPC values may vary from 3.97 to 7.91 USD/kg SL, with an average value of 5.51 USD/kg SL.

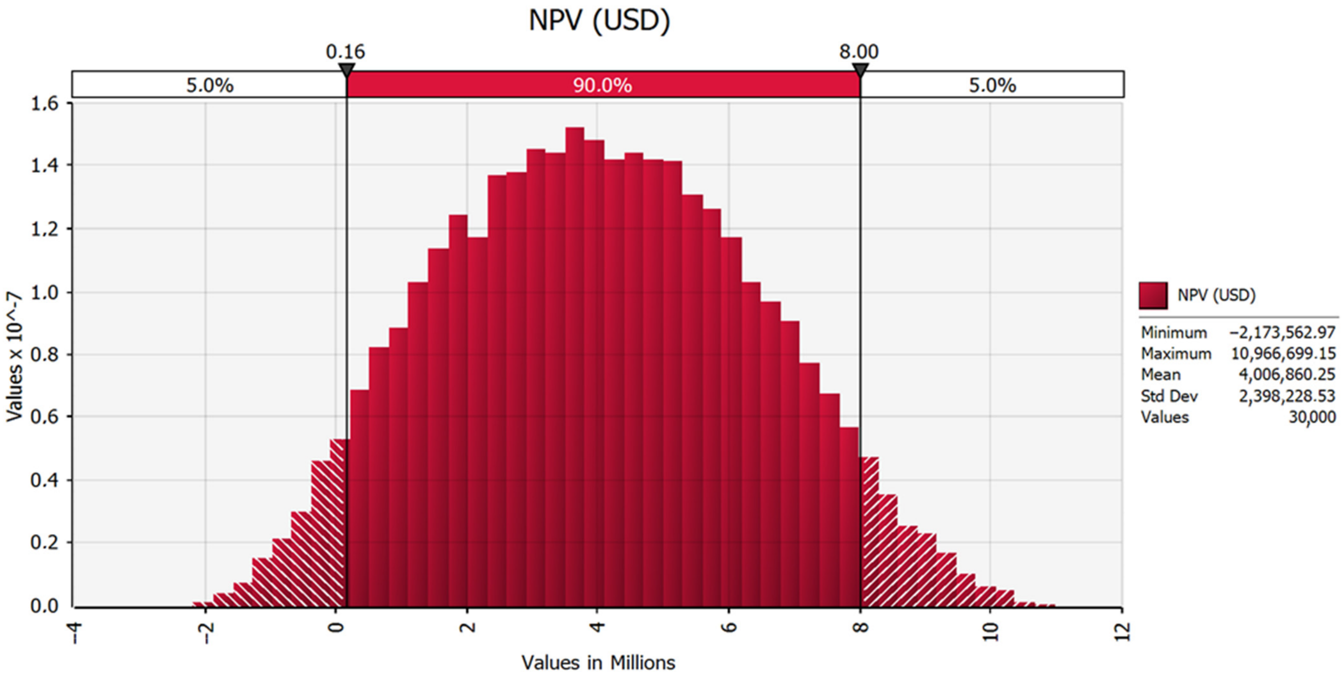

Figure 7. Sensitivity analysis on SL production from WOC by SSF on the net present value (NPV) for the WS scenario under the conditions assumed in the model. Nomenclature: WS: wheat straw; WOC: Winterization oil cake.

The analysis showed that the main contributors to the variation in NPV and UPC were the SL yield and the scaling-up factor. If SL yield varies 10% (base case 0.8 kg SL/kg fat), UPC costs will vary near 8%, from 4.7 to 5.5 USD/kg SL. These results highlight that SL yield is a crucial parameter and must be taken into account when considering alternative substrates. Of course, as stated above, the alternative substrates should have a similar acquisition cost, otherwise the positive effect of enhancing the yield will not be relevant to the financial performance of the process. Also, the physical properties could impact overall finances. Equivalent results were obtained for the scaling factor (here defined as the yield reduction due to the change in the operational conditions when upscaling from a pilot-scale to an industrial-scale—base case 15% of yield loss when upscaling). For instance, if the process has no losses during up-scaling, the SL production increases up to 452 t/y (18% more than the base scenario) with a UPC value of 4.3 USD/kg (16% lower). Sensitivity analysis indicates that the fermentation performance has more influence on the UPC costs than the overall performance of the production process in terms of solvent consumption, material costs, etc. These operational conditions affected less than 1.5% when they varied

10%. Therefore, efforts should be made in terms of increased yields, process efficiency, and overall performance in the upscaling stage.

