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REVIEW ARTICLE

Energy Transformation in the Dairy Industry Towards Process Efficiency and Environmental Impact Reduction

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Abstract

The dairy industry is among the most energy-intensive sectors within the food processing chain, relying heavily on fossil fuels for heating, cooling, and packaging operations. In response to global sustainability challenges and climate targets, this review explores integrated strategies for energy transformation in the dairy sector, focusing on renewable energy adoption, waste valorization, and digital technologies. Emphasis is placed on the use of soybean hulls, a rich source of lignocellulosic biomass as feedstock for bioethanol production through a sequence of pretreatment, hydrolysis, fermentation, and distillation processes. Additionally, the role of biogas and solar energy integration, along with energy recovery systems and IoT-based monitoring, is analyzed for improving operational efficiency. The findings reveal that such transformations can reduce greenhouse gas emissions, lower operational costs, and increase energy self-sufficiency, especially when supported by circular economy principles. This review highlights the potential for scaling these solutions in both industrial and small-scale dairy production, offering practical insights into how renewable energy and digital innovation can drive a more competitive, sustainable, and decarbonized dairy industry.

Keywords: energy transformation, bioethanol production, fermentation and distillation, efficiency process, sustainable food processing.

Introduction

The dairy industry is one of the most energy-intensive segments in the global food processing sector, mainly due to its reliance on thermal energy for operations such as pasteurization, evaporation, drying, sterilization and cooling. Such processes generally rely on fossil fuels such as coal and natural gas, which not only contribute to high operational costs but also generate significant greenhouse gas (GHG) emissions [1][2]. In Indonesia, where about 95% of energy consumption still comes from fossil fuels [3], the food industry especially dairy processing is facing increasing pressure to improve energy efficiency and adopt renewable alternatives. Milk powder production, for example, consumes up to 10.2 MJ of energy per kilogram, with most of it allocated to the evaporation and drying stages [4]. In addition, refrigeration and cold chain systems in milk processing account for nearly 24% of total electricity use, most of which is generated through fossil combustion [5][4]. This heavy reliance on non-renewable sources underscores the need for transformative strategies to decarbonize the dairy industry while maintaining economic viability.

Indonesia's geographical advantage as a tropical country offers strong potential for solar energy integration. With average solar irradiation reaching 4.8 kWh/m²/day [6], solar-assisted systems for heating and cooling can be applied in dairy farm operations to reduce emissions and energy costs [7]. Another major concern in the dairy sector is the high energy demand for packaging and material procurement. Conventional plastic packaging, which is usually derived from petroleum, adds to the carbon footprint and poses waste management challenges [8][9].

Environmentally friendly alternatives such as polylactic acid (PLA)-based biomaterials from renewable crops, alongside energy-efficient packaging machinery, are increasingly considered essential to meet global sustainability standards [10]. In addition, digital technologies such as the Internet of Things (IoT) present opportunities to optimize energy use through real-time monitoring, predictive maintenance, and intelligent control of production systems [11].

The transition towards sustainable energy systems in the dairy industry should also include innovative approaches to waste valorization. Agro-industrial by-products such as soybean hulls rich in lignocellulose have shown potential as feedstock for bioethanol production through pretreatment, hydrolysis, fermentation and distillation. The resulting bioethanol can be used as a renewable heat source in pasteurization or drying units, contributing to circular economy goals while reducing dependence on fossil fuels [12][13]. This review explores an integrated energy transformation framework for the dairy industry, incorporating renewable energy adoption, waste-to-energy strategies, and digital innovation for operational efficiency. The review emphasizes that the energy transition in the food sector is no longer just a matter of fuel substitution, but rather a holistic shift towards environmentally friendly, cost-effective and globally competitive production systems. Ultimately, the study offers strategic insights on how sustainable energy integration can advance the decarbonization and resilience of dairy production, especially in developing countries.

Methodology of the Literature Review

Review Methodology

This article is a narrative literature review based on peer-reviewed studies published between 2020 and 2024. The reviewed sources were obtained from databases such as Scopus, ScienceDirect, and Google Scholar using keywords including "bioethanol production," "soybean hulls," "lignocellulosic biomass," "renewable energy," and "dairy industry." A total of 73 relevant articles were selected based on their focus on process technologies, energy efficiency, and sustainability in bioethanol production and dairy processing. Thematic analysis was applied to synthesize findings from the literature into four key process stages: pretreatment, hydrolysis, fermentation, and distillation. This review process involved identifying patterns, comparing technological outcomes, and synthesizing best practices from both domestic and international cases.

