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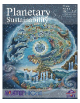

EXERGY-BASED SUSTAINABILITY ANALYSIS OF FOOD PRODUCTION SYSTEMS

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HIGHLIGHTS

- This review paper aims to investigate the potential of the exergy concept as a holistic and comprehensive approach to assessing the sustainability of food production systems.
- While exergy-based analyses have been conducted on certain food production plants, using exergoeconomic and exergoenvironmental analyses for these systems has been relatively limited.
- Future research efforts should be directed toward applying advanced exergy-based methods to analyze existing and emerging food production systems.

GRAPHICAL ABSTRACT

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ABSTRACT

As the global population continues to grow, the sustainability of food production systems is increasingly critical, coupled with escalating environmental concerns. Traditional sustainability assessments primarily focus on resource consumption and waste generation, often overlooking the overall efficiency and quality of energy and matter flows within these systems. This comprehensive review paper explores the potential of the exergy concept as a holistic and comprehensive approach to assessing the sustainability of food production systems. Exergy analysis offers valuable insights into the thermodynamic efficiency, resource utilization, and environmental impacts of these systems. By incorporating exergy principles into sustainability assessments, researchers and policymakers can better understand the strengths, weaknesses, and opportunities for improvement in food production systems. This paper highlights key studies and applications that have utilized the exergy concept, discussing its benefits and limitations.

It also examines the theoretical foundations of exergy and its integration into the analysis of food production systems. The potential of exergy-based analysis as a comprehensive and thermodynamically grounded methodology for evaluating the sustainability of food production systems is explored. The review addresses the advantages, challenges, and potential future directions of exergy-based analysis in the food industry, aiming to foster further research and development.

Nomenclature

C	Carbon percentage (%)
C_p	Specific heat capacity (kJ/kg K)
$\dot{E}$	Energy flow rate (kW)
ex	Specific exergy (kJ/kg)
$\dot{E}x$	Exergy flow rate (kW)
h	Specific enthalpy (kJ/kg)
H	Hydrogen percentage (%)
$\dot{IP}$	Exergetic improvement potential rate (kW)
$\dot{m}$	Mass flow rate (kg/s)
n	Mole number (-)
O	Oxygen percentage (%)
P	Pressure (kPa)
q_{LHV}	Lower heating value (kJ/kg)
$\dot{Q}$	Heat rate (kW)
R	Gas constant (kJ/kg K)
$\bar{R}$	Universal gas constant (kJ/mol K)
s	Specific entropy (kJ/kg K)
S	Sulfur percentage (%)
T	Temperature (°C or K)
x	Mole fraction (-)
$\dot{W}$	Work flow rate (kW)
Y	Mass fraction (%)

Greek Symbols	
φ	Chemical exergy factor (-)
η	Exergy efficiency (%)
ε	Standard chemical exergy (kJ/mol)

Subscript	
0	Reference (dead) state
ch	Chemical
$dest$	Destruction
in	Input
i	Numerator
ki	Kinetics
l	Loss
out	Output
ph	Physical
po	Potential
s	Source
w	Work

Introduction

The global population has experienced a significant increase over the past century. In mid-November 2022, it reached a staggering 8.0 billion, and projections indicate that it will continue to rise, with an estimated increase of nearly 2 billion people over the next 30 years (Zeifman *et al.,* 2022). With such substantial population growth, it is evident that the demand for food has also increased significantly. In addition, as economies have developed worldwide, people's purchasing power has risen, leading to a greater demand for food and a desire for diverse food options (Latham, 2000). However, there is a growing awareness worldwide that current food production and consumption patterns are far from sustainable and have substantial environmental impacts (Pimentel *et al.,* 1999).

Natural resources are crucial for agriculture, which provides people with essential sustenance. Various machinery, such as tractors, trolleys, and cultivators are employed in agricultural activities. In addition, industrial food production systems utilize agricultural commodities to transform them into a wide range of food products and ingredients. However, these processes heavily rely on fossil fuels such as petrol, natural gas, diesel, and fuel oil for energy. Fossil fuels are finite resources and are estimated to be depleted within the next 100–150 years. More importantly, burning fossil fuels releases emissions that contribute to global warming, greenhouse gas emissions, and climate change. Consequently, optimizing resource utilization has become a critical issue today (Ahamed *et al.,* 2011).

Numerous efforts have been made to enhance the sustainability of the food industry, leading to several positive developments. Various methodologies have been proposed for assessing and improving the sustainability of different processes and products. These include emergy analysis, life cycle assessment (LCA), and thermodynamic-based (energy and exergy analyses) methods. The availability of sustainability assessment methods is plentiful; however, the scientific community faces the challenge of establishing useful and operational criteria that connect resource consumption with the services generated effectively (Zisopoulos *et al.,* 2017).

The concept of "emergy" refers to the total quantity of environmental work, both direct and indirect, involved in the production of a product or service. This thermodynamic method aims to convert all the energy, material, and monetary flows associated with the production system into solar emjoules (sej), providing a comprehensive understanding of resource utilization (Aghbashlo *et al.,* 2021). However, the emergy approach has certain limitations, including uncertainties associated with transformity values and the need for allocation decisions (Aghbashlo & Rosen, 2019).

The LCA approach offers a suitable method for evaluating products regarding their environmental implications, human health, ecosystem quality, and global warming throughout their life cycle. LCA provides a broader perspective on production processes by analyzing material and energy consumption, waste streams, and pollutant emissions. Nevertheless, LCA, as an environmental impact assessment approach is not without drawbacks, as it can be subject to arbitrariness and uncertainties (Soltanian *et al.,* 2020).

The energy approach, with its emphasis on assessing the first-law efficiency of energy systems through the analysis of input, output, and generated energetic streams offers valuable insights into the energy flow within a system. It allows for the evaluation of energy conversion processes and their overall efficiency. However, one of its limitations is that it primarily focuses on the quantitative aspects of energy, neglecting the qualitative aspects of energy and material flows (Soltanian *et al.,* 2022). By solely considering the quantity of energy and materials involved, the energy approach overlooks important factors such as the potential for reuse, recyclability, and environmental impact associated with different energy and material sources. It fails to capture varying sustainability and resource efficiency across different energy systems.

