Assessment of energy efficiency and availability in a plant processing vegetable oils

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Abstract. This facility, utilizing two boilers and a 500 kilovolt-ampere generator, has the capacity to refine 100 metric tons of crude cottonseed oil daily into consumable vegetable oil. Its production workflow comprises four key stages: neutralization, bleaching, filtration, and deodorization. An assessment of the plant's efficiency focused on quantifying the energy and exergy dissipation within each stage of the manufacturing sequence. Analyzing the energy consumption of cottonseed oil production, it was determined that processing 100 metric tons of cottonseed yielded 487.04 megajoules (MJ) of edible oil per ton. Electricity contributed a minor share (4.63%), while thermal energy dominated at 95.21%, and manual labor accounted for a negligible 0.11%. The deodorization stage proved to be the most energy-demanding process, consuming 56.25% of the overall energy used. Based on exergy analysis, the plant's efficiency was found to be 38.6%, resulting in a total exergy loss of 29,919 MJ. As a result, exergy analysis highlighted the deodorizer as the least efficient stage, responsible for 52.41% of the energy waste generated during production. A detailed examination of the plant's components pinpointed the boilers as the primary source of inefficiency, contributing to 69.6% of the total energy inefficiency. The study also uncovered other significant areas within the plant where exergy losses occur. Boosting the plant's overall capacity was proposed as a means to lessen the strain on the boilers, thereby lowering heating demands. Additionally, incorporating effective process heat integration strategies could enhance the system's energy efficiency. This approach could potentially lead to significant energy cost savings for the company, ultimately contributing to a healthier profit profile.

INTRODUCTION

Various sectors, including animal husbandry, medicine, and specialized industries, utilize this substance. Due to its widespread use, the industry holds significant economic importance. Data indicates that the nation generates 500,000 metric tons of edible oil each year, with the structured sector contributing 320,000 metric tons and the informal sector accounting for the remaining 180,000 metric tons [1]. The vegetable oil sector has made a substantial contribution to the nation's economy, creating over 10 billion naira in revenue for transportation and related industries. This industry directly supports over 25,000 jobs and indirectly sustains livelihoods for a vast agricultural workforce exceeding one million individuals. Furthermore, the expense of manufacturing, coupled with an unreliable national electricity grid, insufficient petroleum production and distribution, and rising worries about climate change, pose intricate and often contradictory obstacles for industrial activities. To thrive in the fiercely competitive global marketplace, industries are obligated to maintain efficient operational systems.

Reducing energy waste in manufacturing is crucial and should be a top priority. To achieve this, it's essential to identify and optimize the energy consumption of each stage in the production process. By doing so, companies can lower production costs and simultaneously decrease energy waste. Implementing efficient energy usage practices is vital for the success and sustainability of industries. Energy plays a crucial role in process industries, making it essential to minimize energy consumption whenever possible during standard operations.

Traditionally, engineers evaluate the energy usage of a process using the principles of the first law of thermodynamics. However, the exergy method, grounded in the second law of thermodynamics, reveals limitations of this traditional approach. Exergy analysis delves deeper, revealing the degree of irreversibility within thermodynamic processes. This allows for a more precise understanding of where, what kind, and to what extent waste and inefficiencies occur, ultimately leading to a better comprehension of the system's true performance. The growing adoption of the exergy method among researchers has led to significant progress in lowering energy expenses, preserving limited energy supplies, and minimizing environmental harm. Various industrial processes, including sugarcane bagasse gasification, malt beverage manufacturing, flavored yogurt production, and fruit juice processing, have benefited from the implementation of exergy analysis techniques. While numerous studies have explored energy and exergy efficiency in industrial processes, research specifically focusing on the energy and exergy aspects of cottonseed oil extraction remains scarce [2].