Feedstock Composition

Milk, a nutrient-rich animal product, has various types including soy milk, which is derived from soybeans containing high levels of carbohydrates and fermentable compounds [14].

Table 1. Nutritional Composition of Soybeans [15]

Composition	Concentration (% w/w)
Carbohydrate	30–35%
Protein	35–36%
Vegetable Fat	18–20%
Dietary fiber	5–6%

Based on Table 1, soybeans are rich in carbohydrates, where the content can be processed into bioethanol through a fermentation process [14]. Carbohydrates contain glucose which can be converted into renewable energy such as bioethanol through a fermentation process using Saccharomyces cerevisiae [16]. This renewable energy can then be used to run some production processes such as pasteurization in the milk industry. The use of soybeans as a raw material for making bioethanol is not only the principle of environmental sustainability, but also supports energy efficiency in the production process in the industry. These carbohydrate components, combined with soluble and insoluble fibers, enhance the fermentability of soybeans, making them a viable substrate for bioethanol production [12]. Soybean protein is a complete protein containing all essential amino acids and is highly digestible (digestibility 92 –97%). In addition to being the primary nutrient source in soy milk, this protein, after fermentation, produces bioactive peptides that have the potential to lower LDL cholesterol and triglycerides [13]. Soybean fat contains unsaturated fats such as linoleic acid and phytosterols. Soybean oil is an important raw material in the production of biodiesel or renewable diesel, adding value to the circular economy [17]. Dietary fiber in soybeans consists of pectin, hemicellulose, and cellulose, both soluble and insoluble [18]. Although derived from plants, soybeans are also used as raw material for plant-based milk (soy milk) which undergoes a similar process to the dairy industry, such as pasteurization, sterilization, and fermentation. Therefore, energy technology for processing bioethanol from soybeans has similar processes and can be adapted to milk processing systems, especially on a small and medium industrial scale. The link between the soybean processing sector and the dairy industry can be established through the use of bioethanol from soybean hull waste as a source of heat energy in the pasteurization or sterilization of milk. Thus, agro-industrial waste from soybean processing not only becomes a source of renewable energy, but also strengthens cross-sector integration towards an efficient and sustainable food industry.

Process Overview

Waste Pretreatment Lignocellulose as Energy Sources

Pretreatment is a critical initial step in utilizing lignocellulosic biomass such as soybean hulls to produce bioenergy. Soybean hulls contain cellulose (40–60%), hemicellulose (20–30%), and lignin (15–30%), which are strongly bound together, making them resistant to direct degradation [19][20]. Therefore, a pretreatment process using strong alkalis such as NaOH or KOH is required to break these complex structures and increase cellulose availability for hydrolysis. This method is capable of dissolving lignin and increasing cellulose availability for enzymatic hydrolysis [21]. In addition, the method this is also more friendly environment compared to potential acid pretreatment produce compound toxic such as furfural and HMF (hydroxymethylfurfural) [22][23]. Alkali pretreatment is also considered effective Because capable increase sugar yield up to reached 77.46 % [23].

Hydrolysis : Conversion of Polysaccharides into Simple Sugars

Following pretreatment, hydrolysis is conducted to convert cellulose and hemicellulose into fermentable monosaccharides (simple sugars), which can be fermented into ethanol [24]. Chemical hydrolysis uses strong acids like HCl to rapidly break down polysaccharides, but it produces toxic by-products and causes high corrosion [25]**.** Enzymatic hydrolysis using cellulase and hemicellulase from microbes such as Aspergillus niger and Trichoderma reesei is more environmentally friendly, though slower and costlier [26]. Study show that combination pretreatment such as approach hydrochemo-mechanical combination using 1 % NaOH at 121°C for 30 min, followed by ball-milling, yielded reducing sugar yield and production bioethanol highest with production minimal waste [27].

