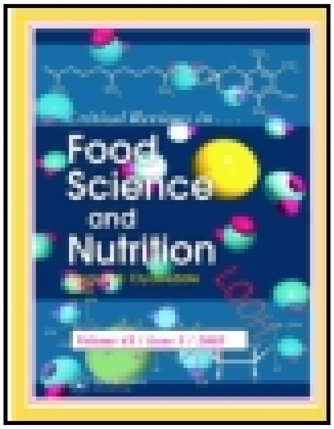

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The Use of Exergetic Indicators in the Food Industry - A Review

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The use of exergetic indicators in the food industry – A review

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Abstract

Sustainability assessment will become more relevant for the food industry in the years to come. Analysis based on exergy including the use of exergetic indicators and *Grassmann* diagrams is a useful tool for the quantitative and qualitative assessment of the efficiency of industrial food chains. In this paper we review the methodology of exergy analysis and the exergetic indicators that are most appropriate for use in the food industry. The challenges of applying exergy analysis in industrial food chains and the specific features that food processes are also discussed.

Keywords: Sustainability, food industry, exergy analysis

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Introduction

The global population will reach 9.6 billion by 2050 (United Nations, 2013). The economic prosperity of a big part of the population is also expected to increase, leading to more affluent diet patterns that support a very demanding food system in terms of natural resources (Gerbens-Leenes, Nonhebel, & Krol, 2010). It is estimated that the current demand for phytomass production will at least double, but with the probability of attaining only 80% or less of the total theoretical potential yield due to competing claims in land usage, while a number of other reasons like the increasing frequency of extreme climatic phenomena, and water and phosphorus scarcity will also worsen the situation (Koning, et al., 2008). As a result, there will be a strong pressure on natural resources, energy, and food. Thus, efficient and complete use of our resources will be of utmost importance.

The main challenges the food industry will face are the need for better agricultural and post-harvest handling practices, for more efficient food production that uses less energy and water, and for minimizing food wastage throughout the complete food chain (Ohlsson, 2014). The total amount of raw materials, water, and energy required along a food chain can be substantial depending on the type of food product produced (Ramirez, 2005). Food waste generation is also considerable since about a third of all the food produced globally is lost within the various steps in the food supply chain. About 7%[1] of this loss is due to industrial processing (Figure 1) which

[1]Calculated by using data of the report of Gustavsson et al. (2011) where the production volumes and the percentage of expected losses occurring at the processing and packaging sector for each commodity group per region, were considered for the estimation of the processing and packaging food losses (in million tonnes).

seems small, but this wasted food still translates into prodigal expenditure of energy, water, fertilizer and land use, all spent in vain.

Many efforts have been undertaken to improve the sustainability of the food industry and a number of positive developments can be observed. For example, Lee and Okos (2011) evaluated successfully different food processing systems that use less water and energy, while Alamilla-Beltran et al. (2011) identified emerging food processing technologies with promising applications such as electroporation, plasma processing, pulsed electric fields, and radiofrequency heating, amongst others. However, the practical implementation of sustainable improvements in the food industry is hindered by the vast product diversity, the specific and limited production times, and the large distribution areas (Klemeš & Perry, 2008). Nevertheless, the need to produce food both effectively and efficiently will become even more profound because the continuation of unsustainable processing practices will contribute to the irreversible depletion of Earth's natural resources.

Several methodologies have been proposed for assessing and improving the sustainability of various processes and products such as mass flow analysis (MFA) (also known as material throughput analysis), energy analysis (EA), life cycle assessment (LCA), Cradle-to-Cradle design (C2C), and pinch analysis amidst others (Braungart, McDonough, & Bollinger, 2007; Dalsgard & Munkoe, 2000; Damour, Hamdi, Josset, Auvity, & Boillereaux, 2012; Giampietro, Bukkens, & Pimentel, 1994; Herrero, Laca, & Díaz, 2013; Kytzia, Faist, & Baccini, 2004; Roy, et al., 2009).

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Clearly, there is no shortage of sustainability assessment methods. Yet, the most challenging task for the scientific community is to agree on useful and operational criteria that can connect resource consumption with the generated services appropriately (Gong & Wall, 2001).

Currently, energy is the most common term the food industry used to understand process and system performance or efficiency. According to Wall (1988), energy should be considered as an indestructible quantity that is conserved in every closed process. Upon transformation of one energy form to another, part of its initial quality is destroyed (irreversibly lost) leading to a lower, degraded quality (Maes & Van Passel, 2014). The concept of energy quality has been described by Van Gool (1980) as the possibility of energy exchange between a donating and an accepting stream. This possibility was defined by Cornelissen (1997) as the "maximum work potential of a material or of a form of energy in relation to its environment", and it is known as available work or exergy, a term which was originally given by Rant and his co-workers (1956) after the Greek words "εξ" (out of) and "έργον" (work). Now, consensus amongst many authors from different scientific fields develops in using exergy analysis (*ExA*) as an objective methodology for assessing the efficiency and hence sustainability of processes and systems, because it is based on the first and second law of thermodynamics, considering both the quantity and the quality of material and energy streams simultaneously without having to resort to subjective weighing factors (Berg, 1980; Rosen, Dincer, & Kanoglu, 2008; Szargut, 2005; Wall, 2009; Dincer, 2002b; Dincer & Rosen, 2013a; Hevert & Hevert, 1980; Maes & Van Passel, 2014; Sciubba, 2009; Zvolinschi, Kjelstrup, Bolland, & van der Kooi, 2007). The advantages of using *ExA* over other assessment methods have been discussed in detail by various authors, e.g. (Gong & Wall, 2001; Dincer & Rosen, 2013c). The basic principles, the general definitions and the differences between energy and exergy have been discussed by Dincer and Cengel (2001) and Dincer (2002b).

BoroumandJazi et al. (2013) reviewed the applications of *ExA* in various industrial sectors in different countries. Luis (2013) focused on the chemical industry and showed that most of the *ExA* publications relate to the energy and thermodynamics-related fields. According to Dincer and Rosen (2013c), *ExA* seems to be applied mainly by European companies and one of the reasons could be their longer-term viewpoints on sustainability. The potential use of *ExA* in the food industry has been demonstrated by Apaiah et al. (2006), and now the interest in research in this field is rapidly growing (Figure 2.a). However, the number of publications in relation to the total number of publications and to the chemical industry, as shown by Luis (2013), is still small, indicating a need for identifying relevant research questions that can better couple *ExA* to food science and technology (Figure 2.b). Therefore, the aim of this review is to evaluate the usefulness of *ExA* as a sustainability assessment tool, to summarize the most commonly used exergetic indicators and their application in the food industry to identify particular features food processes and chains have, and to identify possible future directions for further research.

Applications of exergy analysis in the food industry

Most food process related publications using *ExA* focus on drying technologies (66%), followed by food chains having wider boundaries (10%), and heating/pasteurization processes (6%) (Figure 3.a). The remaining studies deal with other processes such as heating, evaporating, and chilling, and some of them consider whole countries including the agricultural sector (societal chains). The main drying technologies studied are related to general aspects of drying

(17%) but innovative drying methods such as solar drying (19%) and the use of heat pump drying (16%) receive growing attention as well (Figure 3.b). Solar drying case studies have been reviewed by Panwar et al. (2012) and mathematical models for thin or thick layer solar drying have been discussed by Bennamoun (2012). El-Sebaii and Shalaby (2012) described the different types of solar dryers used in the drying of agricultural products. Heat pump drying systems were summarized by Colak and Hepbasli (2009), while Bruttini et al. (2001) suggested operational policies for exergetically sustainable freeze drying of pharmaceutical products. Dincer and Sahin (2004) proposed an exergetic model for the design of thermodynamically efficient moist solid drying operations, while the energetic and exergetic efficiencies as well as general sustainability aspects of dryers have been discussed by Dincer (2011). The reason that drying receives more attention is undoubtedly because it is one of the most energy demanding processes due to the high latent heat of vaporization of water, and the inefficient use of energy in case of spray drying (Aghbashlo, Mobli, Rafiee, & Madadlou, 2013). Most of the publications studied (62%) focus on practical applications of *ExA*, either on experimental rigs or larger scale equipment, while about a third of them (30%) relate to modelling of food processes or chains, and the rest (8%) are literature reviews that do not focus on the food industry but discuss relevant processing technologies (e.g. drying). *Grassmann* diagrams were used in about 17% of the publications to represent exergy flows, an aspect that can be important for visually communicating the results of *ExA* to non-expert stakeholders.