Exergy-based analyses have become increasingly popular in assessing the efficiency, productivity, and sustainability of food production systems. By incorporating the principles of thermodynamics (i.e., first and second laws), the exergy method offers a powerful tool for analyzing and optimizing energy conversion processes. It is a powerful engineering tool, providing insights into the maximum potential of energy or material to generate useful work when in equilibrium with a reference environment. Exergy can be considered a measure of energy quality, representing the upper limit of useful work that can be extracted from an energy system. It recognizes that all energy and material transformations involve entropy generation and irreversible processes, leading to the dissipation of exergy or resources. Therefore, quantifying inefficiencies in terms of exergy destruction provides valuable insights into the economic losses and resource degradation within the studied system. By assessing exergy destruction, a deeper understanding of the link between inefficiencies, economic losses, and resource depletion can be gained. This knowledge enables researchers to identify areas for improvement and implement strategies to enhance the overall performance of food production systems. Exergy-based methods have gained international recognition for their effectiveness in evaluating and optimizing system efficiency, productivity, and sustainability. Figure 1 illustrates the direct impact of exergy destruction on economic loss and resource degradation within the system, as highlighted by Aghbashlo *et al.* (2022). It underscores the importance of considering exergy-based analyses in understanding and addressing the inefficiencies and associated consequences in food production systems.

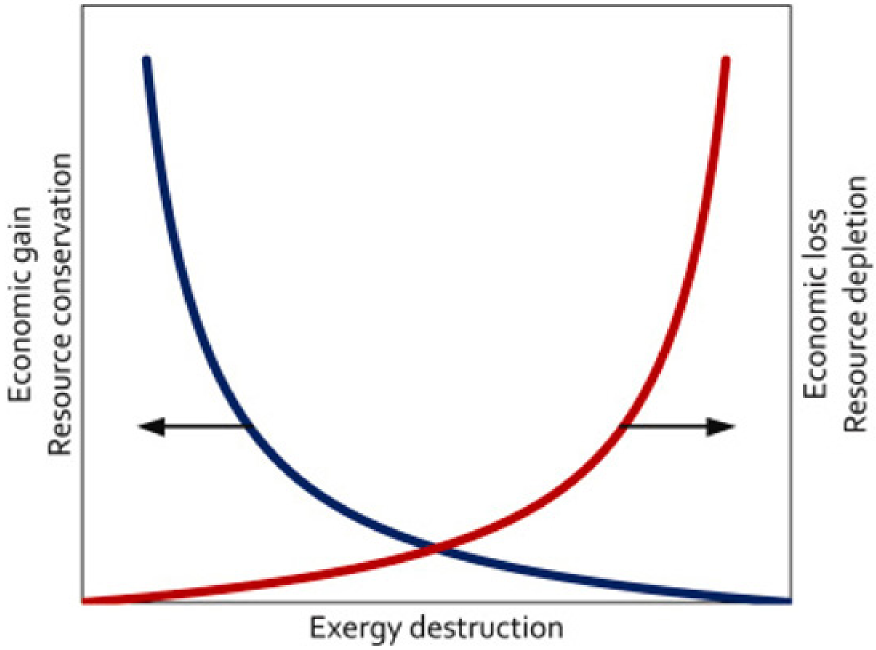

Figure 1: Representation of the relationship between exergy destruction and economic loss/resource depletion (Aghbashlo *et al.*, 2022)

The limited number of publications in the food industry related to exergy-based analyses highlights the need to identify pertinent research questions that can effectively integrate exergy with food science and technology. In light of this, this review aims to offer a comprehensive depiction of the principles of exergy, its theoretical formulations, and its food processing applications. It is crucial to acknowledge the limitations and drawbacks of exergy-based analyses in analyzing food production as it enables the identification of potential areas for future research. By exploring the intricacies of exergy, its practical implications, and its potential to foster sustainable food production, this review aims to make a valuable contribution to the ongoing endeavors toward enhancing the sustainability of the food industry. The understanding and implementation of exergy-based analyses have the potential to provide invaluable insights into optimizing the utilization of resources, improving energy efficiency, and mitigating environmental impacts in food production systems.

Exergy Analysis

Exergy Concept

The energy conservation concept applies to reversible and irreversible processes, ensuring that the total energy within a system remains constant. However, the concept of exergy considers the irreversibilities present in most practical processes. In contrast to energy, exergy is subject to destruction and cannot be kept constant during these processes. Exergy destruction occurs due to irreversibilities such as friction, heat transfer across a finite temperature difference, and chemical reactions with incomplete conversion. These irreversibilities lead to the generation of entropy, which is a measure of the system's disorder or degradation. The extent of exergy destroyed in an energy conversion process is directly proportional to the amount of entropy produced. Unlike reversible processes where exergy is conserved, irreversible processes experience exergy destruction due to the irreversibilities present. This distinction highlights the unique characteristics of exergy, which combines the principles of energy conservation and entropy non-conservation. The work of Rosen *et al.* (2008) emphasizes the significance of the exergy concept in understanding the interplay between energy conservation and entropy generation. By considering both aspects, the exergy concept provides a comprehensive framework for analyzing and evaluating the efficiency and effectiveness of energy conversion processes, considering the thermodynamic irreversibilities that occur in real-world systems.

Figure 2, adapted from the work of Aghbashlo *et al.* (2019) visually illustrates the relationship between energy, entropy, and exergy concepts in a steady-state condition. Based on the first law of thermodynamics, the total energy remains conserved between the input and output sections of a process. On the other hand, the second law of thermodynamics states that the total entropy of a system increases from the inlet to the outlet due to inherent irreversibilities within the system. This increase in entropy reflects the degradation or disorder of the system. Unlike energy and entropy, which are conserved quantities, exergy is subject to destruction. Irreversibilities within the system lead to the generation of entropy and the subsequent destruction of exergy. Consequently, the exergy quantity at the outlet section is lower than at the inlet section. This comparison highlights the limitations of energy analysis alone, as it does not capture the irreversibility features of energy systems. On the other hand, exergy analysis incorporates the concept of irreversibilities and provides valuable insights into the efficiency and effectiveness of processes. By accounting for the exergy destruction, exergy analysis can provide practical guidelines for process optimization and development, facilitating the identification of areas where energy losses occur, and suggesting potential strategies to mitigate them.