ASSESSMENT OF ENERGY CONSUMPTION AND EXERGETIC LOSSES IN THE PRODUCTION OF VEGETABLE OIL

An assessment was conducted to determine the energy needs and exergy losses associated with producing 100 tons of edible vegetable oil daily from cottonseed oil. This facility runs a continuous operation, utilizing three shifts of eight hours each, employing 55 workers per shift. Approximately 27 workers directly participate in the manufacturing process, reflecting the plant's level of automation. The primary energy inputs for the facility consist of electricity, heat, and manual labor. The main electricity supply comes from either the public power network or the company's own power generation equipment. Heat is produced by diesel-powered boilers, which create steam, and cooling is achieved via condenser systems [3].

The manufacturing procedure involves four key stages: neutralization, bleaching, filtration, and deodorization. These stages are supported by two steam boilers and a 500 kVA generator providing the necessary energy. A visual representation of the process, outlining how edible vegetable oil is extracted from cottonseed oil, is presented in Figure 1. Initially, raw cottonseed oil, stored in a vacuum-sealed buffer tank, undergoes heating via a heat exchanger utilizing the residual warmth from previously deodorized oil. A dosing pump delivers phosphorus acid solution to a stationary acid mixer, where it's combined with unrefined oil.

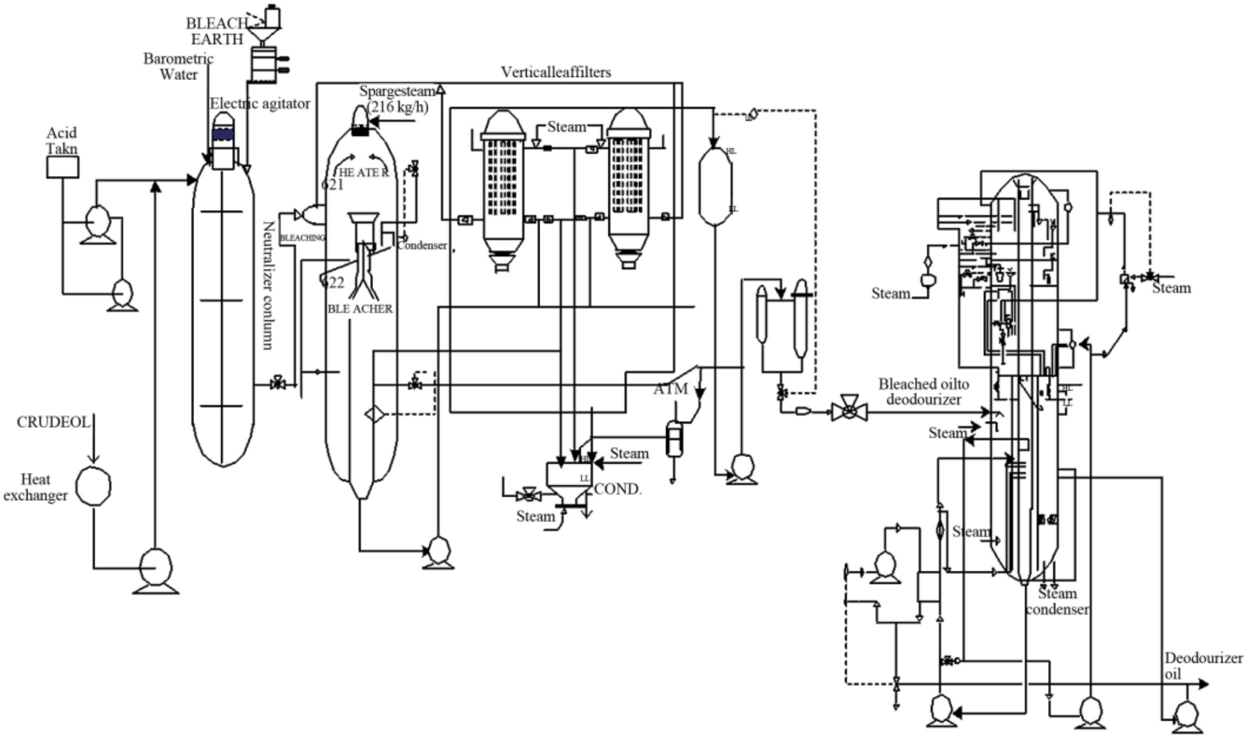

FIGURE 1. Visual representation of the process for making edible vegetable oil.