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Exergy analysis

ExA identifies parts within a system where most of the exergy is wasted and/or destroyed, and it can help to understand better the reasons that causes those inefficiencies (Tsatsaronis & Morosuk, 2012). A typical stepwise procedure to conduct a general *ExA* is described by Dincer and Rosen (2013a)**.** The procedure for applying the exergy analysis methodology in industrial food chains is proposed as follows:

1. Define the system boundaries of the food process or chain including all crucial steps;
2. Determine an environment of reference, which should reflect local environmental conditions;
3. Conduct a mass flow analysis, an energy analysis, and an exergy analysis using only the most relevant forms of exergy to construct *Grassmann* diagrams;
4. Define and calculate thermodynamic indicators;
5. Interpret the results;
6. Propose and assess potential modifications/improvements;
7. Communicate the results.

Defining the system boundaries

The choice of system boundaries for the evaluation of different food processes or chains is an important step because it affects the outcome of the analysis considerably as shown by Seckin et al. (2013). Stanek and Gazda (2014) argued that the system boundaries should be extended when

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renewable resources are included in the analysis, to account for the origin (extraction) of the natural resource. The use of broad system boundaries will give a more detailed overview of the analysed chains, but it can lead to extensive calculations and excessive use of assumptions that complicate the analysis. On the other hand, the use of tighter system boundaries will simplify the analysis but it will also omit the identification of the impact of potentially relevant “external” processes.

Defining the environment of reference

To calculate the available work of each stream, an environment of reference has to be selected. Several reference environment models have been developed and these are discussed by Dincer and Rosen (2013a) who mentioned that one of the most commonly used ones is the natural-environment-subsystem model. In this model, the environmental temperature is adjusted to match the local geographical conditions of the system under study. This approach is used in many of the publications studied in this review. In cases where psychrometric processes or pressure differences are relevant, the humidity of the ambient air and the pressure of the reference environment should be considered as well. For example, Figure 4.a shows how the chemical exergy of 1 kg air changes with increasing its moisture fraction at constant environmental moisture content and at different environmental temperatures (K), while Figure 4.b shows how the total exergy of 1 kg of air changes with increasing both its moisture fraction and its temperature at constant environmental moisture and environmental temperature. This shows that the selection of a particular environment of reference will influence the outcome of an

ExA of, for example, a drying process, since the exergetic contents of all relevant streams and the exergetic efficiencies in the analysed system are calculated in relation to this environment.

Defining the relevant forms of exergy

The most relevant relations for conducting an *ExA* are shown in Table 1. It is common practice to consider only the relevant forms of exergy involved in the process, which are classified into three main categories: the physical, the chemical, and the mixing exergy. The total exergetic content of a stream is the sum of all of those exergies. The physical exergy can be further categorized into thermal, pressure, kinetic, potential, and electrical exergy, of which the three latter ones are fully convertible into work meaning that they are equal to their corresponding energies. The chemical exergy, according to Dincer and Rosen (2013b), "represents the maximum work extractable from a system at the pressure and temperature of the reference environment [non equilibrium state] as it changes to a system with the same composition, pressure and temperature as the reference environment [equilibrium or dead state]". Therefore, the chemical exergy of the stream can be calculated by knowing the chemical composition of a mass stream, expressed in mass fractions, and the specific chemical exergy of each component, which values can be found in literature (Szargut, 1989; G. Wall, 2009). The mixing exergy is relevant when two or more different streams are mixed causing a spontaneous loss in exergy.

The physical exergy forms that are frequently involved in food processing are the thermal, the pressure and the electrical exergies. However, the chemical exergies are typically much larger than the physical exergies. While most of the chemical exergy is usually preserved during food processing, any unused material side stream represents a significant loss on the total amount of exergy, which is generally larger than most losses due to inefficient use of physical exergy. Recently, Jankowiak et al. (2014) compared the extraction of isoflavones from okara (soymilk by-product) by water and by ethanol and showed that, even though water leads to a lower yield of these bioactive components, it is exergetically more efficient than ethanol due to the loss of the latter (chemical exergy loss) during the distillation process and with the spent okara. Evidently, the full use of the raw materials and all material streams involved in a system is more important than the efficient use of physical exergy (e.g., in heating, cooling, and phase changes).

Having all relevant stream exergies calculated, one can construct a *Grassmann* diagram. This diagram shows schematically the types of exergy flows considered in a process or a system. When the chemical exergy flows are excluded from the *Grassmann* diagram, the physical exergy streams can be shown better, which reveal those parts in the chain where most non-material losses occur, making the diagram an effective way of communicating the exergy analysis results.

The use of exergetic indicators

Exergetic indicators, which address different aspects of thermodynamic performance, are useful to obtain a better understanding of the irreversibilities and exergy losses in a food chain. A single exergetic indicator might not be sufficient to describe completely the thermodynamic performance of an industrial food chain. Various exergetic indicators have been used for the exergetic assessment of food processes and food chains as shown in Figure 5, and a summarized (but not exhaustive) list with their definitions and applications is shown on Table 2.

- The *exergetic efficiency* is one of the most frequently used indicators for the sustainability assessment of food processes. It shows how well the exergetic inputs are utilized within the process or chain. It is always lower than the energetic efficiency because it represents the deviation of the current food chain from ideality. It is thus equal to the total amount of useful exergy that emerges from the system ($\sum B_{out,useful}$), divided by the total amount of exergy absorbed by the system ($\sum B_{in}$):

$$n_{exergy} = \frac{\sum B_{out,useful}}{\sum B_{in}}$$

In other words, it shows the loss relative to the maximum theoretical work that could be achieved by the use of processing technologies in the food chain. As a consequence, its maximum achievable value is fixed based on the exergetic efficiencies of the constituent steps in the chain. Therefore, the total food chain efficiency could never reach 100% even if much more efficient technologies would be used.

The exergetic efficiency can be defined in various ways and the exact definition depends on what the analyst considers as an appropriate description (Cornelissen, 1997; Stougie, et al., 2002). The simultaneous use of three different exergetic efficiencies has been demonstrated in an evaporating cooling process (Dincer & Rosen, 2013d) and in an orange juice concentration process (Balkan, Colak, & Hepbasli, 2005). According to Valero (1998), the way the exergetic efficiency is calculated depends on the way the thermodynamic costs (exergetic contents) of the inputs and the products are allocated. The exergetic content should be allocated proportionally to their quantities when different products of the same quality are produced. In this case, the exergetic efficiency should be expressed according to the exergy of the output products over the total exergetic inputs (Valero, 1998). If the exergy inputs are not fully exploited and part of them leaves the system (i.e., are discarded

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as waste and returned to become part of the environment), the exergetic efficiency should be expressed according to the exergy of the output product over the part of the input exergy that was utilized (Valero, 1998).

