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# Emergy and Energy in Agricultural Production Systems: Conceptual Basis

## *Emergía y Energía en Sistemas de Producción Agropecuarios: Bases Conceptuales*

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**ABSTRACT:** Thermodynamics is crucial for understanding and optimizing agricultural and livestock processes, especially in resource use like solar energy, water, and nutrients. The concepts of emergy and exergy are fundamental for assessing energy efficiency and sustainability. Emergy measures the energy of one type used to generate another energy flow, tracking the system's energy "memory." Exergy quantifies the maximum obtainable useful work, reflecting energy quality. Emergy is an ecological-thermodynamic methodology that environmentally values energy, mass, and money flows, quantifying renewable, non-renewable, and market-derived resources. It allows visualizing and calculating flows, determining indices, and facilitating an integrated balance of economy, society, and the environment. Given the increasing demand for livestock products, quantifying energy in quantity, quality, and origin is vital for improving sustainability. This article reviews the theory and application of emergy and exergy in the agricultural sector, analyzing case studies that demonstrate their potential to evaluate and improve energy efficiency and sustainability.
**Keywords:** Thermodynamics, Solar Energy, Energy Eficiency, Sustainability.

**RESUMEN:** La termodinámica es crucial para entender y optimizar los procesos agropecuarios, especialmente en el uso de recursos como energía solar, agua y nutrientes. Los conceptos de emergía y exergía son fundamentales para evaluar la eficiencia energética y la sostenibilidad. La emergía mide la energía de un tipo utilizada para generar otro flujo energético, rastreando la "memoria" energética del sistema. La exergía cuantifica el trabajo útil máximo obtenible, reflejando la calidad de la energía. La emergía es una metodología ecológico-termodinámica que valora ambientalmente los flujos de energía, masa y dinero, cuantificando recursos renovables, no renovables y derivados del mercado. Permite visualizar y calcular flujos, determinando índices y facilitando un balance integral de economía, sociedad y medioambiente. Ante la creciente demanda de productos pecuarios, la cuantificación de la energía, en cantidad, calidad y origen, es vital para mejorar la sostenibilidad. Este artículo revisa la teoría y aplicación de la emergía y la exergía en el sector agropecuario, analizando estudios de caso que demuestran su potencial para evaluar y mejorar la eficiencia energética y la sostenibilidad.
**Palabras clave:** termodinámica, energía solar, eficiencia energética, sostenibilidad.

## INTRODUCTION

### Thermodynamics, Energy Balance, and Emergy in Agricultural Production

The energy balance in agricultural systems is defined as the analysis of energy flows and transformations within a bounded biological system (Yepes & Martínez, 2005). This text outlines the conceptual foundations of emergy and exergy in agricultural production systems. In agricultural contexts, this balance is primarily expressed through the process of photosynthesis, wherein incoming solar radiation is converted into chemical energy by autotrophic organisms (De Jesús et al. 2016). The efficiency of this conversion, denoted as η photosynthesis, is influenced by thermodynamic variables such as temperature (T) and water availability (Ψw) and optimizing these factors is critical for maximizing biomass production.

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In livestock production, the energy balance involves evaluating the conversion of chemical energy contained in ingested feed into various forms of energy, including heat (Q), bodily work (W), and chemical energy stored in products such as meat, milk, eggs, and biomass. The metabolic efficiency (η metabolic) of this process is influenced by factors such as the nutritional quality of the feed and environmental conditions. Thermodynamic studies in livestock systems aim to optimize the rate at which feed energy is converted into valuable products while minimizing energy losses associated with metabolic processes.

The concept of emergy (Em), introduced by Odum (2007), expands conventional thermodynamic analysis by incorporating the equivalent solar energy required both directly and indirectly to generate a flow or product (Brown & Ulgiati, 2013). Emergy quantifies the total energy invested (E_total) in production processes, encompassing both ecosystem-derived energy and energy associated with anthropogenic inputs. This approach offers a holistic perspective on sustainability (S), enabling the assessment of the embodied energy impact in the production of food and animal-derived products. Emergy thus emerges as a critical tool for evaluating the overall efficiency (η_global) of agricultural systems, considering both internal energy flows and the energetic contribution of external resources (Balanta & Nazarit, 2024).