Following this, the oil mixture is directed to a neutralizer, where gums and phosphatides are chemically altered to facilitate their subsequent elimination during bleaching. A designated device precisely measures and adds the necessary quantity of bleaching earth to the tank. Subsequently, the neutralized oil is pressurized and transferred to the bleacher, where it undergoes treatment with bleaching earth or activated carbon to eliminate color-causing pigments. Afterward, steam is used to heat the mixture, ensuring a vacuum environment through the use of a barometric condenser and vacuum pump. Once the target temperature is attained, all moisture within the oil evaporates, finishing the bleaching process. The now-bleached oil suspension is directed to hermetic leaf filters, which separate out the bleaching earth and any settled impurities. Deodorization constitutes the final step in refining vegetable oils. This process, performed at elevated temperatures, involves introducing an open stream while sustaining a high vacuum. This effectively vaporizes and removes any odorous components, channeling them to barometric condensers via a vacuum network. Simultaneously, volatile fatty acids and other odor-causing compounds are eliminated under the lowered pressure, yielding a neutral-tasting final product. The outcome is an odorless product that possesses an agreeable color and flavor profile. Afterward, the unflavored oil is transferred to its final storage location, where oxidants are incorporated to extend its usability.

This facility employed a combination of electrical, thermal, and mechanical power sources to drive its manufacturing processes. Data regarding energy usage and exergy efficiency for every stage of production was either collected on-site or sourced from the factory's energy records. Researchers gathered information about the electrical power output of motors, the characteristics of steam, coolant, and product flows, as well as the performance parameters of boilers and chillers. They also documented the workforce needed for manual tasks and the duration of each process. This data was compiled through a two-month onsite study at the facility. During data collection, several measurement tools were employed. These included a stopwatch to track the duration of each process, a measuring cylinder to determine fuel usage, and a weight scale to assess the mass of both raw and refined oil.

Electrical energy consumption, measured in kilowatt-hours (kWh), was determined by calculating the product of the electric motor's power capacity (kW) and its run time (hours). For this analysis, a motor efficiency of 80% was utilized, as referenced in [2]:

$$E_p = \eta P t \tag{1}$$

The amount of thermal energy added, represented by, was determined by considering the fuel consumption, either diesel or oil-cake, required to produce steam within the boiler system. To express the fuel mass, W, measured in kilograms, as energy in megajoules (MJ), it was multiplied by the specific calorific value, of the fuel, which is measured in joules per kilogram as outlined in reference [2]:

$$E_F = C_f W \tag{2}$$

The energy content of diesel fuel is 42 MJ per kilogram, while oil-cake provides 37 MJ per kilogram, as referenced in source [2].

The estimated manual energy expenditure, denoted as and measured in kilowatts (kW), was derived from [4] suggested figure. Odigboh posits that, considering a peak energy use of 0.30 kW and a 25% conversion efficiency, a typical individual working in a tropical environment can produce roughly 0.076 kW of physical power over an 8 to 10 hour shift:

$$E_m = 0.076 N t (kW * h) \tag{3}$$

The variable 'N' represents the quantity of individuals participating in the undertaking, while 't' denotes the duration, measured in hours, required to successfully complete a specific assignment.

Energy efficiency, measured as energy intensity, indicates the energy consumption needed to generate a specific quantity of vegetable oil. This measurement is calculated by dividing the total energy used, measured in megajoules (MJ), by the weight of edible oil produced, quantified in tonnes:

$$E_i = \frac{E_T}{V_t} \tag{4}$$

Exergy, representing the useful work obtainable from a process flow, is composed of four distinct components: physical, chemical, kinetic, and potential exergy. Quantitatively, this relationship is depicted as:

$$E_x = E_{PH} + E_{CH} + E_K + E_{PT} \tag{5}$$

where

$$E_{PH} = (h - h_0) - T_0 (s - s_0) \tag{6}$$

$$E_{PT} = mgh \tag{7}$$

$$E_K = \frac{mv^2}{2} \tag{8}$$

$$E_{CH} = \sum_i \mu_{0,i} N_i \tag{9}$$

where $\mu_{0,i} = h_{0,i} - T_{0,i} S_{0,i}$ and $N_{0,i}$ = represents the quantity of moles.

