

THERMODYNAMICS AND AGRO-INDUSTRIAL PROCESSES. A REVIEW

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ABSTRACTS

The food industry is moving at great speed to cope with the increase in the world population, in parallel advances in agriculture are providing agricultural technologies that give rise to the yield of food production. All the processes to industrially produce agricultural products involve a complex of equipment that works based on energy exchanges in the form of heat. This article tries to explain the principles and applications of thermodynamics in agro-industrial processes based on heat transfer for food processing. The review was carried out through the search and analytical reading of papers and physical and electronic scientific publications such as Google Scholar, Scopus, Scielo, Redalyc and Doaj. The contextualization of the topic focused on the importance, applicability and development of thermodynamics in agro-industrial processes was established as a contribution to scientific knowledge for the use of equipment, inputs, raw materials and products in food production that provide nutritional value and a benefit to human health.

Keywords: Exchange, energy, heat, production, food

INTRODUCTION

Thermodynamics is a science that involves processes involving changes in temperature, the transformation of energy, and the relationships of heat and work. The world is an accumulation of energy, but man's ability has been crucial to harness that energy in a useful way, generating life changes in today's society. All those phenomena of energy and the laws of transformation of heat into other forms of energy are addressed by thermodynamics. Energy has provided enormous technological growth, but today more than ever it is necessary to analyze its interaction with human activities (Remington Corporation, 2022).

The food industry currently focuses on the utilization of equipment, inputs, raw materials, and products for food production that provide nutritional value and a benefit to human health. Plant and animal products appear as a promising alternative for friendly food production with significant competitive advantages over non-renewable components. Agricultural biomass is one of these compounds and is currently among the most important and commonly used components in the world (Gómez, 2019).

According to (Panchal *et al.*, 2018) All the processes to industrially transform agricultural products involve a complex of equipment that works based on energy exchanges in the form of heat, such as: kettles, autoclaves, boilers, ovens, heaters, coolers, among others; also, equipment that transfers energy in the form of work such as turbines, pumps and compressors.

All this equipment can be studied in terms of energy exchange with the methods and principles of Thermodynamics. Understanding the ways in which energy is transferred and being able to quantify these energy transfers are matters that fall within the competence of thermodynamics; It is there where this science becomes most important, since in every industry it is necessary to be able to quantify the energy required for any process and thus estimate the size of the equipment to be used; this also provides a basis for calculating the costs involved in producing items of this nature (Cieza *et al.*, 2022).

The concern about the depletion of resources and environmental pollution has led to the challenge of researching new designs and production processes with greater energy efficiencies (Ramírez *et al.*, 2014). The food industry requires men and machinery to process products of agricultural origin, or natural products in general; In a broad sense, this industry belongs to the so-called manufacturing processes that are defined as the transformation of raw materials into finished products; it also includes the processes of obtaining other goods and services from a first finished product (Groover, 2017); To transform the raw material of food origin, interrelated steps are executed.

The food industry is moving at high speed to cope with the increase in the world's population, while advances in agriculture are providing agricultural technologies that give rise to the yield of food production. According to (Cedeño, 2018) the need for food to satisfy a constantly growing population is not only determined by obtaining safe food, but also of high quality, in order to provide health to the population.

The most relevant aspects in the food industry are the production and availability of food, safety, quality and innovation; this causes that in food processing where raw materials are manufactured through many operations of processes formed in stages, the chemical composition and/or its energy level change (Jiménez and Caraballo, 2017). Therefore, significant engineering efforts are required to adapt to the demands of quality, safety, functionality and durability of the food product obtained (Cury *et al.*, 2017), allowing a variety of conventional and functional products.

The purpose of this article is to try to explain the principles, applications and development of thermodynamics in agro-industrial processes based on heat transfer for the production of foods that provide nutritional value and a benefit to human health.