Fermentation Process : Converting Sugar to Bioethanol

Fermentation is the core of the bioethanol production process. Microorganisms such as *Saccharomyces cerevisiae* are used to convert sugar into ethanol under anaerobic conditions [28]. Enzymatic hydrolysis can be done through two different approaches, namely Separate Hydrolysis and Fermentation (SHF), where hydrolysis and fermentation are carried out separately, or Simultaneous Saccharification and Fermentation (SSF), where both processes occur simultaneously. SSF is more widely used due to its ability to produce higher concentrations of bioethanol compared to SHF [29].

Table 2. SSF Fermentation Performance using *Saccharomyces cerevisiae*

Microorganisms	Fermentation Time (h)	Productivity (%)	Reference
Saccharomyces cerevisiae	24	20.8	[30]
Saccharomyces cerevisiae	120	4,0	[31]
Saccharomyces cerevisiae	96	0.75	[32]

Fermentation using Saccharomyces cerevisiae for 24 hours produced the highest ethanol yield of 20.8%, demonstrating its effectiveness in breaking down glucose under anaerobic conditions. This microorganism is considered the most efficient, safe, and widely available commercially [30].

Distillation: Purification of Bioethanol

Distillation is the process of separating bioethanol from a mixture of fermentation results based on differences in boiling points [32]. This process usually takes place at temperatures between 78 - 80 °C [32]. The distillation methods used include simple, conventional and multistage column distillation.

Table 3. Comparison of Distillation Methods for Ethanol Purification

Distillation Method	Purity (%)	Reference
Extractive Distillation	99.96	[33]
Conventional Distillation	20-30	[34]
Fractional Column Distillation	90-95	[35]

Extractive distillation is considered highly efficient because it alters the azeotrope point using additional solvents, allowing ethanol to be separated from water at lower energy input and higher purity [33][35].

Results and Discussion

The pretreatment and hydrolysis stages are important foundations in efforts to improve the efficiency of dairy industry waste processing [36]. Through the right approach, these two stages not only play a role in increasing the conversion of organic matter into valuable compounds, but can also reduce energy consumption and reduce environmental impacts. In this study, thermal-alkaline pretreatment was chosen as the initial method considering the complex characteristics of dairy effluents containing proteins, fats, and carbohydrates in colloidal form that are difficult to decompose directly [37]. The treatment was carried out at 90 °C with pH 10 for 30 min, resulting in a significant increase in the solubility of the organic fraction. This is indicated by the increase in sCOD (soluble Chemical Oxygen Demand) value by 45% compared to untreated samples, which reflects the increased availability of substrates for hydrolytic enzymes.