The application of the concepts of emergy (Em) and exergy (Ex) Wall (2011) in animal production systems facilitates:

- Sustainability assessment: Emergy reveals a system's dependence on renewable (E_ren) and non-renewable (E_non-ren) resources, while exergy quantifies the efficiency in utilizing high-quality energy. Contemporary research Zhang *et al.* (2017); Zhan *et al.* (2018); Zhao *et al.* (2018), highlights a clear shift toward sustainable development, significantly driven by emergy evaluation through specific models and indicators. This approach supports ecological accounting grounded in the life cycle of wealth, and the resulting theoretical contributions demonstrate the value of emergy as a valuation method in both eco-accounting and biophysical accounting processes. Ultimately, this fosters ecological sustainability by enabling a comprehensive understanding of the phenomena and elements that constitute natural wealth-an essential factor for development that harmonize economic growth with environmental preservation.
- Identification of critical points: Emergy and exergy analysis can pinpoint stages in the production process with the highest resource demand and energy loss, enabling the implementation of optimization strategies.
- System comparison: Quantifying energy in terms of emergy and exergy allows for the comparison of different agricultural production systems based on their efficiency (η) and sustainability (S).
- Resource use optimization: Understanding the quality and origin of energy supports the design of strategies for more efficient resource utilization, thereby minimizing environmental impact (I).

This article focuses on the analysis of emergy application in agricultural production systems, emphasizing its relevance for assessing sustainability, optimizing resource use, and analyzing case studies aimed at achieving more efficient and resilient management of productive systems.

## DEVELOPMENT OF THE TOPIC

### Theoretical Foundations

This review article is based on a comprehensive documentary research methodology. The search strategy focused on identifying and selecting relevant academic literature from specialized sources. Key terms such as "emergy," "exergy," "agricultural systems," "agriculture," "livestock," "energy efficiency," and "sustainability" were used to gather studies, books, and scholarly articles addressing the conceptual foundations of both methodologies and their application in the agricultural context.

The literature selection was carried out through a review of titles, abstracts, and, when necessary, full texts, prioritizing works that clearly defined the principles of emergy and exergy, and that discussed their conceptual or theoretical application in agricultural and livestock production systems.

A key reference is the study by Martinez & Calderón (2024), who identified a "tree of research trends" in energy analysis. This study outlines the construction of a science tree aimed at understanding the evolution of terms and key authors involved in energy valuation methods with biophysical accounting implications. The tree is based on citation analysis, word co-occurrence, co-citation, and bibliographic coupling. The roots represent the most influential authors, the trunk reflects the main orientations of the field, and the leaves indicate the most recent research lines. The information search for this analysis was conducted in 2022 using Boolean formulas across two academic databases, with results detailed in the original document.

The synthesis of the information was achieved through the extraction and organization of key concepts, fundamental definitions, units of measurement, and the ways in which both methodologies are understood and applied to assess efficiency and sustainability in the agricultural sector. The aim was to identify the similarities, differences, and complementarities of emergy and exergy as conceptual analytical tools in this domain.

This synthesis is presented in a logical structure, beginning with the conceptual foundations of each methodology independently, followed by their specific application to agroecosystems.

Energy is a physical entity that naturally exists in various forms and, together with matter, constitutes the basis of all phenomena occurring in the universe. It is the capacity of a body to perform work, induce change, or bring about transformation. Agricultural production, as a complex system, involves a series of energy transformations from primary sources (sunlight) to final products (meat, milk, eggs, biomass).

Thermodynamics, the science that studies heat, work, and the relationship between them, provides a conceptual framework for analyzing these processes. However, to evaluate the sustainability and efficiency of such systems, it is necessary to go beyond basic energy accounting and consider the quality of the energy being utilized.