In general, the calculation of the efficiency should meet a set of conditions: it should be based on relevant and influential data, it should be easy to calculate, it should have a practical application, and it should be sensitive to changes, thus enabling a range between zero and one (Stougie, et al., 2002). However, the efficiency is a ratio, and, therefore, a relative number that does not necessarily describe its thermodynamic performance completely. For example, Figure 6 shows that the exergetic efficiency of two different food processes is the same, however, in food process A, a considerably larger amount of exergy is lost. Therefore, the exergetic efficiency should always be explicitly defined and considered along with other thermodynamic indicators.

- The second most-used indicator in the publications is the *absolute exergy loss*. Certain exergy losses are associated with the transformation of raw materials into final products within the food chain. Those losses relate to different mechanisms such as heat transfer in thermal processing, induction of phase changes, concentration and mixing. They can be expressed directly by thermodynamic indicators (e.g. cumulative exergy losses and exergetic efficiency), and visualised by *Grassmann* diagrams as the decrease in the size of the arrows going in and out of the system.

  According to Sciubba (2009), exergy loss is a "proper indicator of the global conversion performance of an energy-conversion chain, including complex structures"**.** Exergy loss refers to both to the exergy destroyed irreversibly within a process (internal losses), and also to any other exergy that gets wasted to the environment due to other inefficiencies, e.g. from waste streams or by lack of proper insulation (external losses) (Szargut, et al., 1988; Valero, 1998).

Further insights on thermodynamic process performance can be obtained by the *Advanced Exergy Analysis* (Morosuk, Tsatsaronis, & Schult, 2013). According to this methodology the exergy destruction of a process is split into endogenous losses (due to the operation of a component of the process in real conditions when the rest of its components run in ideal conditions) and exogenous losses (calculated by subtracting the endogenous losses from the overall exergy destruction), as well as in unavoidable losses (that cannot be improved by any technological or economic improvement) and avoidable losses (calculated by subtracting the unavoidable losses from the overall exergy destruction). Szargut (1980) proposes a dependency of exergy losses within the different parts of a multistage process, meaning that a modification in one part of a chain might reduce the local losses but could influence the total losses considerably. The importance of considering the total chain of processes instead of focusing on a single unit operation has been demonstrated experimentally in a milk processing system (Fang, Larson, & Fleischmen, 1995).

- The third most commonly used indicator is the *improvement potential* (IP). Van Gool (1997) argues that the IP should be used for comparing different processes of different scales and even of different sectors, even though the obvious maximum improvement for a given process is its total exergy loss.

- The fourth most commonly used indicator is *entropy generation*, which is related to exergy destruction through the Gouy-Stodola relation (Duhem, 1889; Gouy, 1889a, 1889b, 1889c). Exergy destruction and entropy generation should be considered as parallel (and not opposite) concepts because the former gives information about the work that was irreversibly lost during a process in relation to a reference environment, while the latter marks the uncertainty (or disorder) in the quality of energy that is created during the utilization (degradation) of this useful work, and both are expressions of the second law of the thermodynamics (Kay, 2002).

- The fifth indicator is the *exergy destruction ratio*, which is also known as the depletion number, and it was originally defined by Connelly and Koshland (1997) as the exergy destroyed in a process over the total exergetic input. The exergy destruction ratio indicates a better efficiency with a lower value, contrary to most other indicators. The exergy destruction ratio is the reciprocal of the sustainability index *SI* as proposed by Rosen et al. (2008), which shows how a change in the exergetic efficiency impacts the sustainability of a process.

- The *cumulative exergy loss* is the sixth most-used indicator and it is defined as the summation of the losses that occur during the production of a certain or multiple products (Szargut, 1987). The cumulative exergy losses can be calculated by subtracting the total useful exergy delivered at the last step of the chain (or throughout the chain) from the cumulative exergy consumption (Szargut, 1988).

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Many other indicators have been developed in different scientific fields and have found application in the food industry also but not to a large extent. The use of renewable and non-renewable energy sources can be of relevance in a thermodynamic analysis because both of those energy sources might have the same exergy content but different overall thermodynamic impact, as suggested by Stougie and Van der Kooi (2011). Recently, Maes and Van Passel (2014) introduced the *renewability fraction* that is useful in identifying the actual exergetic value of renewable sources, which considers the sunlight required to produce the renewable resource, the forest abatement costs for carbon dioxide sequestration and oxygen production, and the actual sunlight captured by the process studied. A similar indicator has been used in assessing the performance of strawberry cultivation in greenhouses by different heating methods (Hepbasli, 2011). Dewulf et al. (2000) introduced the *exergetic renewability* defined as the renewable exergy fraction used over the total exergy input, and the *environmental compatibility* defined as the total exergy input over the total exergy input plus the exergy required to abate emissions and wastes. Another promising indicator is *eco-exergy*, a concept developed by Jorgenssen and his co-workers (2007) in which the embodied information in living organisms in the form of DNA is assigned as potential energy work. Other less used indicators are the *specific exergy destruction* (Ducoulombier, Sorin, & Teyssedou, 2007; Catton, Carrington, & Sun, 2011; Tambunan, Manalu, & Abdullah, 2010), the *exergy loss rate* (Pandey & Nema, 2011), the *exergy-to-energy ratio* (Quijera & Labidi, 2013), the *exergy heating effectiveness* (Akpinar, 2010b), the *weighted mean overall exergetic efficiency* (used in a country scale system) (Ahamed, et al., 2011; Xydis, Koroneos, & Nanaki, 2011), the *exergetic factor, productivity lack, relative irreversibility*

(Xiang, Calì, & Santarelli, 2004), and *peak exergy* (used in solar drying analysis) (Cuce & Cuce, 2013; Kumar, Vishwanath, & Gupta, 2012).

Communicating the results of an exergy analysis

Conveying the main outcomes of an *ExA* to non-expert stakeholders can be as important as the analysis itself. Grip et al. (2011) stated that the lack of a strategy in working with *ExA*, the lack of information on the opportunities that it offers, the lack of competence within the organization, the lack of time, and different prioritization strategies, hindered the implementation of *ExA* in Swedish companies. Additionally, companies perceived *ExA* as a method that was not required or was not applicable, or it was difficult to use and to communicate within their hierarchy levels due to the asymmetric knowledge on the topic. It is clear that the communication aspect of an *ExA* should be considered during industrial sustainability assessments seriously.

Thermodynamic sustainability

A process can be considered sustainable in thermodynamic terms when the amount of exergy lost is small during its operation, which results in most of the selected thermodynamic indicators attaining their most optimal values. For example, the cumulative exergy losses and the specific exergy losses should be as low as possible, while the total exergetic efficiency should be the highest possible. In other words, the total thermodynamic price to run the process and to produce one unit of product should be minimal, while the total exergy throughput should be as efficient as possible without degrading its quality.

However, some of the indicators may show conflicting results in practice. For example, Aneke et al. (2012) compared two industrial food chillers that make use of waste heat thermodynamically:

the first one being an organic rankine cycle powered vapour compression refrigeration process and the second one an ammonia-water absorption refrigeration system. They found that for pressure ratios higher than or equal to the breakeven point (where the coefficient of performance is identical for both processes) the first process was more efficient. However, for lower pressure ratios the second process was more efficient even though it produced higher irreversibility. They assigned this paradox to the fact that the absorption refrigeration process included more heat exchangers that are also entropy generators. Such conflicting results require a more in-depth observation of all the obtained values of the indicators and the most relevant one for the studied system should be selected to assess its thermodynamic performance.

Leites et al. (2003) pointed out general rules for the design of thermodynamically efficient chemical processes, which could also be applied within the food industry. An important rule is that the use of high quality energy should be avoided in processes that demand low quality energy (Shukuya, 2013a).