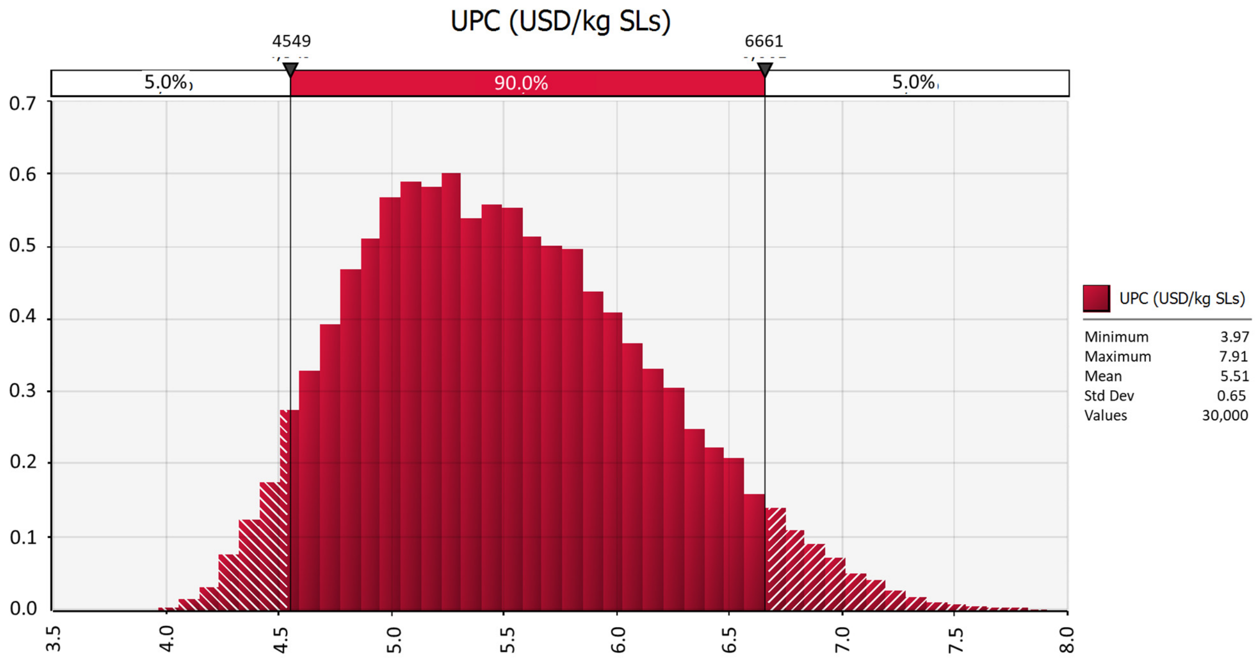

Figure 8. Sensitivity analysis on SL production from WOC by SSF on the unit production cost (UPC) for the WS scenario under the conditions assumed in the model. Nomenclature: WS: wheat straw; WOC: Winterization oil cake.

The sensitivity analysis also highlights the different effects of the selected process variables on the financial parameters. As stated above, SL yield and scaling up factor, both related to SL production capacity, affect UPC and NPV. However, solvent consumption and recovery solvent costs are the main variables contributing to CAPEX, while the cost of the support material, hydrophobic and hydrophilic substrates are the main contributors to OPEX variability.

It is worth noting that the impact of the support material, given its characteristics, will vary the UPC costs due to the quantity needed for the final mixture (mainly based on its WHC and bulk density), its impact in the fermentation (affecting SL yield), and the cost of its acquisition (including transport and manipulation).

Due to the opportunity to connect three edible oil refineries operating in the same region and thus triple the initial amount of WOC, the effect of plant capacity on UPC cost was investigated. However, and to the authors' knowledge, no packed-bed SSF bioreactors are operating at a commercial scale with the design capacity used herein. For this reason, a conservative value for the maximum volume of solid-state fermenters was assumed in 5 m^3. Too large fermenters would, undoubtedly, present a difficult temperature control. Due to these restrictions in the construction and operation of the SSF reactors, scaling up of the process up to 5× times was considered appropriate in case more industries are involved. In this new scenario, no significant changes in the UPC of SL were observed, varying from 5.1 to 4.3 USD/kg SL crystals (−16% in the UPC value for the base case). Based on this model, even with a larger upscaling (up to 5000 t WOC/y), UPC values will not be reduced by more than 20% due to the main restriction, as previously described, of the SSF equipment. It is expected that if a new configuration of SSF is based on a specially designed chamber, the costs in infrastructure and operation would be lowered and the process will become more economically attractive.

4. Conclusions

The model proposed here is the first of its kind for SL production via solid-state fermentation (SSF). This model is designed on a circular bioeconomy approach by using by-products from the food industry (Winterization Oil Cake and molasses) as substrates, in which economic results validate its use as an option for SL production via SSF. The obtained unit production cost for SL is in the upper range for the commonly used petroleum-based surfactants and in the range of SL produced through submerged fermentation. Comparison among different substrates indicated that residues can feasibly be used under a techno-economic point of view, even with a slightly better performance than using raw substrates. Thus, demonstrating that SSF can be a feasible technology to valorize solid oily residues from the food industry. Results highlight the relevance of the physical properties of feedstocks and supports in the financial performance of the process. Extraction of the bioproduct from the solid matrix contributes significantly to production costs and thus alternative DSP technologies should be explored. As SSF is still at bench and pilot scale development to produce marketable products from waste, it is important to perform techno-economic and environmental analyses parallel to process development to ensure economic and environmental feasibility of the final SSF process.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

BS	Biosurfactants
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenses (USD)
CBA	Cost-Benefit Analysis
CEPCI	Chemical Engineering Plant Cost Index (dimension-less)
CF	Coconut fiber
IRR	Internal Return Rate
FOB	Free onboard
MKF	Mango kernel fat
MOL	Molasses
MSP	Minimum selling price
NPV	Net present value
OPEX	Operational Expenses (USD/y)
RH	Rice husk
SL	Sophorolipid
SmF	Submerged Fermentation
SOC	Sunflower oil cake
SO	Soybean oil
SSF	Solid-State Fermentation
UPC	Unit Production Cost (USD/kg)
WHC	Water Holding Capacity
WOC	Winterization Oil Cake
WS	Wheat straw

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