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Nutrition and production related energies and exergies of foods

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ABSTRACT

Nutritional energy (E_n) and nutritional exergy (Ex_n) are the inherent thermodynamic properties of foods; specific cumulative energy (*CEnC*) and exergy (*CExC*) utilization are thermodynamic properties associated with their production. Cumulative specific carbon dioxide emission (CCO_2E) is an environmental parameter used in parallel with the other thermodynamic parameters to describe the specific carbon dioxide emission during production. Interrelation of Ex_n and E_n is assessed by referring to 87 foods. Values of (*CEnC*), (*CExC*) and (CCO_2E) are presented for 146 foods. The data presented here are expected to make it easier to perform energy and exergy balances around people and animals while assessing their diets, and also while assessing food production systems. This paper is expected to serve as a comprehensive source of data in thermodynamic analyses pertinent to food processing and nutrition.

1. Introduction

1.1. Nutritional energy and exergy of the foods

The first law of thermodynamics states that energy is a conserved property, it can neither be created nor destroyed, but converted from one form to another, e.g., from chemical energy to kinetic energy, etc. Based on the second law, exergy (also called availability) is defined as the useful work potential above the dead state. Exergy is the maximum work that a system can produce, if it is brought to thermal, mechanical and chemical equilibrium with its surroundings via reversible processes without violating the laws of thermodynamics [129]. In other words, exergy is the measure of the useful energy of a thermodynamic system, with respect to a datum, which is usually the dead state, after being corrected for the entropy effects [34]. The first studies of exergy analysis were focusing on the assessment of renewable energy sources, where various processes and fuels were weighed with respect to their ability to produce useful work and to identify their impact on the environment, exergy analysis provides a fair tool for comparison [113,132,135,22,5,6]. There are some attempts to define internationally recognized reference points for the exergy calculations (Szargu et al., 2005). As expressed by the Hess's law [82], energy is a state function, energy difference between two states does not depend on the pathway followed. However, the difference of the exergies of these two points is a function of the pathway. The original method used to determine the nutritional calories of foods was measuring directly the energy it produced while burning it completely in a bomb calorimeter. Where, combustion chamber was surrounded by water and the resulting rise in water temperature was measured [43]. When the food, burned in the bomb calorimeter or utilized in the metabolism produces the same chemical reactants this method produces reliable results as suggested by the Hess's law. But, when the outputs of the metabolism and the combustion reactions are different, or when some of the components of the food is not metabolized, the results of these measurements become nonreliable. Therefore, the calorimetric method is not used frequently today, instead composition of the food is determined first, and then the nutritional calories of each nutrient group is added [100].

Wall [147] presented a highly comprehensive study to explain the relation between energy and exergy, where distinction was made clearly between the "*useful energy*" and "*energy*" with numerous examples, by referring to energy dissipation with irreversibilites. Hermann [61] suggested a mathematical relation between the energy and exergy as:

$$(Ex) = \varnothing(En) \tag{1}$$

where, ϕ was the available fraction of the energy. A similar relation may be established between the chemical exergy, Ex_c, and chemical energy as En_c:

$$(Ex_c) = \varnothing_1(En_c) \tag{2}$$

Similar relations will be established also between the nutritional exergy, Ex_n, and the nutritional energy, En_n and chemical energy, En_c, and nutritional energy, En_n:

$$(En_n) = \varnothing_2(En_c) \tag{3}$$

Nutritional energy, En_n, may be determined experimentally; the

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chemical energy, En_c, and the chemical exergy, Ex_c, may be calculated from the energies and exergies of the contributing components of the nutrients. In Eq. (3) parameter ϕ_2 describes the unutilized fraction of the chemical energy, such as the indigestible fraction of the carbohydrates like dietary fiber. Nutritional exergy (Ex_n) may be calculated as

$$\left(Ex_n\right) = (Ex_c)\left(\frac{(En_n)}{(En_c)}\right) \tag{4}$$

Eq. (4) was based on the assumption that the nutrients contribute to (Ex_c) and (En_c) and (Ex_n) and (En_n) the same way. But, these groups can contribute to (En_n) and (En_c) the same way, since all of them cannot be digested, therefore the ratio (En_n)/(En_c) operates like a correction factor in Eq. (4).

Thermodynamic analyses became an important tool in the nutrition studies during the last two decades ([12,13,45,46]; Lusting, 2006; [11,124]). Although the first law of thermodynamics is central to most of these studies, the second law has also begun to be used as a major tool [124,46]. Rodriguez-Illera et al. [118] proposed a link between exergy analysis and nutrition to account for the exergy efficiency in the metabolism of nutrients from foods in the human body. Feinman and Fine [46] after comparing the combustion of glucose and its utilization in the metabolism states that in the combustion process 60% of the chemical energy of glucose is wasted with heat, whereas it is retained in the cell in the form of the ATP in metabolism. Mady and de Oliveira [80] rephrased this observation as "*the fraction of the exergy of the nutrients retained within the bounds of the ATP in the body was about 60%*". A detailed study on the exergy metabolism of carbohydrate utilization in the body has recently been the subject of the studies by Rodriguez-Illera et al. [118]. Most of the nutritional data are available in the literature in "*energy*" context; whereas, the second law analyses will be based on "*exergy*" analyses. This study aims to establish the basis to convert these data from energy to exergy grounds.