METHODOLOGY

The methodological foundation for this research was documentary, based on methodical reasoning from physical and electronic scientific works and publications such as Google Scholar, Scopus, Scielo, Redalyc and Doaj, in order to establish the constructs, generating truthful and accurate information comparable to other updated scientific sources (Guevara *et al.*, 2020). The review was developed in the following phases:

Preparatory or initiation: Thermodynamics and agro-industrial processes were selected as the central theme, conducting research in June 2023 in indexed databases for scientific articles.

Exploration: Google Scholar, Scopus, Scielo, Redalyc, Doaj, among other online sources, were used for documentary search.

Formulation: Establishment of documentary references for the study period, reaching the contextualization of the topic focused on the importance, application and development

of thermodynamics in agro-industrial processes as a contribution to scientific knowledge for food production.

Collection: included the compilation, classification and recording of the information extracted from the reviewed documents. For this purpose, manual categorization was used using Mendeley software.

Selection: the selected material was organized in tables, presented with common characteristics of the documents such as author, year of publication, title, description of the work according to the classification emphasis and the purpose of the study.

Interpretation: From the background analysis, common aspects and distances between the articles were identified to make comparisons that allowed the construction of the arguments of the emerging scientific trends.

Theoretical construction: drafting of the final document to make it known in the national and international scientific community.

3. RESULTS AND DISCUSSION

Fundamentals of Thermodynamics and Heat Transfer

A system is defined as a quantity of matter or a region in space chosen for analysis and the boundary is the real or imaginary surface that separates the system from the surroundings and, in mathematical terms, has zero thickness and cannot contain mass or occupy volume in space (Wong, 2017).

There are 3 types of systems: Closed, isolated and open. A closed system, also called a control mass, consists of a fixed amount of mass and no other can cross the border; An isolated system is a particular case of closed systems in which energy is not allowed to cross the border. An open system, or control volume, is an appropriately chosen region in space, and both mass and energy can cross the boundary. A control volume can be fixed in size and shape, as could also imply a movable boundary (Cengel and Boles, 2012).

Processing methods associated with thermodynamics

For Barrios (2020), food processing and preservation methods are traditionally associated with four concepts, 1) Application of thermal energy to raise the temperature of the product and achieve stability, and extended preservation; 2) Elimination of thermal energy to reduce the temperature of the product and prolong the service life; 3) Removing water from the product structure, and thus achieve a longer service life; 4) Packaging or the step required to maintain product attributes achieved during processing.

In recent years, a new alternative processing concept called "new processing technologies" has appeared globally in food production (Pensel, 2014). The application of ozone in the environment is a concrete possibility, this is feasible as long as the simplicity of the technology and reengineering necessary to materialize it in the plant allow it; in addition, the associated cost and cash flow due to the acquisition of the technology and cost reduction should not exceed the quality parameters associated with it (Barrios, 2020).

Thermal properties of food

Generally, the thermal properties of food must be known to develop the heat transfer calculations involved in the design of the warehouse and refrigeration equipment; they are also necessary to estimate heating, cooling, freezing or drying processes. The thermophysical properties that are required for heat transfer calculations are density, specific heat, thermal conductivity and thermal diffusivity, among others (Borja *et al.*, 2022).

Likewise, fresh fruits or vegetables (vegetables), being living organisms, generate heat through respiration and lose moisture through perspiration on the shelf. Both processes should be included in heat transfer calculations using tables of thermophysical properties measured for food as a reference. Water is the predominant component in most agricultural products, its content significantly influences their thermophysical characteristics; in any case, the water content varies with the crop as well as with the stage of development or degree of maturity when it is harvested (Gómez, 2019). The main thermal properties of food are:

Density (ρ): It is the mass times the unit of volume. Its units in the international system are $\text{kg}\cdot\text{m}^{-3}$. Different forms of density are distinguished that are used in process calculations (Moncada *et al.*, 2013).