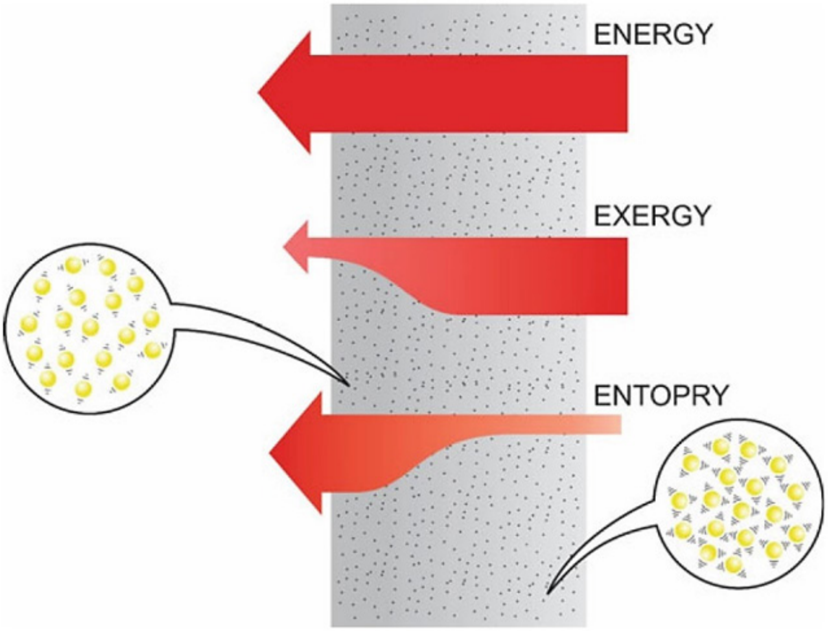

Figure 2: Comparing the principles of energy, entropy, and exergy in a steady-state heat transfer within a wall. Adapted from Shukuya and Hammache (2002). In this illustration, the temperature on the right-hand side is higher than on the left

Mass, Energy, and Exergy Balances for Food Production Systems

The mass balance for a steady-state food production process can be expressed as (Equation 1):

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (1)$$

where represents the mass flow rate within the system. The subscript 'in' indicates the inlet condition, while 'out' refers to the outlet condition.

The general energy balance can be expressed below as the total energy input equal to the total energy output (Equation 2):

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \qquad (2)$$

The exergy balance can be as (Equations 3 and 4):

$$\sum \dot{Ex}_{in} - \sum \dot{Ex}_{out} = \sum \dot{Ex}_{dest} \qquad (3)$$

$$\sum \dot{m}_{in} ex_{in} - \sum \dot{m}_{out} ex_{out} = \sum \dot{Ex}_{dest} \qquad (4)$$

where ex is the specific exergy and $\dot{Ex}_{dest}$ is the exergy destruction rate (irreversibility rate).

The total exergy rate of all streams within food production systems can be calculated by summing their physical, chemical, potential, and kinetic exergy rates. Mathematically, it can be expressed as (Equation 5):

$$\dot{Ex} = \dot{Ex}^{ph} + \dot{Ex}^{ch} + \dot{Ex}^{po} + \dot{Ex}^{ki} \qquad (5)$$

where subscripts $'ph'$, $'ch'$, $'po'$, and $'ki'$ stand for the physical, chemical, potential, and kinetic energies, respectively.

The kinetic and potential exergy values of all streams are often neglected due to their relatively small contributions compared to the other forms of exergy. Therefore, the focus is primarily on the physical and chemical exergies of the streams. The physical exergy of a stream can be determined using its thermodynamic properties, such as specific enthalpy and entropy. These properties can be found in literature and textbooks for most pure streams. By considering the thermodynamic state of the stream and its departure from a reference state, typically the environment, the physical exergy rate of a stream can be calculated. Mathematically, the physical exergy rate of a stream can be expressed as (Equation 6):

$$\dot{Ex}^{ph} = \dot{m}\big(h - h_0 - T_0(s - s_0)\big) \tag{6}$$

where T_0 represents the absolute temperature of the reference state. The variables $'h'$ and $'s'$ denote enthalpy and entropy, respectively. The subscript "0" signifies these properties at the reference state.

The physical exergy rates of mixed liquid and gas streams can be determined by considering the streams' composition and properties. In such cases, it is necessary to account for the individual components present in the mixture and their respective thermodynamic properties (Equations 7 and 8):

$$\dot{Ex}^{ph} = \dot{m}\left[C_p\left(T - T_0 - T_0 ln\left(\frac{T}{T_0}\right)\right)\right] \tag{7}$$

$$\dot{Ex}^{ph} = \dot{m}\left[C_p\left(T - T_0 - T_0 ln\left(\frac{T}{T_0}\right)\right) + RT_0 ln\left(\frac{P}{P_0}\right)\right] \tag{8}$$

where P represents the absolute pressure, P_0 denotes the absolute pressure of the reference state, and R is the gas constant. The specific heat capacity, C_p, can be determined using the following relationship (Equation 9).

$$C_p = \sum_i Y_i\, C_{p,i} \tag{9}$$

where Y_i and $C_{p,i}$ denote the mass fraction and specific heat capacity of the ith stream, respectively.

The calculation of the chemical exergy rate of streams can be as follows (Equation 10):

$$\dot{Ex}^{ch} = \dot{m}n\left(\sum_i x_i\varepsilon_i + \bar{R}T_0\sum_i x_i \ln{(x_i)}\right) \tag{10}$$

where x_i and ε_i represent the molar concentration and the chemical exergy (standard) of the ith stream, respectively. n is the specific mole number and $\bar{R}$ is the universal gas constant.