Energy is available to agroecosystems from two main sources: ecological and cultural. Ecological energy originates from the sun and other natural resources and participates in the production of chemical energy via photosynthesis. Cultural energy, on the other hand, is supplied by humans to optimize biomass production within agroecosystems. Cultural energy sources are divided into biological (of animal or human origin animal or human labor, manure, or biomass energy) and industrial (electricity, gasoline, petroleum, natural gas, fertilizers, machinery, etc.) (Guadiana *et al.*, 2021).

Energy balances, as accounting systems of energy inflows and outflows in food production processes, form the foundation for decision-making regarding the environmental viability of energy investments and the economic profitability of agricultural systems. As a cost estimation methodology, energy balances have been used since the 1970s and have become widespread in developed countries, especially in Europe (Yepes & Martínez, 2005).

Energy analysis seeks to quantify the input and output energy demands of a given system-in this case, an agricultural system (Neira *et al.*, 2013). According to Taiz & Zeiger (2002); Camejo (2012) cited by Guadiana *et al.* (2021), since energy is inherent in everything that can be recognized (even information), an energy metric based on emergy-spelled with an "m"-can be used to assess real wealth on a common basis, although calories of different types are not aggregated (Álvarez *et al.*, 2006).

Agricultural systems are evolving without a predetermined direction. To realign this process, new methodologies for evaluating and designing agricultural systems are required ones that guide them toward a maximum equilibrium among the components of sustainability (Valdés *et al.*, 2009). In line with this, recent data from Colombia, reported in a 2024 study by CORPOEMA, highlight the lack of centralized energy data within the Colombian agricultural sector, with sugarcane being the only notable exception Only four sectors (floriculture, poultry, aquaculture, and pig farming) currently incorporate renewable energy sources. These sectors vary greatly in terms of processes and producer scale.

The agricultural sector accounts for 2.37% of national energy consumption, with 10.9% derived from diesel (ACPM), 4% from gasoline and LPG, and just 0.1% from electricity relative to total national consumption. A striking 86% of energy use is concentrated in lowland regions, where the main productive sectors are located. Moreover, 97.54% of the energy is used for mechanical power, and 97% of total consumption corresponds to fossil fuels. Primary agricultural production leads in energy consumption (25,952 TJ/year), followed by the livestock sector (13,769 TJ/year). Cattle-numbering over 30 million heads-are the largest consumers, due to their daily energy demands. In agriculture, the most energy-intensive processes include harvesting, land preparation, irrigation, and internal transportation, while in livestock production, transportation and feeding account for the highest energy use. In fisheries and aquaculture, fishing activities represent the main energy burden.

Energy analysis is essential in agricultural studies as it strengthens technical and productive decision-making by offering alternatives with greater energy returns-an increasingly important factor given the growing environmental impact (Neira *et al.*, 2013). To achieve meaningful energy efficiency, a holistic approach to the agri-food system is required. In precision agriculture, thermodynamics and emergy serve to optimize irrigation and fertilization, improving both energy and water efficiency (De Melo *et al.*, 2017; Zhou & Yan, 2024; Zhou *et al*., 2018; Odum, 2007; Foley *et al.*, 2011). Similarly, in livestock production, these principles enhance thermal comfort and metabolic efficiency Thornton (2010), thus contributing to system sustainability.

The integration of energy balance and emergy within a thermodynamic framework promotes the development of more sustainable and efficient agricultural models Odum (2007), optimizing resource use and mitigating environmental impacts (Godfray *et al.*, 2010; Foley *et al.*, 2011). In conclusion, the application of thermodynamics and emergy improves efficiency and supports the advancement of more resilient and sustainable production systems.

**Thermodynamic Principles and Their Application in Animal Production**

- First Law of Thermodynamics: Conservation of Energy
    - This principle, which posits the constancy of energy in closed systems, translates in animal production to the equivalence between ingested energy and the energy dissipated or retained.
    - “The first law of thermodynamics, or the law of energy conservation, states that energy cannot be created or destroyed but only transformed from one form to another” (Moran *et al.*, 2014).