Table 1 outlines the essential factors used to assess both energy and exergy within the context of these four operational units.

TABLE 1. Essential factors to evaluate energy and exergy levels throughout the vegetable oil processing procedure.

Fundamental process step	Essential inputs	Significance Importance
Neutralization	Count of individuals	4
	Duration (hours)	4
	Electrical energy output (kilowatts)	36
	Initial temperature of incoming crude oil (Kelvin scale)	302
	Oil temperature at discharge point (Kelvin)	357
	Proportion of water relative to oil mass	0.02
Bleaching	Count of individuals	6
	Duration (hours)	5
	Electrical energy output (kilowatts)	5.4
	Temperature of oil after neutralization, measured in Kelvin.	357
	Temperature of oil after neutralization, measured in Kelvin.	372
	Required steam output (kilograms per hour)	214
	Oil density after neutralization (kilograms per liter)	0.8
	Proportion of water within oil	0.03
Filtration	Count of individuals	2
	Duration (hours)	4
	Electrical energy output (kilowatts)	5.4
	Temperature of oil entering the bleaching process (Kelvin scale)	372
	Temperature of oil exiting the bleaching process (Kelvin scale)	352
	Proportion of water within oil by mass	0.03
Deodorizing	Count of individuals	6
	Duration (hours)	6
	Electrical energy output (kilowatts)	26.1
	Required steam flow rate (kilograms per hour)	512
	Temperature of oil entering the filtration system (Kelvin scale)	352
	Oil discharge point, devoid of odor, Temperature (Kelvin)	472
	Oil's mass per unit volume (kg per liter)	0.84
	Proportion of water relative to oil mass	0.05

Equations 6 through 9 utilize specific enthalpy *h*, measured in kilojoules per kilogram (kJ/kg), and specific entropy *s*, also in kJ/kg•K, for each stage of the process. These values are determined based on the temperature *T* and pressure *P* conditions at each stage. For comparison, h_0 and s_0 are additionally calculated at a standard reference point defined as T_0 = 298.15 K and P_0 = 100 kPa.

In a standard control volume experiencing consistent flow and exergy buildup within its boundaries, the exergy accounting equation can be expressed as follows [6]:

$$\sum_j \left(1 - \frac{T_0}{T_j}\right) Q_j - W_{cv} + \sum_i m_i e_i - \sum_0 m_i e_i - I_{cv} = 0 \tag{10}$$

Q signifies the speed at which heat moves through a dividing line, T_j denotes the temperature at that boundary at a specific moment, W_{CV} indicates the amount of exergy transferred via work over time, *I* reflects the exergy lost per unit time because of irreversible processes happening inside the system. The term $m_i e_i$ captures the exergy flow related to mass movement and associated work, with *i* and *0* labeling the entry and exit points, respectively.

The system's exergy, focusing on its specific flow characteristics, can be represented by the following equation:

$$e = h - h_0 - T_0(S - S_0) + \frac{V^2}{2} + gz \tag{11}$$

Using the symbols "h" and "S" to represent the system's enthalpy and entropy, and h_0, s_0, and T_0 for the dead state's enthalpy, entropy, and temperature (representing the environment), we can describe the overall exergy variation in the system as follows:

$$e_2 - e_1 = h_2 - h_1 - T_0(S_2 - S_1) \tag{12}$$

A predictive model, as outlined by Singh [7], was employed to determine the net exergy variations for process streams entering and exiting every individual stage within the edible vegetable oil production process:

$$e_2 - e_1 = c_p(T_2 - T_1)\left[1 - \frac{T_0}{(T_2 - T_1)ml}\right] \tag{13}$$

$$(T_2 - T_1)ml = \frac{T_2 - T_1}{\ln(T_2 / T_1)} \tag{14}$$

The value for how much heat an edible vegetable oil can absorb per unit temperature rise can be calculated with the following formula:

$$c_p = 4.1868(0.3823 + 0.6183x) \tag{15}$$

The degree to which exergy is lost can be determined using this formula.