An industrial system could improve its exergetic sustainability by avoiding the generation of waste material or heat streams, by re-using those streams, and by making use of renewable energy sources. For example, a feasibility study showed that it is both sustainable and profitable to recover cryo-thermal exergy from a liquefied natural gas regasification process, for deep freezing of agro-food products in the surrounding industries, and for space conditioning in residential and commercial areas nearby (La Rocca, 2011).

Many recent publications focus on the exergetic assessment of drying processes that use solar energy or heat pumps. The advantages of using solar, wind and geothermal power were discussed by Koroneos et al. (2003) who showed that in some cases they can be more efficient

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than non-renewable energy sources. For example, Le Pierres et al. (2007) demonstrated that deep freezing of foods is possible by utilizing solar, low-grade energy. Hermann (2006) quantified the global exergy resources and stressed that it is be possible to meet the global demands in the reduction of energy consumption by best utilizing all known exergetic reservoirs and flows available in our biosphere.

From the information above, it can be concluded that food chains in the future should be designed in such a way that:

1. waste generation is avoided, minimized or re-used, and that the complete raw materials are converted into valuable and useful products
2. exergy destruction during processing is minimized and
3. renewable energy sources are used instead of fossil sources.

Current challenges and future trends in designing sustainable food chains

Several important issues have to be considered when using exergy analysis for more efficient and sustainable food production. First and foremost, the quality and safety of the final product(s) should be guaranteed in any change in a supply chain or processing step. This should be seen as a constraint on any modification that can be proposed. Second, exergy analysis has been developed in the energy conversion and chemical processing industry primarily, and thus will need further development and should gain acceptance in the food industry. We will now shortly discuss these aspects.

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- *Dealing with product safety, product-process interactions, and nutritional aspects in ExA.* Process optimization within the food industry is not straightforward. Even if more sustainable processing technologies can be identified by using *ExA*, those should comply with safety, legislation, and consumer quality criteria. Additionally, the structure of foods, both at macro- and micro-scale, is of great importance to the bioavailability of nutrients and sensorial quality of the product. For example, the digestibility and metabolism of dietary fatty acids is affected both by their structure and their state (Michalski, et al., 2013). *ExA* does not reflect the physico-chemical transformations of different food ingredients that occur during processing (e.g. gelatinization of starch), and, therefore, it says nothing about their nutritive value (Dincer, 2002b).

  The application of the concept of exergy on human metabolism and food consumption has been mentioned by Szargut (2005). The conversion of food in the human body releases heat equal to its lower heating value, however, only a part of this initial chemical energy content is used to run all the complex biochemical processes and most of the heat produced is lost to environment (Shukuya, 2013a). By using calorimetric data, it was shown that ATP hydrolysis is the limiting factor for obtaining the maximum available nutritive exergy, and approximately 60% of this exergy is chemically bound within the human body in the form of ATP (Mady, 2013). Mady et al. (2012) analysed the energy conversion processes within the human body with exergy to develop health performance indicators, while a general procedure for calculating the value of human exergy consumption was given by Shukuya (2013b). The above studies show that nutrition is an important factor to consider when designing a food product. They signify the need for extending *ExA* to include the impact of physico-chemical transformations of food components on their exergetic nutritive quality along the total food chain.

- *Dealing with industrial emissions and waste streams*. The exergy value for useful streams is by definition always positive even if their main physical variable, e.g. temperature, is lower than the environment of reference (Shukuya, 2013a). However, the assignment of exergetic values to waste streams is a matter of debate currently. This issue deserves attention since *ExA* often deals with lost work from waste streams and often suggests their avoidance or their reuse even when that is not possible. All streams that are brought at equilibrium with the environment of reference have zero exergy. This means that the useful work potential of a process stream that is dispersed into the environment will become part of this environment and thus by definition have no exergy anymore. Streams that can cause harm to the environment (e.g. emissions or waste streams), have an exergetic content (e.g. thermal and/or chemical exergy), but cannot or should not be released in the environment as such. They should first be brought into a state that allows them to become at equilibrium with the environment without doing harm. This generally requires additional processing (e.g., waste water treatment, chemical degradation, or even incineration) and therefore requires exergy to be spent. Therefore, harmful emissions bear an exergetic penalty as large as the exergetic investment needed to render them harmless to the environment.

  However, there is, still, no clear agreement on how to treat the exergetic content of such waste streams. Maes and Van Passel (2014) argue that *ExA* cannot capture the immaterial aspects of emissions and waste streams (e.g. land degradation and biodiversity loss), which should be considered by additional metrics in a sustainability assessment.

Gaudreau et al. (2009) criticized exergy analysis, posing that *ExA* is not objective due to the vagueness of the methodology in addressing the impact of waste streams on an infinite reference environment that should actually remain unaltered. Other authors proposed that waste streams should be considered either as constrained or unconstrained, where the former are streams of value (dictated often by economic factors), and the latter are free to impact the environment but have the potential of becoming constrained (valuable) (Dincer, 2002a; Rosen, et al., 2008).

Zhu and Feng (2007) studied the allocation of the cumulative exergy among the separation of multiple products from a stream by introducing a new parameter based on their minimum separation work. A similar approach could be useful for allocating the negative impact of waste streams based on their minimum abatement cost. Nevertheless, whether the exergy content of a toxic or contaminated stream that is released to the environment should be zero, or it should be allocated based on a minimum abatement cost, or even attain a negative value, is a topic that still requires attention.

- *Need for a systematic framework and communication standards*. The importance of the integration of exergy analysis in industrial practice, policy making, taxation, and education has been stressed by many authors (Dincer, 2002b; Gong & Wall, 2001; Tsatsaronis & Cziezla, 1999; Van Gool, 1997). Companies and governmental organizations are more familiar with the use of footprints. The *exergy footprint* was proposed by Caudill et al.

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(2010), which could assist in decision making. However, these types of concepts are still not standardized and integrated to reflect the environmental, economic and social aspects of sustainability (Čuček, Klemeš, & Kravanja, 2012).

Hernando and Hector (2013) demonstrated the use of a framework that combines *ExA* with a quality control model based on HACCP guidelines, on the Andean blackberry cold chain. Such a systematic framework could enhance the implementation of *ExA* by non-expert stakeholders in the future food industries, as part of exergy preservation programs that could be used as mandatory and legislative requirements of governmental sustainability projects.

- *Dealing with variability in data.* Oftentimes, systems with immense system boundaries are assessed by *ExA*, and, therefore, the analysis has to rely on data that are not readily available and can be found only in literature or by using expert knowledge. This implies that the analysis can convey some degree of uncertainty due to variability in literature data. Besides, the analysis outcome is strongly dependent on the model assumptions. Therefore, a consensus amongst the scientific community has to be reached for defining an appropriate methodology for reliable model validation, sensitivity and uncertainty analysis.

- *Method extension*. *ExA* is continuously extended to include economic and environmental aspects. Maes and Van Passel (2014) give an overview of such methodologies like the *Cumulative Exergy Content* developed by Szargut et al. (1988), the *Extended Exergy Accounting* developed by Sciubba (2001), the *Ecological Cumulative Exergy Consumption*

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developed by Hau and Bakshi (2004), and the *Cumulative Exergy Extraction from the Natural Environment* developed by Dewulf et al. (2007). Tsatsaronis and Morosuk (2012) discuss other exergy-based methods like *Exergoeconomics*, *Exergoenvironmental Analysis*, and the *Advanced Exergy Analysis*. The latter methodology has been applied on the drying of herbs and spices by a gas engine heat pump successfully (Gungor, Erbay, Hepbasli, & Gunerhan, 2013). The combination of the objective power of *ExA* with methods stemming from other fields like operations research, can lead to the development of useful decision making tools for cases where conflicting objectives (e.g. profit and sustainability) occur. This combination has been demonstrated in the design of a falling film evaporator (Nishitani & Kunugita, 1983), and of a novel protein food chain (Apaiah & van der Kooi, 2006). Later on, a new graphical method, which identifies the optimum operating parameters of a distillation column and visualizes exergy losses in 3D, has been introduced by Khoa et al. (2010). Further, Vintila (2012) developed an inverse analysis method that accurately measures mass, heat, and exergy transfer coefficients which are essential for describing transfer phenomena in transient multiphase systems.