- In practical terms, this means that the energy from feed is distributed among maintenance, growth, and production, with inevitable losses through heat dissipation and excretion.

- Second Law of Thermodynamics: Entropy and Exergy
  - The second law introduces the concept of entropy, which measures the degree of disorder in a system, and exergy, which quantifies the energy available to perform useful work.
  - The second law of thermodynamics introduces the concept of entropy and states that the entropy of an isolated system always increases in a spontaneous process. (Cengel & Boles, 2015).
  - In animal production, this is reflected in the degradation of feed exergy during digestion and metabolism, with a significant portion dissipated as heat.
  - Exergy analysis therefore enables the evaluation of energy conversion efficiency from feed into animal products, identifying critical points of exergy loss.
- Non-Equilibrium Thermodynamics
  - Animal production systems are open systems, exchanging matter and energy with their environment, and operating under non-equilibrium conditions.
  - Non-equilibrium thermodynamics allows for the understanding of energy and matter flows in these systems, as well as their stability and resilience.
  - The application of this branch of thermodynamics is essential for the design of sustainable animal production systems that minimize environmental impact while maximizing efficiency.

According to Campbell & Tilley (2003), Emergy provides a holistic perspective on sustainability by considering the solar energy embedded in production processes. In the agricultural sector, emergy enables the evaluation of resource-use efficiency and the environmental impact of farming practices. To grasp the importance of this tool, it is necessary to approach it from its conceptual foundations through to its practical applicability in agricultural production systems.

1. The Fundamental Concept: Emergy Transformities (UET)
   - “The emjoule (ej) is the unit of measurement for emergy, representing the equivalent amount of solar energy required to generate an energy flow.” (Odum, 1996, p. 92). This unit enables the comparison of different forms of energy on a common basis, facilitating sustainability assessments.
   - The basis of emergy measurement lies in Emergy Transformities (UET). These transformities are conversion factors that express different types of energy (e.g., fossils, electrical) in a common unit: solar equivalent energy (sej). As Odum (1996), defines it, Emergy transformity is the amount of solar equivalent energy required to produce one unit of energy or matter. This means that each resource or product carries an “energy history” that can be traced back to its solar origin.
   - Conducting an emergy analysis requires consulting up-to-date UET tables. These tables, provided by environmental research centers-offer the necessary conversion factors for a wide range of resources and products.
2. The Measurement Process: Emergy Flow Analysis
   - Emergy flow analysis involves constructing a diagram that represents all the inputs and outputs of the system under evaluation. These may include everything from incoming solar radiation on a field to fertilizers, pesticides, fuel, and the final harvest.
   - Once all flows are identified, data is collected on the quantity of each input and output. For example, the amount of fertilizer may be measured in kilograms, or crop yield in tons.
   - The next step is to multiply each quantity by its corresponding UET. This converts all flows into solar equivalent energy units (sej).
   - Finally, the emergy values of all inputs are summed to obtain the total emergy requirement of the system. This provides a measure of the system’s “energy burden.”
3. Specific Indicators for Emergy Assessment
   - Beyond total emergy, specific indicators can be calculated to evaluate system sustainability. For instance:
     - The Renewable Emergy Ratio (RER) indicates the proportion of emergy derived from renewable sources (Brown & Ulgiati, 2013; Campbell & Tilley, 2003). This indicator is essential for assessing transitions toward production systems that minimize non-renewable resource use.
     - The Emergy Sustainability Index (ESI) combines the RER with the environmental loading ratio to provide a more comprehensive sustainability assessment (Brown & Ulgiati, 2016).
     - Exergy illustrates the loss of useful energy. In an irrigation system, not all electrical energy is converted into water pressure; part of it is lost as heat, demonstrating an increase in entropy (Wall, 2011).