Specific heat: It is the amount of energy, in the form of heat, that a system gains or loses per unit of mass, so that a temperature change of one degree occurs in it, without there being a change in state (Lewis, 2003).

$$C_p = q/m \cdot \Delta T$$

Where: **q** is the heat gained or lost in Joules or Kilojoules (KJ) **m** is the mass (Kg) ΔT is the change in temperature ($^{\circ}\text{C}$ or $^{\circ}\text{K}$) **C_p** is the specific heat (KJ/Kg $^{\circ}\text{C}$) or (J/Kg $^{\circ}\text{C}$).

Enthalpy: It is the caloric content or energy level of a material, referring to the one at an arbitrary temperature at which it assigns zero level, generally -40°C for frozen products or 0°C for other systems (Lewis, 2003).

The amount of heat to heat or cool a material from a temperature **T₁** to **T₂** is for **m** the mass of the material; **H₂** and **H₁** the enthalpies at temperatures **T₁** and **T₂** respectively

$$q = m (H_2 - H_1)$$

Thermal conductivity: It is the measure of the ability of a material to conduct heat. For food it depends mainly on its composition. The definition of thermal conductivity is found in Fourier's law (Lewis, 2003):

$$q = kA \cdot (dT/dx)$$

Where **dT/dx** is the temperature gradient in the x-direction. The constant of proportionality **k** is the thermal conductivity (**W/m \cdot K**).

Thermal diffusivity: It is the thermal conductivity divided by the product of the specific heat and density. Its SI units are $\text{m}^{-2}\cdot\text{s}^{-1}$. It is used to determine heat transfer rates in solid foods in different ways (Lewis, 2003).

$$\alpha = k/\rho c_p$$

Effect of porosity: Only density and thermal conductivity are sensitively affected by porosity. For the calculation, the property is first assessed by assuming the food is non-porous, and then the value is adjusted to include expressions that contemplate porosity (Choi and Oikos, 1986).

$$V_j = W_j/\rho_j$$

$$\sum W_j/\rho_j$$

Water activity in food

Water is one of the main components of food that favors or affects its texture, shape and physicochemical properties. In addition, the amount of water in the food is the main cause of spoilage and the growth of microorganisms (Breda *et al.*, 2012). Water activity can be defined as the fraction of the water content that is free and available to carry out various chemical reactions that affect its stability (Ramírez *et al.*, 2014)

Water plays an essential role in the structure and preservation of food, hence the importance of various methods of food preservation are based on the decrease in the availability of water, physically eliminating it by drying, isolating it in the form of ice crystals or fixing it by adding sodium chloride or sucrose. giving rise to water not available for the growth of microorganisms (Bustos, 2019).

Heat Transfer in Food

Thermal conductivity and thermal diffusion describe the characteristic heat transmission of food substances and how quickly the product is heated or cooled during heat treatment (Borja *et al.*, 2022). Heat is transmitted by three different mechanisms, called conduction, convection, and radiation. Conduction is the main mechanism of heat transmission in solid materials, while convection is primarily appropriate for fluids.

Food refrigeration

Cooling is a process that involves lowering or maintaining the heat level of a body or space. Therefore, we speak of a greater or lesser amount of heat or of a greater or lesser thermal level (level that is measured with temperature), cooling is a thermodynamic process in which heat is extracted from the object under consideration (reducing its thermal level), and taken to another place capable of admitting that thermal energy without problems or with very few problems (Barreiro and Sandoval, 2016). The fluids used to carry heat energy from one space to another are called refrigerants.

Thermodynamic Principles in Ice Formation

All foods (plant, animal) are diluted aqueous solutions. The amount of water in the feed defines the formation of ice in direct relation to the higher freezing temperature. The freezing temperature of a food is the temperature at which the first stable ice crystals appear. According to (Bustos, 2019) the formation of an ice crystal first requires nucleation, which can be homogeneous or heterogeneous, the latter being the most frequent in the case of food, where nuclei are formed on suspended particles or on the cell wall.

The crystallization that originates during the freezing of a food is the formation of a systematically organized solid phase from a solution. The crystallization process includes the nucleation and growth stages of the crystals, ice is produced when the system is

sufficiently undercooled. Subcooling is the difference in temperatures below the initial freezing point of the system (Orregon, 2013).