In addition, the chemical exergy rate of the fuel can be estimated as follows (Aghbashlo *et al.,* 2016) (Equation 11):

$$\dot{Ex}^{ch} = \dot{m}ex^{ch} = \dot{m}\varphi q_{LHV} \tag{11}$$

where q_{LHV} represents the lower heating value of the combustion fuel, and φ denotes the chemical exergy factor of the fuel (López *et al.,* 2014) (Equation 12):

$$\begin{aligned}\varphi = 1.0401 + 0.1728\left(\frac{H}{C}\right) + 0.0432\left(\frac{O}{C}\right)\\ +0.2169\left(\frac{S}{C}\right) \times \left(1 - 2.0268\left(\frac{H}{C}\right)\right)\end{aligned} \tag{12}$$

where H, C, O, and S are hydrogen, carbon, oxygen, and sulfur mass fractions, respectively. The lower heating value of the consumed fuels can be estimated as follows (Equation 13):

$$q_{LHV} = \sum_i Y_i\, q_{LHV,i} \tag{13}$$

where $q_{LHV,i}$ is the lower heating value of the ith stream.

The exergy rate of work equals its energy rate. This equivalence stems from the understanding that work is a form of energy, and the exergy of a stream represents its maximum available useful work potential. Hence, the exergy rate associated with work can be directly calculated using the energy rate associated with the work process (Equation 14).

$$\dot{Ex}_w = \dot{W} \tag{14}$$

where $\dot{W}$ denotes the work rate.

The rate of heat loss to the surroundings from a closed system can be calculated by conducting an energy balance on the system. Once the heat loss rate is determined, it can be converted into the corresponding exergy rate by taking into account the temperature difference between the system and its surroundings (Equation 15):

$$\dot{Ex}_l = \dot{Q}_l\left(1 - \frac{T_0}{T_s}\right) \qquad (15)$$

where $\dot{Q}_l$ and T_s represent the heat loss rate and source temperature, respectively.

The exergy efficiency (universal definition) of food production systems can be measured using the following formula (Equation 16):

$$\eta = \frac{\dot{Ex}_{out}}{\dot{Ex}_{in}} \times 100 = \left(1 - \frac{\dot{Ex}_{dest}}{\dot{Ex}_{in}}\right) \times 100 \qquad (16)$$

To analyze and assess the efficiency of a food production system, various additional exergetic performance parameters can be calculated. One such parameter is the exergetic improvement potential rate, which measures the potential for enhancing the system's exergetic performance. The exergetic improvement potential rate is calculated by comparing the actual exergy destruction rate of the system with the maximum achievable exergy destruction rate. Mathematically, it can be expressed as (Equation 17):

$$\dot{IP} = (1 - \eta)\left(\dot{Ex}_{in} - \dot{Ex}_{out}\right) \qquad (17)$$

Methodology for Exergy Analysis of Food Production Systems

For analyzing a food production process from the exergetic viewpoint, it is essential to establish a system boundary that defines the control mass or volume under consideration. Once the system boundary is defined, a comprehensive diagram illustrating the mass and energy flows within the process should be prepared. Labeling or numbering all incoming and outgoing mass and energy streams at the system boundaries is crucial. Figure 3 exemplifies a typical diagram used in food production systems, specifically showcasing a bactocatch-assisted pasteurization line employed in cheese production at a dairy plant. This diagram visually represents the various streams of mass and energy involved in the process, enabling a clear understanding of the inputs and outputs at different stages. By creating such a diagram and labeling the relevant flows, analysts can effectively assess the exergy characteristics of the food production process. This schematic facilitates the identification of areas with potential for improvement, optimization, and increased overall efficiency.

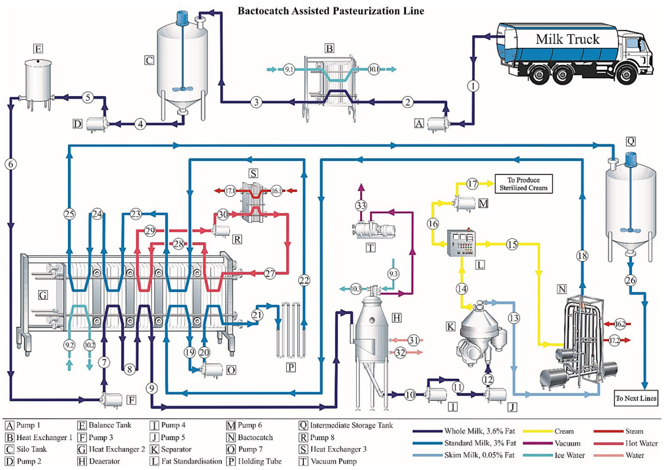

Figure 3: A schematic diagram of a bactocatch-assisted pasteurization line (Nasiri *et al.,* 2017). With permission from Springer Nature. Copyright © 2017

Once the schematic diagram of a food production system is developed, it serves as a foundation for establishing mass, energy, and exergy balances for the system under investigation. These equations are essential for understanding the mass, energy, and exergy flows occurring throughout the process. The chemical and physical exergy values of all mass and energy streams within the system can be determined by applying the mass, energy, and exergy balance equations. This calculation allows for a detailed assessment of the exergy content and quality of each stream, providing valuable insights into the energy potential and thermodynamic efficiency of the system. These parameters provide valuable insights into the efficiency, effectiveness, and sustainability of the food production process. The obtained results can be presented in numerical or graphical form, depending on the preference and requirements of the analysis. For example, Figure 4 illustrates a typical Grassmann diagram, a graphical representation used to visualize the exergetic performance of a red wine production process. Such diagrams can effectively communicate the exergy flows, losses, and efficiencies within the system, aiding in identifying areas for improvement and optimization.