Artificial neural networks have also been used for predicting the exergetic performance of fish oil microencapsulation by spray drying (Aghbashlo, et al., 2012c). Their optimal topology for predicting the energy and exergy in a fluidized bed dryer was determined by using response surface methodology integrated with a genetic algorithm (Nazghelichi, Aghbashlo, & Kianmehr, 2011) in both a static and a recurrent mode (Nazghelichi, Aghbashlo, Kianmehr, & Omid, 2011). Response surface methodology was used in combination with exergy analysis for determining the optimal process conditions for the drying of olive leaves (Erbay & Icier, 2009b), of herbal leaves (Karimi, Rafiee, Taheri-Garavand, & Karimi, 2012), and for identifying the main factors that affect the performance of thin layer drying of pomegranate arils (Nikbakht, Motevali, & Minaei, 2013).

A more detailed method that extends *ExA* by considering the coupling of driving forces to minimize entropy production (i.e. exergy destruction) through the use of non-equilibrium thermodynamics was proposed by Kjelstrup et al. (2004). A related field is that of finite time thermodynamics which aims at elucidating the most optimal thermodynamic path or mode of operation of processes that produce the minimum amount of entropy (or destroy a minimum amount of exergy) (Andresen, 2011). The potential of those methodologies seems very exciting but their application within the food industry is yet to be explored.

Conclusions

ExA is a methodology to assess the sustainability of food chains, based on objective thermodynamic laws. The results of *ExA* do not provide a direct solution, but they lead to a better understanding of the reasons for the occurrence of losses. Although *ExA* in the food industry is still in its infancy, it shows a growing trend with most of the applications targeting on drying processes due to the high energy requirements involved in those processes. Exergetic indicators can be used to provide insight for potential improvements along the complete food chain. The most commonly used ones in the food industry are the *exergetic efficiency*, the *absolute exergy loss*, the *improvement potential*, the *entropy generation*, the *exergy destruction ratio*, the *exergetic factor*, and the *cumulative exergy losses*. A food chain is thermodynamically

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sustainable when the selected exergetic indicators attain their most optimal values. Each process along the food chain should be designed to utilize all the available quality of its input(s), and to degrade it in the best possible manner, i.e. destroying the least amount of exergy while generating the minimum amount of entropy, by avoiding the production of waste streams, or reusing them in case where avoidance is not possible. However, when waste streams are to be reused, the proper allocation of their exergetic content should be considered carefully as this is still a matter of debate amongst the scientific community. Moreover, care should be taken when defining system boundaries because these can affect the outcome of the analysis considerably. Replacing fossil fuel energy sources with renewable energy sources will also contribute in improving the exergetic sustainability of a food chain.

This review identifies several points of attention for *ExA* to gain acceptance in the food industry. Firstly, it is clear that any modification in the design of a food chain should comply with quality and safety standards, and any impact of physico-chemical transformations occurring during processing of food components on their nutritive quality should be quantifiable. Secondly, there is a need for the scientific community to reach a consensus for the appropriate use of model validation, sensitivity, and uncertainty analysis techniques whenever dealing with variability in literature data or experimental uncertainty in *ExA*, and, therefore, enhancing the robustness of the assessment. Thirdly, the communication of the results of an *ExA* to non-expert stakeholders can be difficult and it can be as important as the analysis itself. Considering the above points, it is clear that the acceptance of *ExA* by the industrial food sector as a credible sustainability assessment method will be enhanced through developing a unified framework that provides guidelines for the design of food products of maximum nutritive value by using processes that destroy a minimum amount of exergy along the complete food chain.

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List of symbols

a	Water activity
B	Exergy
b_o	Specific chemical exergy
D_p	Exergy destruction ration
f	Exergetic factor
m	Mass
N	Number of moles
N_s	Entropy generation number
n	Efficiency
P	Pressure
Q	Thermal energy
R	Universal gas constant
S	Entropy
T	Temperature
V	Volume
x	Mole fraction
IP	Improvement potential
RI	Relative irreversibility
SI	Sustainability index
CEC	Cumulative exergy consumption

CEL	Cumulative exergy losses
SED	Specific exergy destruction

Greek letters

α	Exergetic renewability
β	Beta value (used in eco-exergy analysis)
ξ	Productivity lack
λ	Renewability performance indicator

Subscripts

o	Environment of reference
i	Stream
j	Component
th	Thermal
pr	Pressure
e	Electrical
eco	Eco-exergy

Highlights

- Exergy analysis can be used to assess the sustainability of industrial food chains
- Studies that apply exergy analysis on food processes show an increasing trend
- Nutritive aspects will become relevant in exergy analysis studies in the future

- The allocation of exergetic values in industrial waste streams lacks clarity
- A systematic framework could support exergy analysis implementation

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References

Aghbashlo, M., Kianmehr, M. H., & Arabhosseini, A. (2008). Energy and Exergy Analyses of Thin-Layer Drying of Potato Slices in a Semi-Industrial Continuous Band Dryer. *Drying Technology*, *26*, 1501-1508.

Aghbashlo, M., Kianmehr, M. H., & Arabhosseini, A. (2009). Performance analysis of drying of carrot slices in a semi-industrial continuous band dryer. *Journal of Food Engineering, 91*, 99-108.

Aghbashlo, M., Mobli, H., Madadlou, A., & Rafiee, S. (2012). Influence of spray dryer parameters on exergetic performance of microencapsulation processes. *International Journal of Exergy, 10*, 267-289.

Aghbashlo, M., Mobli, H., Rafiee, S., & Madadlou, A. (2012a). Energy and exergy analyses of the spray drying process of fish oil microencapsulation. *Biosystems Engineering, 111*, 229-241.

Aghbashlo, M., Mobli, H., Rafiee, S., & Madadlou, A. (2012b). Optimization of emulsification procedure for mutual maximizing the encapsulation and exergy efficiencies of fish oil microencapsulation. *Powder Technology*, *225*, 107-117.

Aghbashlo, M., Mobli, H., Rafiee, S., & Madadlou, A. (2012c). The use of artificial neural network to predict exergetic performance of spray drying process: A preliminary study. *Computers and Electronics in Agriculture, 88*, 32-43.

Aghbashlo, M., Mobli, H., Rafiee, S., & Madadlou, A. (2013). A review on exergy analysis of drying processes and systems. *Renewable and Sustainable Energy Reviews, 22*, 1-22.

Ahamed, J. U., Saidur, R., Masjuki, H. H., Mekhilef, S., Ali, M. B., & Furqon, M. H. (2011). An application of energy and exergy analysis in agricultural sector of Malaysia. *Energy Policy, 39*, 7922-7929.

Akbulut, A., & Durmuş, A. (2010). Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer. *Energy, 35*, 1754-1763.

Akinoso, R., Lawal, I. A., & Aremu, A. K. (2013). Energy requirements of size reduction of some selected cereals using attrition mill. *International Food Research Journal, 20*, 1205-1209.

Akpinar, E. K. (2004). Energy and exergy analyses of drying of red pepper slices in a convective type dryer. *International Communications in Heat and Mass Transfer, 31*, 1165-1176.