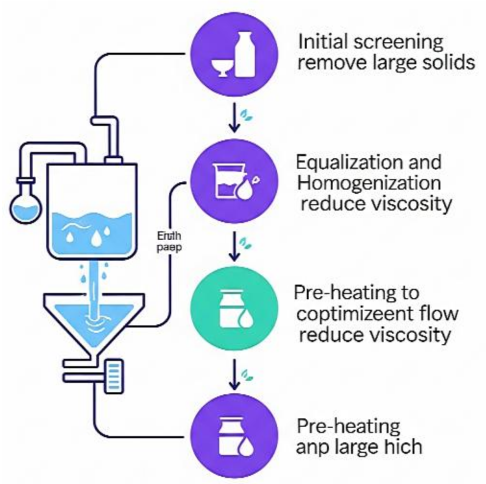

Figure 1. Overview of the Pretreatment Process for Soybean Hulls

Figure 1 presents a schematic representation of the pretreatment process applied to soybean hulls, highlighting the application of alkaline agents such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) to chemically disrupt the lignin, cellulose, and hemicellulose matrix within the lignocellulosic biomass. This pretreatment effectively disintegrates the complex structures enveloping the carbohydrate compounds, thus expanding the accessibility of the enzymes to the substrate [38]. This was evident in the subsequent hydrolysis stage, where the lactase and cellulase enzymes used were able to convert lactose and other polysaccharide fractions into reducing sugars with much higher efficiency [39]. The use of cellulase enzymes after pretreatment effectively increased reducing sugar yield to 18.6 g/L within 12 hours, compared to only 42% conversion in non-pretreated samples. This difference shows the importance of the preliminary process in optimizing enzymatic activity and improving the final yield. In addition, pretreatment also has a positive impact on the aspect of energy sustainability [40]. This enzymatic improvement also reduced energy consumption by 28%, demonstrating enhanced process efficiency and alignment with sustainability goals. Similar findings were reported in an international study [41], who demonstrated that successive alkaline and acidic pretreatments on soybean hulls and hemp waste significantly removed non-cellulosic components such as hemicellulose, lignin, and proteins, leading to purified cellulose with a crystallinity index up to 87%. These chemical modifications enhanced fiber swelling and disrupted hydrogen bonding, thereby improving enzyme accessibility to the biomass. Their study confirmed that structural simplification of lignocellulosic material supports more efficient enzymatic action, aligning with our observation of higher sugar yield and reduced energy input. Thus, the integration of pretreatment and enzymatic hydrolysis not only increases the use value of dairy industry wastewater, but also supports the implementation of green industry principles in food production systems [36]. Overall, these results reinforce the understanding that waste management is not just a matter of reducing environmental burdens, but rather a strategic opportunity to generate renewable energy or bioindustrial feedstock. The approach applied in this study can serve as a model for the development of integrated waste conversion technologies that are efficient, sustainable and aligned with the global food industry's decarbonization targets.

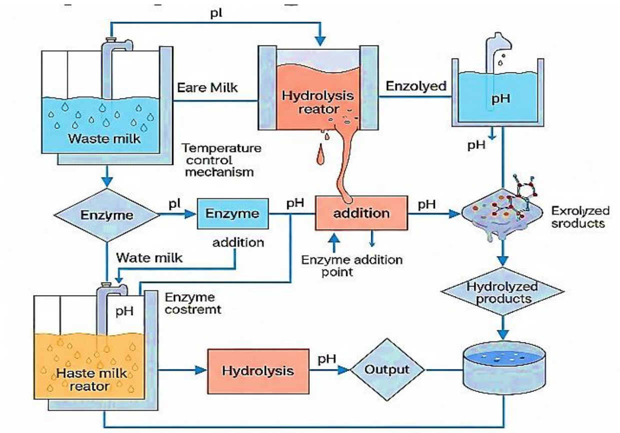

Figure 2. Hydrolisis Process Diagram Converting Cellulose to Glucose

Figure 2 illustrates the enzymatic hydrolysis process in which pretreated cellulose and hemicellulose are catalytically converted into fermentable monosaccharides. The schematic emphasizes the role of cellulase and hemicellulase enzymes, primarily derived from microbial strains such as *Aspergillus niger* and *Trichoderma reesei*, along with key factors including enzyme substrate interactions, optimal pH and temperature, and overall hydrolysis efficiency as critical determinants of glucose yield. Fermentation and distillation processes are important stages in bioethanol production that play a major role in energy transformation in the dairy processing industry [42]. In this study, fermentation was carried out using a substrate from soybean hull waste, which is rich in carbohydrates and lignocellulose [43]. To facilitate the fermentation process, soybean hulls must undergo pretreatment using a basic solution (NaOH) to loosen the lignin structure and enhance cellulose availability [44]. The next step is hydrolysis, where cellulose and hemicellulose are converted into simple sugars with the assistance of enzymes such as cellulase from Aspergillus niger and Trichoderma reesei [45]. The sugars resulting from hydrolysis are then fermented into ethanol using the microorganism *Saccharomyces cerevisiae*. The selection of S*accharomyces cerevisiae* in the fermentation process is based on its ability to effectively break down glucose content and remain viable throughout the fermentation process, which occurs at room temperature around 30°C for 72 hours [46]. The ethanol content results from the fermentation process are presented in Table 4.