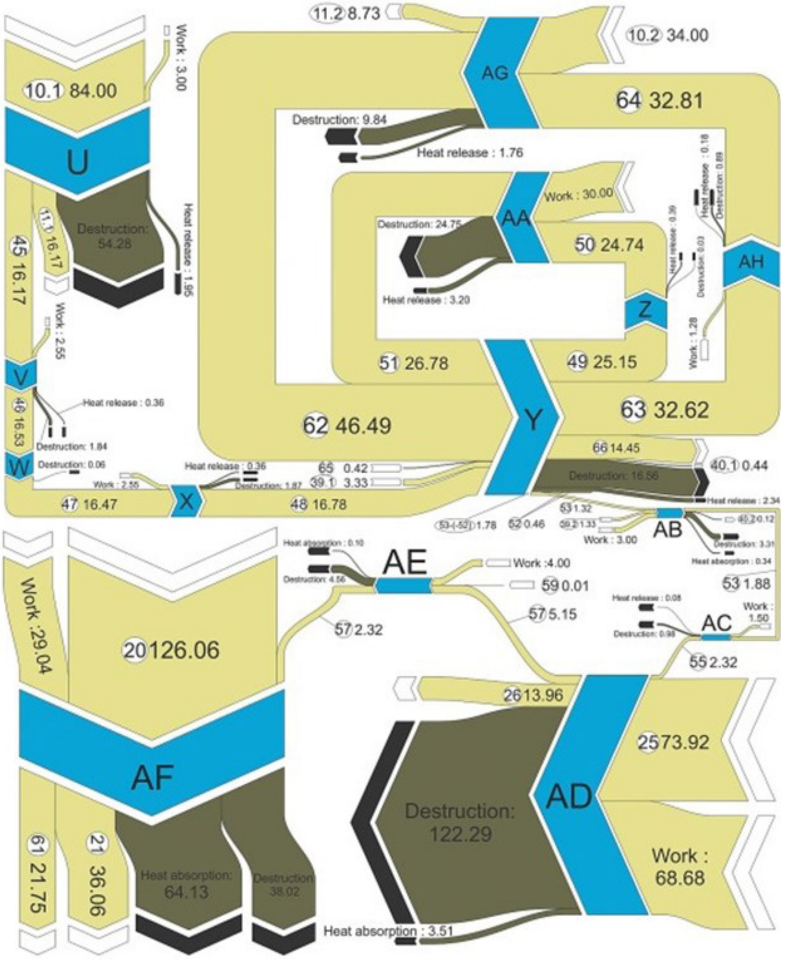

Figure 4: Exergy flow diagram of red wine production process (Dowlati *et al.,* 2017a). With permission from Elsevier. Copyright © 2017

Application of Exergy Analysis for Food Production Systems

Addressing the rising global population's increasing demand for food production necessitates a sustainable approach considering thermodynamic, economic, and environmental factors. While energy analysis has traditionally been used to address these challenges, it has limitations in providing a comprehensive understanding of the sustainability of food processing systems. This issue is due to the inability of energy-based indices to accurately quantify the irreversibilities inherent in energy conversion processes. In recent years, there has been a notable shift towards applying exergy-based approaches to understand better and make informed decisions regarding the sustainability of food processing systems. This shift is driven by the recognition of the importance of both energy and environmental issues. Table 1 summarizes key applications where exergy-based methods have been applied to analyzing and optimizing food processing systems, highlighting the significance of these approaches. By utilizing the principles of exergy analysis, researchers and stakeholders aim to improve the efficiency and environmental performance of food production processes.

In a study by Waheed *et al.* (2008), an energy and exergy analysis was performed on the orange juice manufacturing industry in western Nigeria. The findings revealed that the pasteurizer was the major source of exergy loss, exhibiting an inefficiency of over 90%. This inefficiency primarily stemmed from using steam to heat the process stream. Similarly, Şahin *et al.* (2010) investigated the exergy and energy efficiencies of sugar production processes in the Kayseri sugar plant in Turkey. Their analysis identified the fourth step of production, specifically sugar crystallization, as having the lowest exergy efficiency, measuring at 40.0%. Fadare *et al.* (2010) conducted energy and exergy analyses on malt drink production in Nigeria. Among the four main operation units studied, it was found that the packaging house accounted for the majority of exergy inefficiency, with a loss of 92.16%. The brew house followed with a contribution of 7.17% to the total exergy loss while the silo house, and filter room had negligible losses of less than 1%. These studies highlight the significance of energy and exergy analyses in identifying inefficiency and providing valuable insights for optimizing industrial processes in the orange juice, sugar, and malt drink production industries.

In a study conducted by Sogut *et al.* (2010), the exergetic and energetic performance of a quadruple-effect evaporator unit in tomato paste production was evaluated. The results showed that the highest exergy destruction occurred in the first effect, amounting to 158.2 kW. Bapat *et al.* (2013) investigated the impact of heat recovery devices on quintuple-effect evaporation in Indian sugar industries. Their findings indicated that using heat recovery devices resulted in an average exergy efficiency of approximately 16.18% higher compared to quintuple effect evaporation without heat recovery. Alta and Ertekin (2015) analyzed the energy utilization and exergy losses in the production unit operations of frozen cherry in Antalya, Turkey. Notably, the energy efficiency of the entire system was determined to be 65.74% while the exergy efficiency was found to be 8.95%.

Jokandan *et al.* (2015) conducted a comprehensive exergy analysis on a pasteurized yogurt production plant in Iran. Their study determined that the specific exergy consumption of the pasteurized yogurt was 841.34 kJ/kg, employing the mass allocation concept. Mojarab Soufiyan *et al.* (2016) conducted a detailed exergy analysis of a commercial tomato paste plant with a double-effect evaporator in Tehran, Iran. The study found that the boiler combination was responsible for over 82% of the total destroyed exergy in the plant, making it the primary component contributing to exergy waste. Moreover, the universal exergy efficiency of the first-effect and second-effect evaporative units was determined to be 65.33%, and 56.60%, respectively. In a study by Garg *et al.* (2016), an exergy and energy approach was applied to analyze a sugarcane juice production and clarification unit in India. The findings revealed that the exergy and energy efficiencies of the raw juice production stage were 59.27%, and 83.05%, respectively. The juice clarification stage also exhibited exergy and energy efficiencies of 71.23%, and 80.65%, respectively.