Akpinar, E. K. (2005a). Energy and exergy analyses of drying of eggplant slices in a cyclone type dryer. *Journal of Mechanical Science and Technology, 19*, 692-703.

Akpinar, E. K. (2005b). Thermodynamic analysis of the apple drying process. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 219*, 1-14.

Akpinar, E. K. (2007). Thermodynamic analysis of strawberry drying process in a cyclone type dryer. *Journal of Scientific & Industrial Research, 66*, 152-161.

Akpinar, E. K. (2010a). Drying of mint leaves in a solar dryer and under open sun: Modelling, performance analyses. *Energy Conversion and Management, 51*, 2407-2418.

Akpinar, E. K. (2010b). Exergy analysis associated with heat transfer during heating of slab products. *International Journal of Exergy, 7*, 66-75.

Akpinar, E. K. (2011). Drying of parsley leaves in a solar dryer and under open sun: Modelling, energy and exergy aspects. *Journal of Food Process Engineering, 34*, 27-48.

ACCEPTED MANUSCRIPT

Akpinar, E. K., Midilli, A., & Bicer, Y. (2005). Energy and exergy of potato drying process via cyclone type dryer. *Energy Conversion and Management, 46*, 2530-2552.

Akpinar, E. K., Midilli, A., & Bicer, Y. (2006). The first and second law analyses of thermodynamic of pumpkin drying process. *Journal of Food Engineering, 72*, 320-331.

Akpinar, E. K., & Sarsilmaz, C. (2004). Energy and exergy analyses of drying of apricots in a rotary solar dryer. *International Journal of Exergy, 1*, 457-474.

Alamilla-Beltrán, L., Welti-Chanes, J., Chanona-Pérez, J. J., Perea-flores, M. d. J., & Gutierrez-López, G. F. (2011). Emerging Technologies for Food Processing. In *Food Processing Handbook* (pp. 205-224): Wiley-VCH Verlag GmbH & Co. KGaA.

Amantéa, R. P., Fortes, M., Martins, J. H., & Ferreira, W. R. (2013). Numerical Simulation Techniques for Optimizing Thermodynamic Efficiencies of Cereal Grain Dryers. *Drying Technology, 31*, 672-683.

Andresen, B. (2011). Current trends in finite-time thermodynamics. *Angewandte Chemie - International Edition, 50*, 2690-2704.

Aneke, M., Agnew, B., Underwood, C., & Menkiti, M. (2012). Thermodynamic analysis of alternative refrigeration cycles driven from waste heat in a food processing application. *International Journal of Refrigeration, 35*, 1349-1358.

Apaiah R. K., L. A. R., van der Kooi H.J. (2006). *Desigining food supply chains - A structured methodology: A case on Novel Protein Foods.* Wageningen University.

Apaiah, R. K., Linnemann, A. R., & Van Der Kooi, H. J. (2006). Exergy analysis: A tool to study the sustainability of food supply chains. *Food Research International, 39*, 1-11.

Assari, M. R., Basirat Tabrizi, H., & Najafpour, E. (2013). Energy and exergy analysis of fluidized bed dryer based on two-fluid modeling. *International Journal of Thermal Sciences, 64*, 213-219.

Balkan, F., Colak, N., & Hepbasli, A. (2005). Performance evaluation of a triple-effect evaporator with forward feed using exergy analysis. *International Journal of Energy Research, 29*, 455-470.

Bapat, S. M., Majali, V. S., & Ravindranath, G. (2013). Exergetic evaluation and comparison of quintuple effect evaporation units in Indian sugar industries. *International Journal of Energy Research, 37*, 1415-1427.

Bennamoun, L. (2012). An overview on application of exergy and energy for determination of solar drying efficiency. *International Journal of Energy Engineering, 2*, 184-194.

Berg, C. A. (1980). Process integration and the second law of thermodynamics: Future possibilities. *Energy, 5*, 733-742.

Bolaji, B. O. (2011). Exergetic analysis of solar energy drying systems. *Natural Resources, 2*, 92-97.

BoroumandJazi, G., Rismanchi, B., & Saidur, R. (2013). A review on exergy analysis of industrial sector. *Renewable and Sustainable Energy Reviews, 27*, 198-203.

Boulemtafes-Boukadoum, A., & Benzaoui, A. (2011). Energy and exergy analysis of solar drying process of mint. In *Energy Procedia* (Vol. 6, pp. 583-591).

Boyar, S., Akdeniz, R. C., & Hepbasli, A. (2012). Performance evaluation of an extruder system in a mixed feed factory. *Journal of Food, Agriculture and Environment, 10*, 524-527.

ACCEPTED MANUSCRIPT

Braungart, M., McDonough, W., & Bollinger, A. (2007). Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. *Journal of Cleaner Production*, *15*, 1337-1348.

Bruttini, R., Crosser, O. K., & Liapis, A. I. (2001). Exergy analysis for the freezing stage of the freeze drying process *Drying Technology*, *19*, 2303-2313.

Catton, W., Carrington, G., & Sun, Z. (2011). Exergy analysis of an isothermal heat pump dryer. *Energy*, *36*, 4616-4624.

Caudill, R. J., Olapiriyakul, S., & Seale, B. (2010). An exergy footprint metric normalized to US exergy consumption per capita. In *Sustainable Systems and Technology (ISSST), 2010 IEEE International Symposium on* (pp. 1-6).

Celma, A. R., & Cuadros, F. (2009). Energy and exergy analyses of OMW solar drying process. *Renewable Energy*, *34*, 660-666.

Chowdhury, M. M. I., Bala, B. K., & Haque, M. A. (2011). Energy and exergy analysis of the solar drying of jackfruit leather. *Biosystems Engineering*, *110*, 222-229.

Colak, N., Balta, M. T., Icier, F., Kuzgunkaya, E., Hepbasli, A., & Erbay, Z. (2010). Exergy analysis of food drying processes. In I. Dincer, A. Hepbasli, A. Midilli & T. Hikmet Karakoc (Eds.), *Global Warming - Engineering Solutions*.

Colak, N., Erbay, Z., & Hepbasli, A. (2013). Performance assessment and optimization of industrial pasta drying. *International Journal of Energy Research*, *37*, 913-922.

Colak, N., & Hepbasli, A. (2007). Performance analysis of drying of green olive in a tray dryer. *Journal of Food Engineering*, *80*, 1188-1193.

ACCEPTED MANUSCRIPT

Colak, N., & Hepbasli, A. (2009). A review of heat pump drying: Part 1 – Systems, models and studies. *Energy Conversion and Management, 50*, 2180-2186.

Colak, N., Kuzgunkaya, E., & Hepbasli, A. (2008). Exergetic assessment of drying of mint leaves in a heat pump dryer. *Journal of Food Process Engineering, 31*, 281-298.

Connelly, L., & Koshland, C. P. (1997). Two aspects of consumption: using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology. *Resources, Conservation and Recycling, 19*, 199-217.

Cornelissen, R. L. (1997). *Thermodynamics and sustainable development: The use of exergy analysis and the reduction of irreversibility*. University of Twente, Enschede, The Netherlands.

Corzo, O., Bracho, N., Vásquez, A., & Pereira, A. (2008a). Energy and exergy analyses of thin layer drying of coroba slices. *Journal of Food Engineering*, *86*, 151-161.

Corzo, O., Bracho, N., Vásquez, A., & Pereira, A. (2008b). Optimization of a thin layer drying process for coroba slices. *Journal of Food Engineering*, *85*, 372-380.

Cuce, E., & Cuce, P. M. (2013). Energetic and exergetic performance assessment of solar cookers with different geometrical designs. *International Journal of Ambient Energy*, 1-8.