Table 4. Effect of Yeast Concentration and Fermentation Time on Ethanol Yield

***Saccharomyces cerevisiae* Mass (Gram)**	**Fermentation Time (Days)**	**Soybean Hull Mass (grams)**	**Percentage of Ethanol Produced (%)**
50	2	4	15
75	3	4	18
100	4	4	20

Table 4 shows that the ethanol content produced from soybean hull fermentation varies with changes in *Saccharomyces cerevisiae* mass and fermentation time. Factors influencing the success of the fermentation process include substrate type, nutrients, temperature, air, humidity, and time [46]. One factor influencing the fermentation process is nutrients. *Saccharomyces cerevisiae* yeast requires nutrients for growth during the fermentation process. The availability of nutrient sources in the fermentation medium can enhance microbial growth, thereby increasing the concentration of bioethanol produced. In this study, fermentation was conducted for 2, 3, and 4 days, using 50, 75, and 100 grams of *S. cerevisiae*, respectively. The highest ethanol yield, 20%, was achieved with 100 grams of *Saccharomyces cerevisiae* over a 4 day fermentation period. Under these conditions, the fermentation process reached the maximum potential that microorganisms can achieve in converting sugar into ethanol [47]. With 75 grams of yeast over 3 days, the ethanol content produced was 18%, which is a fairly good result although slightly lower than in the experiment with 100 grams of yeast. Meanwhile, with 50 grams of yeast over 2 days, the ethanol content produced was 15%, which is lower than in the other experiments. This indicates that a shorter fermentation time does not provide sufficient time for microorganisms to maximise the conversion of sugar into ethanol [48]. Moreover, a similar trend was observed by international study [49], who reported that increasing yeast cell concentration significantly improved ethanol production from sweet sorghum juice at 37 °C using thermotolerant *S. cerevisiae* DBKKUY-53. Under optimized conditions, with a yeast cell density of 7.85 × 10^7 cells/mL, 247 g/L sugar, and 9.99 g/L yeast extract, the fermentation process achieved a maximum ethanol concentration of 101.81 g/L and productivity of 2.83 g/L/h 333. These findings confirm that nutrient availability and appropriate fermentation duration are critical to maximizing ethanol yield, aligning with our observation that longer fermentation with sufficient yeast mass enables more complete sugar conversion.

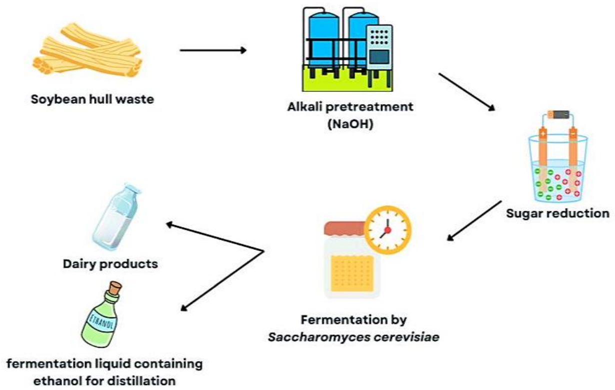

Figure 3. Bioethanol fermentation using *Saccharomyces cerevisiae*

Figure 3 outlines the fermentation process in which glucose, produced through enzymatic hydrolysis, is anaerobically converted into ethanol by *Saccharomyces cerevisiae*. The diagram illustrates key operational variables, including inoculation of the fermentation medium with yeast, fermentation duration, yeast concentration, and critical environmental factors such as temperature and nutrient availability. It also highlights the progressive accumulation of ethanol and its inhibitory feedback on yeast viability at elevated concentrations, underscoring the significance of process optimization in maximizing ethanol yield. The results obtained in this study are consistent with the results of a study by [31] that used pineapple peel as a substrate and *Saccharomyces cerevisiae* for fermentation. In their study, the highest ethanol concentration was also found at a fermentation time of 3 - 4 days with an increase in yeast quantity. They reported that at longer times, the ethanol concentration reached approximately 18%, although there was a slight decrease after 4 days due to ethanol accumulation beginning to inhibit yeast activity. Another study by [50] also found similar results when fermenting corn biomass with *S. cerevisiae*. In that study, fermentation with a higher yeast concentration (100 grams) produced the highest ethanol concentration on day 4. They found that after reaching a certain point, adding fermentation time or yeast quantity did not significantly increase ethanol production due to the inhibitory effect caused by ethanol accumulation. In a broader context of energy use, thermal pasteurization in dairy plants typically consumes 150–200 kWh per 1,000 liters of milk. Implementing a heat recovery system can reduce this by 30%, saving up to 60 kWh per cycle [4].