1.2. Energy and exergy utilization in food production

The nexus of food, energy and water is very sophisticated. The production and processing of food consume approximately 70% of the human use of fresh water. Modern agriculture, uses approximately 30% of total global energy for land preparation, fertilizer production, irrigation and sowing, harvesting, transportation of crops, and processing and distribution of foods [49]. Reduction of the energy utilization and the subsequent CO_2 emission is among the topics of the research focusing on improving the renewable energy utilization and sustainability in the food industry. Among the usual recommendations, like preferring the renewable energy in production [88,157], there are also highly unusual proposals in the literature, such as dieting on edible insects [109] or designing the diet based on the criterion of GHG emission reduction [143].

1.2.1. Energy and exergy utilization in agricultural production

Photosynthesis converts solar energy into chemical energy via starch synthesis [27]. Leaves are the solar energy receptors of the plants and the seeds usually consume the chemical energy stored within their structure to synthesize them at the initial stages of germination [96]. Only the light, which is in the wavelength range of 400–700 nm (which constitutes about 45% of the total solar energy), may be used in photosynthesis. Exergy analysis of the process of photosynthesis has been described in detail by Petela [104,105]. About 25% of the referred 45% may be absorbed by the plants; the rest is lost by various reasons, including reflection. Receiving non-optimal levels of radiation reduces the efficiency of the photosynthesis further; therefore, only 3–6% of total solar radiation may be used in photosynthesis [138,84]. Ways to increase the photosynthetic efficiency of the plants is being actively researched to improve their yields, especially those of the grain crops [77]. Degerli et al. [31] after performing the assessment of energy and exergy efficiencies of *farm to fork* grain cultivation and bread making processes in Turkey and Germany concluded that the amount of the land required to produce the same amount of wheat in Turkey is 3.34 times of that required in Germany; this ratio is 2.30 with rye.

In addition to the renewable solar energy, agriculture of the plants generally require indirect non-renewable energy, in the form of fertilizers. Global fertilizer consumption especially that of the nitrogenous fertilizer, has increased by several orders of magnitude during the past 50 years [68]. Ammonia production is the backbone of the nitrogenous fertilizer production process. Ammonia is usually produced in high temperature and high pressure reactors, a typical example, Du Pont process was used to be carried out at 500 °C and 900 atm in the presence of promoted iron catalyst to obtain 40–85% of conversion [125]. Producing ammonia is a highly energy intensive process – about 1090–1250 m^3 of natural gas is used to produce 1 metric ton of anhydrous ammonia. In the US, in the late 1990s and early 2000s, 70–80% of the energy need of the fertilizer production was supplied from natural gas, approximately 3% of the total natural gas production was allocated to ammonia production and almost 90% of the ammonia output was used by the fertilizer industry [53]. By the early 2000s, energy utilization in the chemical fertilizer factories approached to the theoretical minimum [72]. Chemical fertilizers induce fertilization via supplying nutrients to the plants; microbial fertilizers may induce secretion of the growth hormones, convert nitrogen of the air in a chemical form which may be utilized by the plants, or may dissolve the rocks or other minerals of the soil to make them available to the plants [28,76]. Substitution of the chemical fertilizers with their microbial counter parts may either decrease, or eliminate totally, the need for the chemical fertilizers [120].

1.2.2. Energy and exergy utilization in food processing

Energy and exergy efficiencies may be employed to evaluate the efficiency of the same system based on the first and the second law of thermodynamics, respectively. Exergy is an extensive property to measure the effectiveness or real value of an energy form [17]. Chronologically, energy efficiency draw attention after the Arab-Israeli war, when the oil prices quadrupled between October 1973 and January 1974 [101]. The first law of thermodynamics states that energy is conserved; that is energy can neither be created nor destroyed. The concept of exergy draw attention after 2000s, when ways of improving the energy efficiency of the systems had almost been exhausted and a new concept is needed for further developments [96]. The second law of thermodynamics defines "*entropy*", as a measure of the losses involved in the processes. The exergy balance equation can be derived by multiplying the entropy balance equation with temperature of the system and subtracting it from the energy balance equation. Exergy balance provides insight on the irreversibilities reducing the performance of a system, and helps to quantify the losses and proposes measures for minimization of the loss. Exergy analysis is being applied increasingly to evaluate and optimize the efficiency of various energy-intensive manufacturing processes and become very popular for evaluating their sustainability. Dinçer [35], argued that achieving reductions through exergy analysis in energy use and environmental emissions may increase sustainability of a process. Exergy is usually destructed and may be lost in a process; therefore, exergy analysis provides more realistic and more meaningful assessments when compared with energy analysis as demonstrated with drying [35], industrial yogurt production [63] and ethanol production with fermentation [3]. Conceptual discussion presented by Kanoglu et al. [66] with numerical comparisons of energy and exergy analyses explains clearly the importance of the exergy efficiency for improved energy management.

In Turkey, sugar beet plantation was expected to 2.5 million t in 2017 [141], therefore exergy losses in sugar production has tremendous economic consequences. In a landmark study, Bayrak et al. [10] reported that in sugar production process, most of the irreversibilities occurred in the vapor production, sherbet mixing, and bagasse