Nasiri *et al.* (2017) conducted a study on an industrial-scale ultrafiltrated cheese production plant in the northwest region of Iran. Based on actual operational data, their analysis revealed that the specific exergy destruction of ultrafiltrated cheese production amounted to 2330.42 kJ/kg. The study further highlighted that the steam generation system contributed the most to the overall thermodynamic inefficiency, accounting for 57.40% of the specific exergy destruction. Genc *et al.* (2017) focused on analyzing the exergy of a red wine production line. Their research reported an overall system exergy efficiency of 41.8%. Additionally, the total exergy destruction rate of the system was determined to be 344.08 kW. In another study by Mojarab Soufiyan *et al.* (2017), an exergy analysis was performed on a long-life milk processing plant. The research indicated that the steam generation system exhibited significant exergy destruction, with an inefficiency of 60.70%. Furthermore, the specific exergy destruction of the long-life milk processing was determined to be 345.50 kJ/kg.

In their study, Dowlati *et al.* (2017b) carried out a thorough exergetic performance analysis of an ice cream manufacturing plant. Their findings indicated that the water steam generator, refrigeration system, and ice cream production line exhibited functional exergetic efficiencies of 17.45%, 25.52%, and 5.71%, respectively. These results shed light on the areas of exergy loss and inefficiency within the various components of the plant, providing valuable insights for potential improvements and optimization. In the exergy analysis of a yogurt drink production plant by Mojarab Soufiyan and Aghbashlo (2017), the specific exergy destruction of the pasteurized yogurt drink was determined to be 442 kJ/kg using the mass allocation method. This analysis provides insights into the exergy losses occurring during the production of yogurt drinks, allowing for targeted improvements to enhance efficiency. Singh *et al.* (2019a) applied exergy analysis to a cream pasteurization plant in India. They determined the exergy efficiency of the whole plant to be 66.11%.

Singh *et al.* (2019b) conducted an exergy analysis of a ghee production plant in the dairy industry. They reported the universal exergy efficiency for the entire plant as 34.21%, indicating the overall effectiveness of exergy utilization. In a similar study by Singh *et al.* (2019c), energy and exergy analyses were conducted for an ultra-high-temperature milk pasteurization plant in northern India. The overall energy efficiency of the plant was determined to be 86.36%, highlighting its performance in terms of energy utilization. The total specific exergy destruction, representing exergy losses was 219.23 kJ/kg. Başaran *et al.* (2020) performed energy and exergy analyses to compare different heating methods for producing strawberry jam in a vacuum-jacketed agitated vessel. They found that the inductive batch system exhibited the highest exergy efficiency at 32.67%, followed by the water-heated system, and the heat transfer fluid-heated system with 6.51%, and 6.13%, respectively. This comparison highlights the impact of heating methods on exergy utilization and provides insights into the most efficient option for strawberry jam production.

Singh *et al.* (2020) conducted an energetic and exergetic analysis of a comprehensive dairy food processing plant. The plant exhibited high energy and exergy efficiencies, with 92.72%, and 82.13%, respectively. Among the different processing units, the skim milk pasteurization unit achieved the highest exergy efficiency at 88.32%, indicating its effective utilization of exergy resources. Sheikhshoaei *et al.* (2020) performed an exergy analysis of a pistachio roasting system. The study revealed that the roasting unit contributed 19.6% of the total exergy destruction while the drying unit accounted for 80.4% of the exergy losses. Khorasanizadeh *et* *al.* (2021) conducted a comprehensive exergetic assessment of an industrial-scale orange juice production plant. The overall exergy destruction rate in the entire plant was determined to be 17.7 MW. The steam generation unit was identified as the main contributor, responsible for 76.2% of the total exergy destruction. In contrast, the mixing and pasteurization units exhibited the lowest overall exergy destruction at 1.5%. This analysis highlights the significance of specific plant components in terms of exergy losses, aiding in identifying areas for potential optimization.

In their study, Uçal *et al.* (2023) conducted an assessment of whole milk powder manufacturing using a cumulative exergy consumption approach that covered both the dairy farm stage for raw milk production and the dairy factory stage for milk powder production. The results highlighted the significance of the raw milk production stage as the primary contributor to energy and exergy consumption as well as carbon dioxide emissions. Specifically, 68.3% of the total net cumulative exergy consumption in the system was attributed to this stage. This finding underscores the importance of considering upstream processes such as raw material production, when conducting comprehensive energy and exergy analyses of food production systems. Abuelnuor *et al.* (2023) conducted energy and exergy analyses of a sugar production plant in Sudan, focusing on four main operation units: Boiler, turbine, mills, and sugar-distributed heating system. The results indicated that the boiler unit exhibited the highest exergy destruction and the lowest energy efficiency among all the units, accounting for 81.39% of the total exergy destruction, and a system-wide energy efficiency of 43.63%. This finding highlights the significance of the boiler unit in terms of exergy losses and energy inefficiencies within the sugar production process.