Mass balances in agro-industrial processes

Mass balance is the main calculation within agribusiness, it helps to control the quantities of raw material that enter and leave the manufacturing processes. This makes it easier to identify the amount of finished product that will be obtained from a certain amount of raw material available (Huxsoll & Bolin, 2019).

Balance in mixing processes: It consists of mixing substances until a homogeneous result is obtained, as detailed in Figure 1 (Valiente, 2016):



Figure 1. Balance in mixing processes (Valiente, 2016). In original language Spanish

Balance in evaporation processes: It is an operation to concentrate a dissolved solid in a liquid, the solution is placed at boiling temperature, so that the liquid evaporates and the most concentrated solid is left in the solution. This is obtained by using equipment called evaporators, as shown in Figure 2 (Valiente, 2016).

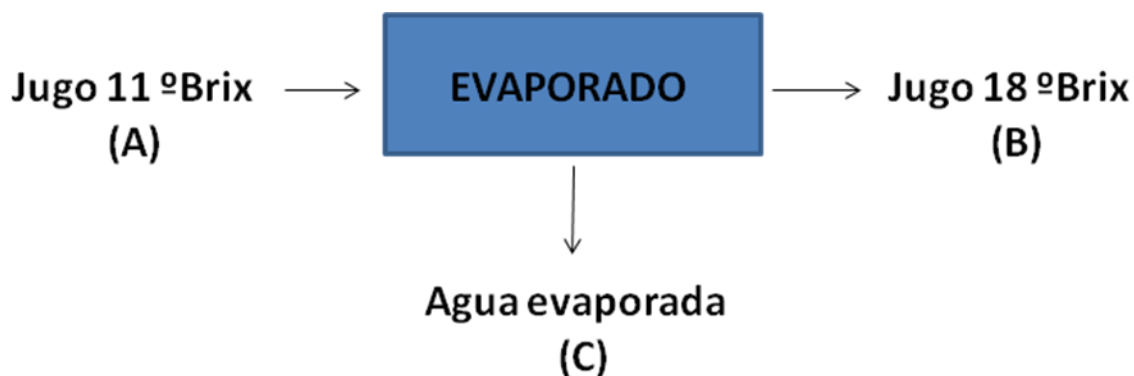


Figure 2. Balance in evaporation processes (Valiente, 2016). In original language Spanish

Balance in dehydration processes: It is the reduction of the amount of water in a product, lowering its percentage of moisture. It can be performed under controlled conditions of hot air flow, temperature and humidity, detailed in Figure 3 (Valiente, 2016).

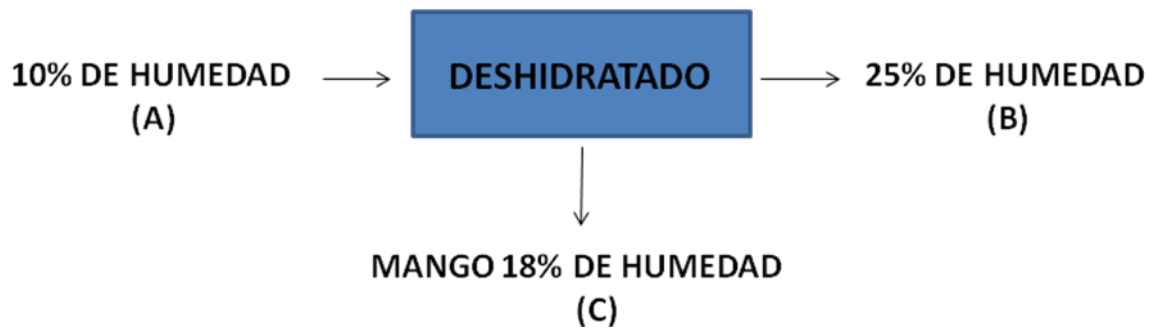


Figure 3. Balance in dehydration processes (Valiente, 2016). In original language Spanish

Energy efficiency

Energy efficiency is a very controversial issue that has been debated around the world, taking into account the Paris Agreement which was discussed during the XXI Conference on Climate Change (COP 21) by the 195 member countries, adopted on December 12, 2015 and opened for signature on April 22, 2016 (OLADE, 2017).