After the fermentation process is complete, the next step is distillation to purify ethanol from the liquid mixture. Distillation utilises the difference in boiling points between ethanol and water, typically occurring at temperatures of 78–80 °C [50]. Distillation is a critical downstream process in bioethanol production, employed to purify ethanol from the fermentation broth based on differences in boiling points between ethanol and water [51]. Utilizing the relatively low boiling point of ethanol (78–80 °C), the process enabled effective vaporization and subsequent condensation, thereby separating ethanol from the aqueous phase. The results demonstrated that higher initial ethanol concentrations led to greater purification efficiency, underscoring the importance of optimizing upstream fermentation parameters to enhance the effectiveness of the distillation step. These findings are consistent with those reported by international study [52] who highlighted that high gravity (HG) fermentation not only increases final ethanol titers but also contributes to energy savings during distillation. Their study reported a maximum ethanol concentration of 113.3 g/L using *Saccharomyces cerevisiae* NP01 under HG conditions, which facilitated a more energy-efficient recovery process. However, they also cautioned against the use of very high gravity (VHG) fermentation, noting that excessively high sugar and ethanol concentrations can impose osmotic and product inhibition stresses on yeast cells, resulting in suboptimal fermentation performance. Consequently, HG fermentation was deemed more favorable for large-scale applications due to its balance between ethanol yield and energy efficiency during recovery.

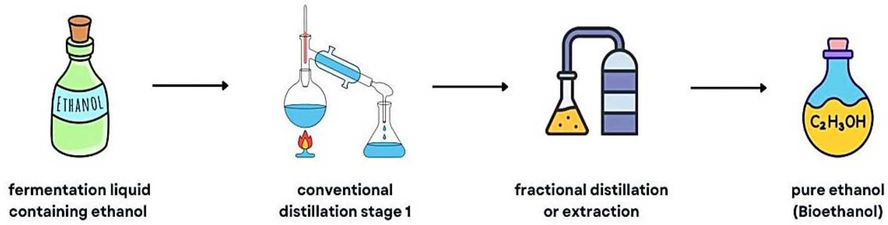

Figure 4. Distillation Process of Fermented Ethanol Mixture

Figure 4 depicts the distillation process used to separate ethanol from the fermentation broth, leveraging the difference in boiling points between ethanol and water. The schematic compares various distillation techniques—including conventional, fractional, and extractive methods—while emphasizing ethanol purity outcomes and associated energy demands. It also illustrates how initial ethanol concentration influences distillation performance, with advanced techniques shown to achieve ethanol purities exceeding 95%, thus affirming distillation as a pivotal downstream process in ensuring the viability of bioethanol as a renewable thermal energy source for dairy industry applications. The distillation results of the three initial ethanol levels show that the higher the concentration of fermented ethanol, the higher the purity that can be achieved after distillation. Ethanol from 15% fermentation generally produces ethanol with a final purity of about 30 - 40% after one stage of conventional distillation. Whereas ethanol from 18% and 20% fermentation can be distilled more efficiently and yield a purity of about 50-60% depending on the method and number of distillation stages used. However, to achieve higher purity levels (≥ 95%), advanced distillation techniques such as fractionated distillation or extractive distillation are required. Research by international study [53] shows that the use of extractive distillation can increase ethanol purity to 99.96%, with higher energy efficiency than conventional distillation. This is because the extractive method uses additional compounds to change the azeotrope point, so that the separation of ethanol from water becomes easier and does not require as much energy as repeated distillation. A relevant comparison can be drawn from a study international, which investigated a methane-assisted catalytic upgrading of vacuum residue. Although the focus was on hydrocarbon fractions rather than ethanol, the study offers a valuable benchmark for distillation performance. Their process significantly altered the distillation profile, with the naphtha fraction increasing from 0% to 24%, the medium distillate from 0% to 44%, and the heavy residue decreasing from 85% to 14%. These findings illustrate how catalytic innovations can enhance product separation and increase the yield of lighter, more valuable fractions.