Table 1: The use of exergy analysis for investigating and optimizing food production systems

Product	**Objective**	**Main Operation Units**	**Remarks**	**Reference**
Orange juice	Measuring energy consumption pattern and exergy destruction in a fruit juice processing industry in Western Nigeria.	Sorting, cleaning, grating, crusher, screw finisher, centrifuge and holding tank, pasteurizer, packaging.	The pasteurizer exhibited the highest exergy inefficiency, accounting for over 90% of the total losses. The packaging stage contributed to approximately 6.60% of the overall exergy inefficiency.	(Waheed *et al.,* 2008)
Sugar	Energy and exergy analyses of the Kayseri sugar plant in Turkey.	Raw juice production, juice clarification, juice concentration, sugar crystallization.	The highest exergy efficiency values were obtained: 74.3% for the juice concentration process, 71.1% for juice clarification, 49.7% for raw juice production, and 40.0% for sugar crystallization.	(Şahin *et al.,* 2010)

Malt drink	Determining the exergy inefficiency and energy consumption pattern in a Nigerian brewery.	Silo house, brew house, filter room, packaging house.	The exergy loss in the operation units was distributed as follows: Silo house (0.27%), brew house (7.17%), filter room (0.39%), and packaging house (92.16%). Among them, the packaging house had the highest exergy loss, with the pasteurizer accounting for 59.75% of the overall system inefficiency.	(Fadare *et al.,* 2010
Tomato paste	Energy and exergy analyses of a quadruple-effect evaporator unit.	Washing, pre-heating, pulp cleaning, evaporating, pasteurizing, packaging.	The first effect experienced the highest exergy destruction with a magnitude of 158.2 kW, which accounted for 52.7% of the exergy input into the first effect. On the other hand, the third effect demonstrated the highest exergy efficiency, reaching an impressive value of 93.3%.	(Sogut *et al.,* 2010)

Sugar	Comparing the performance of two different quintuple-effect evaporation units using exergy analysis in Indian sugar industries.	Case A is a quintuple-effect evaporation unit without heat recovery devices while case B uses heat recovery devices.	In case A, the average exergy efficiency was recorded at 70.53%. Among the components, the second effect exhibited the highest exergy destruction, reaching a magnitude of 1562.20 kW. On the other hand, case B demonstrated a higher average exergy efficiency of 86.71%. In this instance, it was the first effect that experienced the greatest exergy destruction, with a value of 1871.68 kW.	(Bapat *et al.,* 2013)
Frozen cherry	Measuring the energy and exergy consumption patterns of the frozen fruit and vegetable manufacturer in Antalya, Turkey.	Pre-washing, stemming, pitting, individually quick frozen.	The system exhibited energy and exergy efficiencies of 65.74% and 8.95%, respectively. Among the different processes analyzed, the exergy analysis revealed that the individually quick frozen unit contributed to the highest exergy destruction, accounting for over 90% of the total. The pitting process followed with a smaller contribution of 3.38% to the overall exergy destruction.	(Alta & Ertekin, 2015)

Yogurt	Using the exergy concept to analyze a pasteurized yogurt production plant in Iran.	Boiler, refrigeration, milk standardization/ pasteurization, yogurt production.	The specific exergy consumption of pasteurized yogurt was measured at 841.34 kJ/kg. The analysis showed that steam generation accounted for the largest portion of the specific exergy consumption, contributing 82.62%. The above-zero refrigeration, milk standardization/ pasteurization, and yogurt production lines followed with contributions of 9.36%, 2.80%, and 5.21%, respectively.	(Jokandan *et al.,* 2015)
Tomato paste	Using the exergy concept to investigate a tomato paste plant with a double-effect evaporator in Tehran, Iran.	Steam generator, tomato paste production line.	The analysis uncovered that a significant portion, accounting for over 82% of the total exergy destruction in the plant, took place in the boiler combination, particularly within the steam generator unit. Moreover, the universal exergy efficiency of the first-effect evaporative unit was calculated to be 65.33% while for the second-effect evaporative unit, it was determined to be 56.60%.	(Mojarab Soufiyan *et al.,* 2016)

Sugar	Exergy and energy analyses of a sugarcane juice production and clarification unit in India.	Raw juice production, juice clarification, juice thickening, sugar crystallization.	The exergy efficiency of the raw juice production stage was determined to be 59.27% while the energy efficiency for this stage was found to be 83.05%. In the juice clarification stage, the exergy efficiency was calculated to be 71.23%, and the corresponding energy efficiency was found to be 80.65%.	(Garg *et al.,* 2016)
Cheese	Using the exergy concept to study an ultrafiltrated cheese production plant in northwest Iran.	Boiler, refrigeration, Bactocatch-assisted pasteurization, ultrafiltrated cheese production.	The specific exergy destruction of the ultrafiltrated cheese production process was quantified at 2330.42 kJ/kg. It was determined within the components comprising the production system that the steam generation system played a significant role in thermodynamic inefficiency, contributing to 57.40% of the specific exergy destruction.	(Nasiri *et al.,* 2017)

Red wine	Using the exergy concept to investigate a red wine production line.	Mechanical harvesting, vatting, draining, final fermentation.	The overall system demonstrated an exergy efficiency of 41.8%. Additionally, the total exergy destruction rate within the system was measured to be 344.08 kW.	(Genc *et al.,* 2017)
Milk	Exergy analysis of a long-life milk processing plant in Iran.	Boiler, refrigeration, milk reception, pasteurization, and standardization line, ultra-high-temperature milk processing.	The steam generation system was found to be the primary contributor to the specific exergy destruction in long-life milk processing, accounting for 60.70% of the total. The specific exergy destruction for the long-life milk processing was calculated to be 345.50 kJ/kg.	(Mojarab Soufiyan *et al.,* 2017)
Ice cream	Using the exergy concept to analyze an ice cream manufacturing plant located in Tehran, Iran.	Boiler, refrigeration, ice cream production.	The functional exergetic efficiency values for the water steam generator, refrigeration system, and ice cream production line were computed as 17.45%, 25.52%, and 5.71%, respectively. Consequently, the overall functional exergetic efficiency of the process was determined to be 2.15%. The specific exergy destruction was also calculated to be 719.80 kJ/kg.	(Dowlati *et al.,* 2017b)

Yogurt drink	Application of exergy analysis to a yogurt drink production plant.	Steam generation, above-zero refrigeration, milk reception, pasteurization, and standardization line, yogurt drink production line.	Using the mass allocation method, the specific exergy destruction of the pasteurized yogurt drink was determined to be 442 kJ/kg.	(Mojarab Soufiyan & Aghbashlo, 2017)
Cream	Exergy analysis of a cream pasteurization plant in India.	Regeneration, heating, cooling, chilling.	The exergy efficiency of the cream pasteurization plant was determined to be 66.11%. The cumulative value of exergy destruction in the plant was estimated to be 11.39 kW.	(Singh *et al.,* 2019a)
Ghee	Using the exergy concept to investigate a ghee production plant in India.	Butter churner, butter melter, ghee boiler, ghee clarifier.	The plant demonstrated a universal exergy efficiency of 34.21%, and a specific exergy destruction value of 438.61 kJ/kg. It is worth noting that the ghee boiler, which is involved in ghee production, accounted for 39% of the total cost rate of exergy destruction.	(Singh *et al.,* 2019b)