This concept is fundamental within agro-industrial production and is defined as the relationship between the energy that is clearly used versus the energy that is fully used (Vanegas and Botero, 2012); being the correct use of raw materials, water, fuels and electricity, one of the fundamental elements within an environmentally friendly agro-industrial production.

Applications of thermodynamics in agro-industrial processes

Thermal Processes in Food Manufacturing

Heat transfer can be effected by three mechanisms: radiation, conduction, and convection. Radiation consists of the transfer of heat by means of electromagnetic waves; conduction is a type of heat transport that takes place in solids and is produced by direct transmission of molecular energy, and convection consists of the transfer of heat by groups of molecules that move by density difference or by agitation (Fuentes, 2020).

However, there are no foods that are heated purely by convection or conduction. Those that have a greater consistency are heated by conduction and in those cases it is considered that there is no movement inside the container during heating or cooling. Similarly, for foods that have a lower consistency, the heating curves refer to that of products that are heated by convection (Panchal *et al.*, 2018). During heating and cooling, food is considered to be in constant motion due to currents that are raised by temperature differences.

In this sense, Gómez (2019) determined that, through the processes of pulping, demucilaginating and parchment, 61.5% of the mass of the initial fruit coffee is removed. Then, 20% of that mass is extracted, which corresponds to the water evaporated during drying and finally, only 18.5% of the initial mass is transformed into a finished product or gold coffee at 12% humidity on a wet basis. The exergetic efficiencies were calculated for each stage of the process, among which drying stood out as the stage with the highest use of resources with 98.6%.

Similarly, Jaimes *et al.*, (2012) used the 1st and 2nd laws of thermodynamics to determine the irreversibilities of the African palm oil extraction process, identifying the location and magnitude of the main exergy sinks during manufacturing. Energy, entropy and exergy balances were performed, which were 993.1 GJ/h. It was also identified that pressing and digestion are the stages with the highest exergetic losses with a value of 388.7 and 225.7 GJ/h, respectively. Exergetic efficiencies were calculated for each stage of the process, among which drying stood out with 99% and clarification with 97%

Dairy production

The application of the first law of thermodynamics in the dairy industry ratifies that this is a science and perhaps the most important tool in agro-industrial engineering since it is responsible for describing the processes that involve changes in temperature during the transformation of energy and the relationships between heat and work (Proaño, 2018). In the dairy industry, heat transfer is used for pasteurization and in the manufacture of cheese and butter.

According to Panchal *et al.*, (2018) the principles of physical science and fundamental sciences study the processes in which energy is transferred as heat and work, as well as fluid dynamics and mass flows, which are applied in the treatment and transformation of milk. The use of these principles is reflected in the design of equipment, development of new process lines and in the mechanization and automation of manufacturing.

In the dairy industry, most of the operations and processes that are carried out involve the exchange of heat. An example of this is the heat treatment that occurs in milk when it is cooled in the collection of raw milk and when it is pasteurized (Cieza *et al.*, 2022).

In this regard, Proaño (2018) applied energy efficiency systems within the dairy industry, in order to obtain improvements in production costs, reduce environmental impacts and, above all, promote more efficient agro-industrial production. Automation helped optimize the operation of many pieces of equipment, making them efficient and guaranteeing autonomous operation at a low cost, without having to depend on the human factor in critical processes in which people can fail more frequently. The creation of refrigeration compressors with more advanced technologies made cooling systems more efficient, reducing cost and uptime compared to compressors of older technologies.

Likewise, Borja *et al.*, (2022) developed a mathematical model for thermal milk storage tanks during the control of the outlet temperature in the cooling and heating process. Three different curve behaviors were determined for both the energy balance of the thermal tank, its transfer function in the heating of the milk and the behavior of both reception, cooling and heating up to the temperature of 80 °C.