$$I_{ff} = \frac{I}{\sum I_{all}} \tag{16}$$

The concept of I_{ff} represents the system's inefficiency, calculated as the proportion of irreversibility occurring within individual processes compared to the total irreversibility across all processes. The energy input that yields productive work within the system can be formulated as follows [7]:

$$W_u = (e_2 - e_1) - T_0 R_S \tag{17}$$

Exergy variation, denoted as $e_2 - e_1$ – is calculated by considering the exergy of individual components (e_x) per unit mass and their corresponding mass flow rates (*m*). Equation (14) clearly demonstrates that the change in exergy results from a combination of useful work (*W*) performed and entropy generation (R_S) at the prevailing ambient temperature (T_0). The entropy production, essentially representing energy dissipated due to irreversibilities, can be viewed as a form of work loss.

To assess the effectiveness of a system in achieving its intended outcome, its efficiency is measured by comparing the exergy generated to the exergy input. This can be expressed as a percentage, showing the proportion of supplied exergy that the system effectively utilizes for its intended purpose [6,8].

$$\eta = 1 - \left(\frac{I_{loss}}{e_{in}}\right) \tag{18}$$

OUTCOMES AND ANALYSIS

Processing 100 metric tons of cottonseed oil into edible vegetable oil took 23 hours. Due to a complete interruption in power from the main grid, a backup generator was employed throughout the entire manufacturing procedure. The generator, along with boilers 1 and 2, which ran on oil cake and diesel respectively, consumed fuel at an average rate of 21.0, 45.7, and 56.3 kilograms per hour. Consequently, the overall energy expenditure for manufacturing was calculated at 48,703 megajoules, resulting in an average energy intensity of 487 megajoules per metric ton.

Table 2 illustrates the energy usage trends observed in the primary operational processes. Calculations indicate that the overall energy supplied to the production facilities amounted to 23333.64 megajoules (MJ), comprising primarily thermal energy (95.23%), followed by electrical energy (4.65%) and a minimal contribution from manual input (0.12%). Energy expenditure was dominated by deodorization, requiring 13127.96 MJ, representing 52.26% of the total. Bleaching came in second, consuming 9224.21 MJ or 39.53%, while neutralization used 899.18 MJ

(3.85%). Filtration proved to be the most energy-efficient process, utilizing only 81.9 MJ, which is 0.35% of the overall energy consumption.

Analyzing the exergy of the system revealed areas where efficiency was lacking and highlighted potential improvements for reducing exergy waste within each stage of the four key production processes for cottonseed oil. The exergy assessment was structured by examining both the exergy contained within process streams and the exergy supplied by external utilities. An analysis of exergy within each process step was conducted to pinpoint significant energy inefficiencies and assess opportunities for technological advancements in cottonseed oil manufacturing.

TABLE 2. Information regarding the consumption of time and energy during the vegetable oil refinement process.

Fundamental process step	Duration (hours))	Electrical power, measured in megajoules.	Heat energy, measured in megajoules.	Manually applied energy, measured in megajoules.	Overall energy content, measured in megajoules	(%)
Neutralization	4	532.7	360	5.3	899.17	3.84
Bleaching	5	95.03	9118.22	11.33	9224.60	39.52
Filtration	4	79.1	-	2.6	81.89	0.34
Deodorizing	6	377.27	12741.22	9.44	13127.95	56.25
Total	19	1084.32	22220.42	28.88	23333.63	99