Čuček, L., Klemeš, J. J., & Kravanja, Z. (2012). A Review of Footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production, 34*, 9-20.

Dalsgard, H., & Munkoe, L. (2000). Process integration in the Danish food industry - A case study. *International Journal of Applied Thermodynamics, 3*, 163-170.

ACCEPTED MANUSCRIPT

Damour, C., Hamdi, M., Josset, C., Auvity, B., & Boillereaux, L. (2012). Energy analysis and optimization of a food defrosting system. *Energy, 37*, 562-570.

Dewulf, J., Bösch, M. E., Meester, B. D., Vorst, G. V. d., Langenhove, H. V., Hellweg, S., & Huijbregts, M. A. J. (2007). Cumulative Exergy Extraction from the Natural Environment (CEENE): a comprehensive Life Cycle Impact Assessment method for resource accounting. *Environmental Science & Technology, 41*, 8477-8483.

Dewulf, J., Van Langenhove, H., Mulder, J., van den Berg, M. M. D., van der Kooi, H. J., & de Swaan Arons, J. (2000). Illustrations towards quantifying the sustainability of technology. *Green Chemistry, 2*, 108-114.

Dincer, I. (2002a). On energetic, exergetic and environmental aspects of drying systems. *International Journal of Energy Research, 26*, 717-727.

Dincer, I. (2002b). The role of exergy in energy policy making. *Energy Policy, 30*, 137-149.

Dincer, I. (2011). Exergy as a potential tool for sustainable drying systems. *Sustainable Cities and Society, 1*, 91-96.

Dincer, I., & Cengel, Y. (2001). Energy, Entropy and Exergy Concepts and Their Roles in Thermal Engineering. *Entropy, 3*, 116-149.

Dincer, I., & Rosen, M. A. (2013a). Chapter 2 - Exergy and Energy Analyses. In D. Ibrahim & A. R. Marc (Eds.), *Exergy (Second Edition)* (pp. 21-30): Elsevier.

Dincer, I., & Rosen, M. A. (2013b). Chapter 3 - Chemical Exergy. In D. Ibrahim & A. R. Marc (Eds.), *Exergy (Second Edition)* (pp. 31-49): Elsevier.

Dincer, I., & Rosen, M. A. (2013c). Chapter 5 - Applications of exergy in industry. In D. Ibrahim & A. R. Marc (Eds.), *Exergy (Second Edition)* (pp. 75-82): Elsevier.

ACCEPTED MANUSCRIPT

Dincer, I., & Rosen, M. A. (2013d). Chapter 6 - Exergy analysis of psychrometric processes. In D. Ibrahim & A. R. Marc (Eds.), *Exergy (Second Edition)* (pp. 83-100): Elsevier.

Dincer, I., & Sahin, A. Z. (2004). A new model for thermodynamic analysis of a drying process. *International Journal of Heat and Mass Transfer, 47*, 645-652.

Draganovic, V., Jørgensen, S. E., Boom, R., Jonkers, J., Riesen, G., & van der Goot, A. J. (2013). Sustainability assessment of salmonid feed using energy, classical exergy and eco-exergy analysis. *Ecological Indicators, 34*, 277-289.

Ducoulombier, M., Sorin, M., & Teyssedou, A. (2007). Thermodynamic bounds for food deep chilling tray tunnel operation. *International Journal of Thermal Sciences, 46*, 172-179.

Duhem, P. (1889). Sur les transformations et l' equilibre en Thermodynamique - Note de M.P. Duhem. *Comptes Rendus de l'Academie des Sciences Paris, 108*, 666-667.

El-Sebaii, A. A., & Shalaby, S. M. (2012). Solar drying of agricultural products: A review. *Renewable and Sustainable Energy Reviews, 16*, 37-43.

Erbay, Z., & Hepbasli, A. (2013). Advanced Exergy Analysis of a Heat Pump Drying System Used in Food Drying. *Drying Technology, 31*, 802-810.

Erbay, Z., & Hepbasli, A. (2014). Application of conventional and advanced exergy analyses to evaluate the performance of a ground-source heat pump (GSHP) dryer used in food drying. *Energy Conversion and Management, 78*, 499-507.

Erbay, Z., & Icier, F. (2009a). Optimization of drying of olive leaves in a pilot-scale heat pump dryer. *Drying Technology, 27*, 416-427.

Erbay, Z., & Icier, F. (2009b). Optimization of hot air drying of olive leaves using response surface methodology. *Journal of Food Engineering, 91*, 533-541.

Erbay, Z., & Icier, F. (2011). Energy and exergy analyses on drying of olive leaves in tray drier *Journal of Food Process Engineering, 34*, 2105-2123.

Erbay, Z., Icier, F., & Hepbasli, A. (2010). Exergetic performance assessment of a pilot-scale heat pump belt conveyor dryer. *International Journal of Energy Research, 34*, 249-264.

Erbay, Z., & Koca, N. (2012a). Energetic, Exergetic, and Exergoeconomic Analyses of Spray-Drying Process during White Cheese Powder Production. *Drying Technology*, *30*, 435-444.

Erbay, Z., & Koca, N. (2012b). Investigating the effects of operating conditions on the exergetic performance of a pilot-scale spray-drying system. *International Journal of Exergy*, *11*, 302-321.

Erbay, Z., Koca, N., Kaymak-Ertekin, F., & Ucuncu, M. (2014). Optimization of spray drying process in cheese powder production. *Food and Bioproducts Processing*.

Fang, Z., Larson, D. L., & Fleischmen, G. (1995). Exergy analysis of a milk processing system. *Transactions of the American Society of Agricultural Engineers, 38*, 1825-1832.

Fissore, D., Pisano, R., & Barresi, A. A. (2014). Applying quality-by-design to develop a coffee freeze-drying process. *Journal of Food Engineering*, *123*, 179-187.

Fortes, M. (2004). Second-law modeling of deep bed drying processes with a simulation study of wheat air-recirculated fluidized-bed drying. In *14th International Drying Symposium (IDS 2004)* (Vol. A, pp. 18-32). Sao Paulo, Brazil.

Fortes, M., & Ferreira, W. R. (2004). Second law analysis of drying - Modeling and simulation of fluidized bed grain drying. In *14th International Drying Symposium (IDS 2004)* (Vol. A, pp. 301-308). Sao Paulo, Brazil.

Fortes, M., Martins, J. H., Amantéa, R. P., & Ferreira, W. R. (2009). Transient and spatial energy and exergy analysis of deep-bed corn drying. In *American Society of Agricultural and Biological Engineers Annual International Meeting 2009* (Vol. 1, pp. 226-233).

Fritzsche, A. F., Hahnemann, H. W., & Rant, Z. (1956). Rundschau. *Forschung auf dem Gebiet des Ingenieurwesens A, 22*, 33-37.

Gaudreau, K., Roydon, A. F., & Murphy, S. (2009). The tenuous use of exergy as a measure of resource value or waste impact. *Sustainability, 1*, 1444-1463.

Gerbens-Leenes, P. W., Nonhebel, S., & Krol, M. S. (2010). Food consumption patterns and economic growth. Increasing affluence and the use of natural resources. *Appetite*, *55*, 597-608.

Giampietro, M., Bukkens, S. G. F., & Pimentel, D. (1994). Models of energy analysis to assess the performance of food systems. *Agricultural Systems*, *45*, 19-41.

Gong, M., & Wall, G. (1997). Exergy use in the Swedish society 1994. In *TAIES '97* (pp. 453-460). Beijing, China.

Gong, M., & Wall, G. (2001). On exergy and sustainable development—Part 2: Indicators and methods. *Exergy, An International Journal*, *1*, 217-233.