On the other hand, various studies have made it possible to identify certain industries, and processes, as potential alternatives for the integration of Solar Thermal Systems (SST), based on factors such as geographical distribution of plants, weather conditions, operating temperatures, among other characteristics that may have an impact on the energy performance of these systems. Thus, TSS are presented as an option in the dairy industry, whose thermal processes usually reach maximum temperatures in the order of 130 °C (Panchal *et al.*, 2018).

In this context, Fuentes (2020) determined that the integration of an SST, for water preheating in sterilizing plants of the dairy industry, made it possible to generate thermal

energy at a competitive cost with respect to the displaced fossil fuel, which corresponded to natural gas (NG) or liquefied petroleum gas (LPG) depending on the location of the plant. It was possible to reach a value of 1.22 USD/MWh_{th} below the reference cost of displaced fossil fuel, which occurred by using Fresnel collectors as a capture technology.

Sausage production

Nowadays, sausages can be defined as a mixture of minced meat, fat, salt, curing agents, sugar, spices and other additives, which is introduced into natural or artificial casings and subjected to a fermentation process carried out by microorganisms, followed by a drying phase (Moreno 2018). On the other hand, once the mixture has been prepared, the mass obtained is subjected to the sausage process inside the previously prepared casings. For this, stuffers are used that have smooth and not very long nozzles, to prevent the dough from heating up due to the friction produced.

According to Jiménez and Caraballo (2017), the presence of air in the sausage product should be avoided, to ensure good heat treatment, for which vacuum fillers can be used. Depending on the type of sausage cooked, cooking is carried out at temperatures between 75-80° C, for variable periods of time ranging from 10 to 120 minutes and with high relative humidity between 98 and 100 percent.

Currently, the most applied refrigeration technologies in cooling processes in meat industries are those that base their operation on cryogenics, operating with Nitrogen as a refrigeration fluid. In this regard, Ferrari (2018) designed a cryogenic cooling system consisting of a cryogenic cabinet, a cryogenic tank and a liquid nitrogen distribution system; The response variable of the process was represented by the cooling speed of the pieces of cooked ham, while the factors that affected its behavior were the temperature of the chamber, air circulation velocity, relative humidity and size of the chamber, and as for the economic feasibility of the project, it was obtained that it represented attractiveness, after making a profit on the calculations of net present value (NPV), internal rate of return (IRR) and payback period (pay-back).

Preparation of panela

In recent years, panela production has played an important role in the economic and social development of several regions of South America, whose income from the sale of the product has improved their quality of life. The non-centrifuged sugar known as panela (Colombia, Guatemala, Panama, Ecuador, Bolivia and Venezuela), rapadura (Brazil and Ecuador) and chancaca (Peru and Chile), is produced from the evaporation of water from the juices from sugarcane after the milling stage (Gamero, 2018).

In this order, Ordóñez *et al.*, (2013) designed a model in Matlab for a multiple-effect evaporation system for panela production in order to provide a contribution to the technological development of this agribusiness. The mathematical model developed was divided into two different processes involved in obtaining the final product (panela): a) the control of the sugar concentration and b) the control of the level in the effects of the evaporator. The pressure difference between each evaporator allowed the dynamics of judo from higher to lower pressure, decreasing until a boiling point was achieved at a lower temperature in the next effect.

Similarly, Wong (2017) developed a methodology based on thermodynamic analysis to determine energy and production indicators in order to know the current state of the

panela burner and the production process, and thus determine the innovations that could be implemented to increase the competitiveness of the granulated panela production chain. increasing energy and production efficiency in the paneling modules.

For his part, Laca (2020) designed a boiler or steam generator, fed by sugarcane bagasse, replacing combustion gases because with this steam it is much more feasible to control temperatures for the production of panela. As a result, a boiler energy efficiency of almost 83% was obtained, a steam/fuel ratio (bagasse) of 1,785. Additionally, after the interactions, a combustion gas outlet temperature value of the preheater of 179.4°C was found.