**Advanced Applications of Emergy and Exergy Concepts in Agricultural Production**

1. Thermodynamic Modeling of Metabolic Processes
   - “Thermodynamic modeling allows for the simulation of animal metabolic processes, facilitating the optimization of diets and environmental management.” (Thornton & Herrero, 2010).

- "These models can predict feed conversion efficiency, heat production, and waste generation, enabling informed decision-making for managing production systems." (Kebreab *et al.*, 2016).

2. Exergy Analysis of Production Systems
   - "Exergy analysis is applied to evaluate the efficiency of animal production systems as a whole, accounting for all energy and material flows." (Wall, 2011).
   - "This approach helps identify opportunities to enhance efficiency and reduce environmental impact, such as waste-to-energy recovery and resource use optimization." (Eriksson & Nielsen, 2017).
3. Environmental Impact Assessment through Thermodynamics
   - "Thermodynamics, combined with tools such as life cycle assessment and emergy analysis, enables the evaluation of the environmental impact of animal production systems." (Beauchemin *et al.*, 2011).
   - "This facilitates the identification of strategies to reduce carbon footprint, water consumption, and pollutant emissions." (Rotz *et al.*, 2019).

### Case Studies Approaching Emergy Estimation

Agostinho *et a*l. (2010): This specific study analyzes emergy in corn production in Brazil, providing useful comparative data. It presents the emergy calculation for one ton of corn produced on a 10-hectare farm. The system is defined by its boundaries and components, including soil, water, seeds, fertilizers, machinery, fuel, and transportation. The identified input energy flows comprise solar radiation (100 GJ), precipitation (500 m$^3$), fertilizers (5 tons), fuel (1,000 liters), seeds (1 ton), and machinery operation (50 hours). These inputs are subsequently converted into emjoules using the corresponding transformity factors.

The second example illustrates the emergy calculation to produce 1,000 liters of milk on a farm with 50 dairy cows. The system is defined by its boundaries and components, which include pasture, water, concentrated feed, milking equipment, refrigeration, and transportation. The identified energy inputs are pasture (20 tons), water (10,000 liters), concentrated feed (5 tons), electricity (500 kWh), and transport (100 km). These inputs are then converted into emjoules using their respective transformity factors to calculate the total emergy invested (TEI). Additionally, the emergy of the product (TEP) is calculated for the 1,000 liters of milk, along with the emergy efficiency ratio (EER).

## CONCLUSIONS

- The analysis of the research trend tree reveals a significant evolution in the understanding and application of emergy-from its relationship with energy transformity and system self-organization to its more concrete application in the assessment of environmental load and sustainability.
- The application of thermodynamic principles, grounded in the concepts of emergy and exergy, provides a comprehensive tool for evaluating the efficiency and sustainability of agricultural production systems. Compared to traditional approaches that focus solely on energy quantity, these models incorporate the quality, origin, and energy trajectory of the resources used, offering a complete and balanced view of productive performance.
- It is evident that emergy analysis provides an integrative perspective of productive processes by accounting for all direct and indirect energy involved. This method helps identify the dependency on external resources and the hidden energy load within production systems. Exergy analysis, in turn, assesses the efficiency with which systems convert that energy into useful work, highlighting critical points of loss and energy degradation.
- The case studies presented in this work, both in agricultural (corn production) and livestock (milk production) contexts, serve as simplified examples that demonstrate the applicability and analytical value of these methods. The differences in the Emergy Efficiency Ratio (EER) between the two systems underscore the need to tailor strategies according to the type of production, always prioritizing energy use optimization and environmental impact reduction.
- In the context of climate crisis and increasing food demand, having methods that integrate the ecological and energetic dimensions of production becomes essential.
- Emergy and exergy analysis in the evaluation of agricultural systems can be key to designing more efficient, resilient, and environmentally responsible models. It is therefore necessary to strengthen the use of these tools within academic, technical, and policy spheres, and to expand their application across diverse territorial and productive scales.

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