Another comparison can be seen from a study by international study [54] who simulated distillation using ChemCAD. They showed that the pressure and temperature of the distillation column had a major effect on the purity level, where lower pressure and tightly controlled temperature allowed an increase in ethanol purity to 95% in just two stages of fractionated distillation. With the fermentation results in this study reaching initial ethanol levels of up to 20%, the opportunity to obtain high purity ethanol after distillation is very large, especially when supported by advanced distillation technology. This means that bioethanol production from soybean hull waste not only produces renewable energy, but also has the potential to provide high efficiency in the purification process. This is in line with the journal's focus on energy transformation in the dairy industry, where pure ethanol can be used as an alternative heat source in thermal processes such as pasteurization or sterilization. In other words, the use of appropriate distillation methods not only improves the quality of bioethanol, but also supports the goals of energy efficiency and environmental sustainability, especially when combined with feedstock sources derived from organic waste.

The transition from thermal to renewable energy in the soy milk industry significantly improves efficiency and operational effectiveness. The use of bioethanol from soybean hull waste as an energy source not only reduces dependence on fossil fuels but also optimizes production processes such as pasteurization and heating. A international study [41] shows that the utilization of biogas from organic waste can increase energy efficiency by up to 30%, while reducing greenhouse gas emissions. Additionally, integrating heat recovery systems and digital technologies like the Internet of Things (IoT) for real-time monitoring can reduce energy consumption by up to 20% [40], while improving process reliability and stability. The use of this technology demonstrates that energy transformation is not only an environmentally friendly approach but also an effective strategy for achieving overall process efficiency [6].

From an economic perspective, while the initial investment for technologies such as solar panels, efficient bioethanol distillation systems, and bioreactors is relatively high, long-term operational costs can be significantly reduced. This is due to reduced fossil fuel consumption and the utilization of soybean hull waste as a local and renewable energy source. Processes like extractive distillation can even produce bioethanol with a purity of up to 99.96%, enhancing economic energy value [35]. The continuous availability of raw materials and a technological approach that supports the principles of a circular economy make this system more sustainable. Such sustainable production approaches are not only environmentally friendly but also enhance industrial competitiveness through cost efficiency and waste reduction [17]. Thus, this energy transformation is highly worthy of widespread adoption as a strategic step toward a sustainable and competitive plant-based processing industry in the future.

Energy transformation in the dairy industry significantly reduces production costs and enhances waste management through the use of heat exchangers, which recover thermal energy for reuse in heating milk or process water [55]. With this system, previously wasted heat energy can now be reused for heating raw milk or process water, thereby reducing the need for additional fuel and lowering daily production costs. [56]. The use of renewable energy sources such as bioethanol from soybean hulls and biogas from organic waste reduces dependence on fossil fuels, which are subject to volatile prices and supply [57]. Although initial implementation of technologies such as hydrolysis, fermentation, and distillation systems requires significant investment, in the long term, the costs can be offset by sustainable energy efficiency. In fact, the industry also gains benefit economy addition through processing valuable waste sell, such as bioethanol, which was previously only become residue not useful [58].

From an environmental perspective, this energy transformation brings a significantly positive impact. Environmentally, these alternatives reduce emissions ofCO_2 and CH_4, contributing to climate change mitigation [59]. These emissions previously lots produced from burning material burn fossils used for heating and cooling in the milk production process. On the other hand, the conversion organic waste such as skin soybeans and residues results fermentation become source energy renewable show approach friendly harmonious environment with draft economy circular [60]. This approach not only reduces the amount of waste disposed into the environment, but also produces energy that can be reused in the production process [61].

Energy transformation in the dairy industry not only provides short-term benefits, but also serves as a key strategy to achieve overall industrial sustainability industry in a way overall one of the the purpose is for support national targets towards net zero emission by 2050 [62]. By integrating renewable energy sources such as solar power, bioethanol, and biogas, the industry actively contributes to the decarbonization of the food sector, a step increasingly demanded by global policies and international trade standards adoption [63]. In addition, the use of system energy independent, such as biodiesel and bioethanol for lighting and equipment control, help factory become more independent in a way energy and reduce network dependency electricity national which is still dominated by materials burn fossil [64]. No less important, The adoption of Internet of Things (IoT) and Al-based digital technologies enables a more adaptive, efficient, and transparent production process. The system this support taking decision data based in management energy, maintenance machines, and control quality in real-time [65]. These initiatives not only extend the lifespan of industrial equipment and reduce operational costs, but also improve process efficiency and have a positive environmental impact [66]. While the initial investment for an integrated bioethanol system (pretreatment, fermentation, distillation) is estimated at IDR 200–300 million for a small-scale unit, operational savings from reduced LPG and electricity use can recover the capital cost within 4–6 years. Moreover, byproducts such as fermentation slurry can be utilized as organic fertilizer, further enhancing the system's value. Compared to purchasing fossil-based LPG at IDR 12,000/kg, utilizing self-produced bioethanol from waste biomass can reduce thermal processing costs by 25–35% [50]