The plant's exergy consumption was categorized into two distinct segments. The initial analysis focused on the exergy usage within the four primary operational groups. Subsequently, the second segment investigated exergy dissipation across all plant components, encompassing both the utility systems (boilers 1 and 2). The initial assessment focused on analyzing several factors within the process stream, including exergy variations, obtainable work, steam exergy consumption, entropy production, effluent waste, and the inefficiencies inherent in each production stage. The analysis revealed that fluctuations in oil exergy were directly linked to unit operations exhibiting differences in inlet and outlet temperatures, a characteristic present in all the examined operations. The filtration process resulted in a decrease in exergy, a consequence of the oil's temperature reduction. Additionally, the work generated by the process involved a combination of electrical and mechanical power sources (as shown in Table 3).

TABLE 3. Energy analysis of food production processes for vegetables.

Elements	Variation in useful energy (MJ)	Meaningful labor (MJ)	Energy transformations within utility systems and process flows (measured in MJ).	Unidirectional Change (MJ)	Discharge of wastewater (MJ)	Overall exergy destruction (MJ)	Percentage of Ineffectiveness
Neutralization	193	538.1	360.97	705		705	7.78
Bleaching	123	106.37	2915	2897	474	3372	37.20
Filtration	–156	81	0	238		238	2.62
Deodorizing	1686	386.72	2914	1614	3131	4746	52.35
Total	1846	4714	6190	5456	3606	9064	100

Electrical energy, being a form of pure exergy, serves as a primary energy input. Despite the inherent entropy produced by human labor, which was previously disregarded in work calculations, its impact is now recognized and incorporated. A detailed analysis of each unit operation's performance is displayed in Table 4. Examining the production processes through the lens of exergy allows us to establish a hierarchy of energy losses within the plant. Viewing it this way, the deodorizer exhibited the greatest entropy increase, contributing to over 50% of the total losses. Subsequently, bleaching, neutralization, and filtration processes also showed significant entropy generation. These irreversibilities stem from substantial temperature variations between the incoming and outgoing flows of both oil streams, along with the energy consumption associated with heating and cooling operations. A technical examination of the deodorizer's components reveals that a significant amount of its inefficiency stems from excessive energy consumption during heating and cooling processes. Specifically, the deodorizer column was responsible for 34% of the overall exergy waste, with the steam condensers contributing the remaining 66%. These figures highlight the substantial energy inefficiencies associated with heating and cooling operations within the deodorizer system. Exergy assessments consistently reveal this pattern, stemming from the tendency of heat's exergy to significantly lag behind its energy content, especially when temperatures approach the reference point as noted by Fadare et al [3]. In contrast, other system components experience negligible irreversible and outflow losses.

TABLE 4. Performance metrics for plant components, focusing on exergy utilization and associated inefficiencies.

Elements	Exergy effectiveness %	Loss percentages
Neutralization	53.4	2.35
Bleaching column	4.2	9.68
Bleaching condenser	-	1.58
Filtration	-	0.79
Deodorizer column	57.8	5.39
Deodorizer condenser	-	10.46
Boiler 1	23.8	30.11
Boiler 2	29	39.57

This second category examined the overall performance of the entire system, encompassing all elements such as boilers. Table 5 presents a comprehensive summary of exergy efficiencies and the corresponding exergy loss percentages for each component. Analysis reveals that boiler inefficiencies significantly outweigh losses in other parts of the system. Specifically, boilers contribute to 69.7% of the total exergy losses, compared to the deodorizer's 10.47%. The boilers' poor performance stemmed from substantial energy waste caused by excessive entropy production during their operational state. The high-temperature environment within the combustion chambers led to a rise in the irreversibility of the combustion process, resulting in comparatively low exergetic efficiencies for the boilers. Despite the bleaching column's modest exergy efficiency and relatively small exergy losses, these figures stem from the fundamental nature of how they are calculated. Exergy efficiency, being a comparative measure, expresses the ratio of useful output to input, capped at a maximum of 1. In contrast, exergy losses represent the absolute difference between potential and actual exergy, allowing for a wider range of values. The concept of exergy efficiency doesn't apply to condensers and filters [11], as their function is to eliminate excess thermal energy rather than produce useful output. The determined exergy efficiency of the cottonseed oil processing facility stood at 38.5%, a figure signifying substantial potential for enhancement. Nevertheless, certain inefficiencies are inherent to the system due to limitations imposed by physics, technology, and economic factors.