Milk	Energy and exergy analyses of ultra-high-temperature milk pasteurization plant located in the northern part of India.	Centrifugal pump, balance tank, centrifugal pump, regeneration unit, homogenizer, regeneration unit, heating coil, chiller.	The ultra-high-temperature milk pasteurization plant achieved an overall energy efficiency of 86.36%, indicating high energy utilization. Furthermore, the total specific exergy destruction in the plant was determined to be 219.23 kJ/kg.	(Singh *et al.,* 2019c)
Strawberry jam	Comparing induction-assisted batch processing and conventional production using energy and exergy analyses.	Vacuum-jacketed agitated vessel with (1) water, (2) heating oil (heat transfer fluid) or (3) inductive heater.	The inductive batch system showcased the highest energy and exergy efficiencies among the assessed heating systems. It achieved an exceptional energy efficiency of 95.00%, and an exergy efficiency of 32.67%. Comparatively, the water-heated system with an electric heater achieved an energy efficiency of 82.27%, and an exergy efficiency of 6.51%. Similarly, the heat transfer fluid-heated system demonstrated an energy efficiency of 92.38%, and an exergy efficiency of 6.13%.	(Başaran *et al.,* 2020)

Skim milk, whole milk, cream, and ghee	Energy and exergy analyses of dairy food processing plant.	Skim pasteurization unit, whole milk pasteurization unit, cream pasteurization unit, ghee production unit.	The milk processing plant achieved impressive overall energy and exergy efficiencies of 92.72%, and 82.13%, respectively. Among the individual units within the plant, the skim milk pasteurization unit demonstrated the highest exergy efficiency of 88.32%. It was followed by the whole milk pasteurization unit with an exergy efficiency of 81.50%. The cream pasteurization unit achieved a slightly lower exergy efficiency of 52.28% while the ghee production unit had the lowest exergy efficiency at 37.73%.	(Singh *et al.,* 2020)
Pistachio	Exergy analysis of a pistachio roasting system located in Kerman, Iran.	Roasting, drying.	For 1 kg of unshelled pistachio, the roasting and drying units contributed 20.3%, and 79.7% to the exergy utilization, respectively. In contrast, their contributions to the exergy destruction were calculated as 19.6%, and 80.4%, respectively.	(Sheikhshoaei *et al.,* 2020)

Orange juice	A detailed exergetic assessment of an industrial-scale fruit juice production plant.	Steam generation, above-zero refrigeration, mixing, pasteurization.	The total exergy destruction rate in the entire plant was measured at 17.7 MW. The steam generation process accounted for most of this destruction, representing 76.2% of the overall exergy losses. In contrast, the mixing and pasteurization lines had the lowest exergy destruction, contributing only 1.5% to the overall inefficiency of the plant.	(Khorasanizadeh *et al.,* 2021)

Whole milk powder	A cumulative exergy consumption approach for evaluating whole milk powder production from the farm to the dairy factory.	Raw milk production (dairy farm stage), powder production (dairy factory stage).	The study’s findings indicated that raw milk production was responsible for 68.3% of the total net cumulative exergy consumption in the system. Among the processes within the dairy factory, spray drying exhibited the highest energy and exergy consumption, followed by evaporation and pasteurization. These three processes collectively contributed to 98.3% of the total energy consumption, 94.6% of the total exergy consumption, and 95.7% of the total carbon dioxide emissions in powder production.	(Uçal *et al.,* 2023)

Sugar	Energy and exergy analyses of a sugar production plant in Sudan.	Boiler, turbine, mill, sugar distributed heating system.	Within the sugar production plant analyzed, the boiler was identified as the unit with the highest exergy destruction, accounting for 81.39% of the total system inefficiency. It also exhibited the lowest energy efficiency of the entire system (43.63%). The boiler was the primary contributor to irreversibilities, with an exergy destruction of 34.393 MW, significantly higher than the 2.857 MW exergy destruction observed in the mills.	(Abuelnuor *et al.,* 2023)

Conclusion

Exergy analysis is valuable in examining and optimizing food production systems by identifying thermodynamic inefficiencies and irreversibilities. The increasing concern for energy consumption and environmental impact has led to a growing interest in utilizing exergy analysis in these systems. Furthermore, the utilization of exergy methodologies presents an opportunity to merge thermodynamic performance with economic and environmental considerations, leading to more holistic approaches such as exergoeconomic and exergoenvironmental analyses. These approaches facilitate decision-making processes prioritizing productivity and sustainability within food production systems. The exergy approach, along with its extensions, is expected to serve as a powerful tool for designing resource-efficient, cost-effective, and environmentally friendly food production processes. Although exergy-based analyses have been applied to certain food production plants, the implementation of exergoeconomic and exergoenvironmental analyses in these systems has been somewhat limited. Future research should employ advanced exergy-based methods concurrently to enhance the thermodynamic, economic, and environmental performance of existing and new food production systems.

To evaluate the overall consumption of natural resources across various food production pathways, it is recommended to adopt a farm-to-fork strategy that combines exergy analysis with life cycle assessment. This comprehensive evaluation framework, known as exergetic life cycle assessment allows for a holistic assessment. In such studies, non-energetic or non-physical externalities must be quantified and incorporated into the analysis using the extended exergy accounting concept, allowing for a comprehensive assessment of the system's sustainability. Furthermore, using renewable energy resources is encouraged to meet some or all of the energy requirements in food processing. By valorizing the waste generated in food production systems into valuable chemicals and fuels, it is possible to enhance their overall exergoeconomic and exergoenvironmental performances further.

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