The novelty of this study lies in the integration of renewable energy production based on soybean hull waste with the application of digital systems such as the Internet of Things (IoT) for energy efficiency in the dairy industry. This approach has not been widely discussed in an integrated manner in the context of plant-based or animal-based milk processing [11][41]. Its practical contribution is evident in the potential application of this model at the small and medium-sized industry (SME) scale, particularly in regions with high availability of agro-industrial waste. With this strategy, industry players can reduce fossil fuel consumption by up to 30% and transform waste into a high-value economic energy source, while supporting the transition toward a circular economy and net-zero emissions [17][72].

Aplication

The main focus is on the utilization of heat recovery systems in thermal processes such as pasteurization. Rather than being discarded as waste, thermal energy is recaptured and reused to heat raw milk or other process streams, resulting in substantial reductions in primary energy consumption [67]. The implementation of high-efficiency heat exchangers and IoT-based energy management systems allows real-time control and optimization, significantly improving thermal efficiency and reducing energy consumption [68]. Digital technologies also play a significant role, particularly through the implementation of energy management systems equipped with real-time monitoring and sensor-based control [69]. These tools facilitate data-driven decision-making and continuous performance optimization, leading to improved energy use and operational reliability. Overall, this section provides strong evidence that energy transformation in the dairy industry can be effectively realized through a combination of technological, operational and strategic interventions. Beyond thermal energy optimization and digital monitoring systems, the integration of renewable energy sources plays a significant role in energy transformation in the dairy processing industry such as process efficiency. In addition to digital systems, biogas from anaerobic digestion of soybean hulls contributes to thermal energy and electricity supply, while solar panels supply part of the power demand for lighting and control, moving the facility toward energy self-sufficiency [70]. This approach not only reduces dependence on fossil fuels but also contributes to the mitigation of greenhouse gas emissions and more effective waste management [71]. In addition, a solar photovoltaic system has been installed to supply part of the operational electricity demand, particularly for lighting and control equipment. The combination of renewable energy integration and process efficiency measures enables the dairy facility to achieve more sustainable energy performance and move closer to energy self-sufficiency at the plant level [72].

This integrated approach also holds practical relevance for small and medium-sized dairy enterprises (SMEs), particularly in rural areas where soybean processing byproducts are abundant. By utilizing local biomass and simple digital monitoring, SMEs can reduce fossil energy use, lower emissions, and improve production efficiency. This aligns with circular economy principles and supports national sustainability efforts in energy and industry [17][50][64].

Conclusion

Energy transformation in the dairy industry, through renewable integration, heat recovery, and digital technologies, reduces greenhouse gas emissions, improves efficiency, and supports circular economy practices, creating a model that is scalable and applicable across industrial levels. Through the integration of renewable energy sources—such as solar power, bioethanol derived from soybean hulls, and biogas from organic waste—the dairy industry can significantly reduce its dependence on fossil fuels, lower greenhouse gas emissions, and transform waste into valuable resources. These approaches also align with global efforts to achieve net-zero emissions and adopt circular economy principles. Beyond technical benefits, such transformation has economic and operational implications. The use of heat recovery systems and IoT-based digital monitoring can improve thermal efficiency and reduce energy costs by up to 30%, especially in high-energy processes like pasteurization and sterilization. Although initial investments in infrastructure (e.g., fermentation reactors, solar panels, distillation units) may be high, long-term energy savings and value-added by-products can offset these costs and generate new revenue streams. Furthermore, the approaches presented in this study offer scalable, replicable models applicable to both large-scale dairy operations and SMEs, especially in developing countries with abundant agro-industrial waste. These findings suggest that energy transformation in the dairy industry can serve as a catalyst for broader industrial decarbonization, food security, and rural economic empowerment. Future research should focus on system integration, lifecycle assessments, and policy frameworks to support the mainstream adoption of these solutions at national and international levels.

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