Likewise, Espinoza (2017) carried out a numerical model and simulation, using techniques and tools of computational fluid dynamics and finite volume analysis, of the heat transfer process from combustion gases to sugarcane juice, through an open heat exchanger (pyrotubular pan), in order to compare the results in the flow velocity, temperatures, thermal power of each pan and thermal stresses generated from each of the designs, and select the most efficient. The work improved the efficiency of the panela production process by using pyrotubular pans instead of flat finned pans in the first stage of evaporation.

Synthesis of chemical and biotechnological processes

Lignocellulosic residues (mainly composed of cellulose (30-45%), hemi cellulose (20-35%) and lignin (10-20%)) are considered a promising raw material to obtain a wide range of products due to their high availability and low economic value (Forero *et al.*, 2015). The development of biorefinery schemes from this lignocellulosic biomass can be used as a chemical product platform (Moncada *et al.*, 2013).

This is the case of furfural, which can be obtained from the acid hydrolysis of these lignocellulosic residues and whose main application is the production of furfuryl alcohol, which represents 88% of its final application. Among other uses of furfural is the extraction of butadiene (5%) and the remainder (7%) is used in the production of chemical, pharmaceutical and flavoring intermediates (Raman and Gnansounou, 2015).

In this regard, Raman and Gnansounou (2015) studied the optimization of the furfural production process from ripe oil palm bunches using a pretreatment with dilute sulfuric acid followed by a dehydration process without using an additional catalyst. From the optimal conditions of the dehydration process (198°C and 11 minutes of residence time), a furfural yield of 57.6 g/kg of dry EFB was obtained.

For their part, Aristizábal *et al.*, (2015) evaluated from an economic and environmental point of view the production of ethanol, octane, nonane, furfural and hydroxymethylfurfural (HMF) from sugarcane bagasse and coffee soca under the concept of biorefinery. From the economic evaluation, production costs were obtained between 0.38 – 0.91 USD/kg for furfural and between 0.41 and 1.83 USD/kg for ethanol.

Chemical fertilizer production

Chemical fertilizers, their production and their massive use, are the basis of the industrial expansion of agriculture today. The rarefaction of nitrate mining deposits at the end of the nineteenth century was the trigger for a whole series of scientific experiments aimed at obtaining nitrogen fixation from the air and the mass production of nitrogen fertilizers at low cost and rapid expansion (Estupiñan and Quesada, 2010).

The Haber-Bosch synthesis involves the use of high temperatures and high pressure to combine hydrogen and nitrogen (from the air) with a view to the production of ammonia (NH₃). However, although the extraction of nitrogen from the air does not cause any rarefaction problems, the annual process of synthesis of 500 million tons of chemical fertilizers consumes 1% of the world's energy supplies (Smith, 2012) and, additionally, the health and environmental consequences of the release of ammonia and other nitrates have become evident since the end of the twentieth century.

4. CONCLUSIONS

Thermodynamics goes beyond the application of physical principles that study the processes in which energy is transferred such as heat and work, as well as fluid dynamics and mass flows that are applied in the treatment and transformation of agricultural products. The implementation of this science presents several challenges of adaptation and implementation in order to achieve optimal performance in the coming years.

Thermodynamics has to advance in parallel with the pace of agriculture by providing agricultural technologies that contribute to the yield of food production, to cope with the increase in the world's population. The need for food to satisfy an ever-growing population is not only determined by obtaining safe, but also high-quality food with nutritional value.

The use of thermodynamic principles is reflected in the design of equipment, development of new process lines and in the mechanization and automation of raw material transformation. It is a challenging challenge that requires men, equipment and machinery with state-of-the-art technology to process products of agricultural origin, or natural products in general.

The concern about the depletion of natural resources and environmental pollution brings the challenge of researching new designs and production processes with greater energy efficiency. The future of life on the planet is marked by the application of thermodynamics in equipment and instruments that improve daily activities and solve the problems of increasingly dynamic agro-industrial processes.

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