Minimizing preventable plant losses is achievable by expanding the plant's capabilities, thereby lessening the burden on the boiler, a concept previously proposed by Dalsgard [12]. Furthermore, implementing effective heat integration strategies can decrease the consumption of both cooling and heating resources. The goal of heat integration is to pinpoint and connect any unused hot and cold fluid streams currently operating independently. Composite lines are created to optimize energy alignment. These lines have direct equivalents in exergy balance calculations [13]. Implementing this method allows for extended production periods, minimizing unnecessary energy loss and the associated exergy degradation caused by operational processes like startup, shutdown, cleaning, and sterilization. Adopting this proposal could enable the company to lower its substantial energy costs, subsequently leading to a boost in profitability.

While data on energy consumption for cottonseed oil processing is lacking, this research draws comparisons to similar processes used for producing edible oils from soybeans, sunflowers, olives, and other non-vegetable sources, as documented in existing studies.

This research reveals that the energy demands associated with the production process are less than those observed for vegetable oils derived from soybeans, sunflowers, and olives [10] (see Table 5). This discrepancy likely stems from several factors, including inherent variations in the energy needs of each production stage and the scope of the energy analyses conducted. Although the outcome exceeded levels observed in industries like organic fertilizer manufacturing [9] and fruit juice processing [5], it suggests that extracting edible oil from cottonseed demands a greater energy input compared to these methods. As exergy inefficiencies for these oils (sunflower) weren't documented, direct comparisons were precluded. Finding comparable studies proved challenging due to the unique nature of the process. Nevertheless, this research can be contextualized by referencing the pasteurizer inefficiency identified by Fadare et al. The study found a deodorizer inefficiency of 52.4%, while [11] documented an evaporator inefficiency of 68%. Additionally, previous research [12] indicated an inefficiency rate of 59.74% for a related process. These figures represent the most significant efficiency shortcomings identified across key production stages, both in existing publications and within the scope of this current investigation.

TABLE 5. Energy consumption measurements across diverse research sources.

Procedure	Energy use per unit of output (megajoules per tonne)	Reference
Manufacturing of compacted, organic-based plant nutrients	349.0000	[9]
Manufacturing of granulated, natural plant nutrients.	279.0000	[9]
Cultivation and extraction of oil from sunflowers	7794.3000	[10]
Масла, полученные из растений	487.0379	Present work

CONCLUSIONS

Researchers pinpointed four key stages in the production procedure: neutralization, bleaching, filtration, and deodorization. An energy analysis indicated that electricity (4.63%), heat (95.22%), and manual labor (0.11%) constituted the primary energy sources used in the process. Calculations showed an average energy requirement of 487 megajoules per kilogram of product. Notably, the deodorization stage proved to be the most energy-demanding, consuming 13,127 megajoules, which represented over half (51.3%) of the total energy input for production. The company primarily relied on diesel fuel and used cooking oil byproducts to fuel its steam boilers, while diesel engines provided electricity generation.

Analyzing the exergy efficiency of individual processing stages highlights the entropy generated and resources wasted in each step. Notably, every part of the plant exhibits a unique level of entropy creation. Within the primary production group, the deodorizer emerges as the biggest contributor to exergy loss, responsible for more than half the total exergy depletion. Furthermore, boiler 2 demonstrates the lowest exergy efficiency, contributing 39.5% to the overall losses incurred.

Minimizing energy waste within the system is achievable by expanding the plant's capabilities, thereby lessening the burden on the boilers. Furthermore, integrating process heat can enhance both energy efficiency and the overall financial success of the operation. The study demonstrates that exergy analysis provides a valuable method for identifying areas to optimize energy consumption.

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