Gouy, G. (1889a). Sur l' energie utilisable. *Journal de Physique, 8*, 501-518.

Gouy, G. (1889b). Sur l' energie utilisable et le potentiel thermodynamique - Note de M. Gouy. *Comptes Rendus de l'Academie des Sciences Paris*, *108*, 794.

Gouy, G. (1889c). Sur les transformation et l'equilibre en Thermodynamique. *Comptes Rendus de l'Academie des Sciences Paris, 108*, 507-509.

Grip, C. E., Elfgren, E., Soderstrom, M., Thollander, P., Berntsson, T., Asblad, A., & Wang, C. (2011). Possibilities and problems in using exergy expressions in process integration. In *World Renewable Energy Congress* Linkoping, Sweden.

Gungor, A., Erbay, Z., & Hepbasli, A. (2011a). Exergetic analysis and evaluation of a new application of gas engine heat pumps (GEHPs) for food drying processes. *Applied Energy, 88*, 882-891.

Gungor, A., Erbay, Z., & Hepbasli, A. (2011b). Exergoeconomic analyses of a gas engine driven heat pump drier and food drying process. *Applied Energy, 88*, 2677-2684.

Gungor, A., Erbay, Z., & Hepbasli, A. (2012c). Exergoeconomic (Thermoeconomic) Analysis and Performance Assessment of a Gas Engine–Driven Heat Pump Drying System Based on Experimental Data. *Drying Technology, 30*, 52-62.

Gungor, A., Erbay, Z., Hepbasli, A., & Gunerhan, H. (2013). Splitting the exergy destruction into avoidable and unavoidable parts of a gas engine heat pump (GEHP) for food drying processes based on experimental values. *Energy Conversion and Management, 73*, 309-316.

Gustavsson, J., Cederberg, C., Sonesson, U., Otterdijk, R. v., & Meybeck, A. (2011). Global food losses and food waste - Extent, causes and prevention. In (pp. 37): Food and Agriculture Organization of the United Nations.

Hau, J. L., & Bakshi, B. R. (2004). Expanding Exergy Analysis to Account for Ecosystem Products and Services. *Environmental Science & Technology, 38*, 3768-3777.

Hepbasli, A. (2011). A comparative investigation of various greenhouse heating options using exergy analysis method. *Applied Energy, 88*, 4411-4423.

ACCEPTED MANUSCRIPT

Hepbasli, A., Colak, N., Hancioglu, E., Icier, F., & Erbay, Z. (2010). Exergoeconomic analysis of plum drying in a heat pump conveyor dryer. *Drying Technology, 28*, 1385-1395.

Hepbasli, A., Erbay, Z., Colak, N., Hancioglu, E., & Icier, F. (2010). An exergetic performance assessment of three different food driers. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 224*, 1-12.

Hermann, W. A. (2006). Quantifying global exergy resources. *Energy, 31*, 1685-1702.

Hernández-Díaz, W. N., Hernandez-Campos, F. J., Vargas-Galarza, Z., Rodríguez-Jimenes, G. C., & García-Alvarado, M. A. (2013). Coffee grain rotary drying optimization optimizacion del secado de granos de cafe en un secador rotatorio. *Revista Mexicana de Ingeniera Qumica, 12*, 315-325.

Hernando, F. M. D., & Hector, C. A. (2013). An exergetic cold chain methodological analysis on horticultural productive chains to evaluate productivity and competitiveness - Study case Andean blackberry. *International Journal of Agriculture and Forestry, 3*, 16-28.

Herrero, M., Laca, A., & Díaz, M. (2013). Chapter 15 - Life Cycle Assessment Focusing on Food Industry Wastes. In K. Maria & W. Colin (Eds.), *Food Industry Wastes* (pp. 265-280). San Diego: Academic Press.

Hevert, H. W., & Hevert, S. C. (1980). Second law analysis: An alternative indicator of system efficiency. *Energy, 5*, 865-873.

Ho, J. C., Wijeysundera, N. E., & Chou, S. K. (1986). Energy analysis applied to food processing. *Energy, 11*, 887-892.

Hoang, V.-N., & Rao, D. S. P. (2010). Measuring and decomposing sustainable efficiency in agricultural production: A cumulative exergy balance approach. *Ecological Economics, 69*, 1765-1776.

Icier, F., Colak, N., Erbay, Z., Kuzgunkaya, E. H., & Hepbasli, A. (2010). A Comparative Study on Exergetic Performance Assessment for Drying of Broccoli Florets in Three Different Drying Systems. *Drying Technology, 28*, 193-204.

Inaba, H. (2007). Heat and mass transfer analysis of fluidized bed grain drying. In *Memoirs of the Faculty of Engineering* (Vol. 41, pp. 52-62): Okayama University.

Jankowiak, L., Jonkman, J., Rossier-Miranda, F.J.,van der Goot, A.J.,Boom, R.M. (2014). Exergy driven process synthesis for isoflavone recovery from okara. *Energy*, doi: 10.1016/j.energy.2014.07.013

Jin, Y., & Chen, X. D. (2011). Entropy production during the drying process of milk droplets in an industrial spray dryer. *International Journal of Thermal Sciences, 50*, 615-625.

Jørgensen, S. E. (2007). Evolution and exergy. *Ecological Modelling, 203*, 490-494.

Kamate, S. C., & Gangavati, P. B. (2009). Exergy analysis of cogeneration power plants in sugar industries. *Applied Thermal Engineering, 29*, 1187-1194.

Karimi, F., Rafiee, S., Taheri-Garavand, A., & Karimi, M. (2012). Optimization of an air drying process for Artemisia absinthium leaves using response surface and artificial neural network models. *Journal of the Taiwan Institute of Chemical Engineers, 43*, 29-39.

Kay, J. J. (2002). Musings on the second law and life. In R. J. Minkel (Ed.). http://www.jameskay.ca/musings/thermomusings.pdf.

 ACCEPTED MANUSCRIPT

Keutenedjian Mady, C. E., Silva Ferreira, M., Itizo Yanagihara, J., Hilário Nascimento Saldiva, P., & de Oliveira Junior, S. (2012). Modeling the exergy behavior of human body. *Energy, 45*, 546-553.

Khoa, T. D., Shuhaimi, M., Hashim, H., & Panjeshahi, M. H. (2010). Optimal design of distillation column using three dimensional exergy analysis curves. *Energy, 35*, 5309-5319.

Kjelstrup, S., Rosjorde, A., & Johannessen, E. (2004). Non-equilibrium thermodynamics in industry. In T. M. Letcher (Ed.), *Chemical thermodynamics for industry*: RSC Publishin.

Klemeš, J., & Perry, S. (2008). Methods to minimise energy use in food processing. In J. S. Klemeš, R.

Kim, J. K. (Ed.), *Handbook of water and energy management in food processing* (pp. 136-199): Woodhead Publishing Series in Food Science, Technology and Nutrition.

Koning, N. B. J., Van Ittersum, M. K., Becx, G. A., Van Boekel, M. A. J. S., Brandenburg, W. A., Van Den Broek, J. A., Goudriaan, J., Van Hofwegen, G., Jongeneel, R. A., Schiere, J. B., & Smies, M. (2008). Long-term global availability of food: continued abundance or new scarcity? *NJAS - Wageningen Journal of Life Sciences, 55*, 229-292.

Koroneos, C., Spachos, T., & Moussiopoulos, N. (2003). Exergy analysis of renewable energy sources. *Renewable Energy, 28*, 295-310.

Kumar, N., Vishwanath, G., & Gupta, A. (2012). An exergy based unified test protocol for solar cookers of different geometries. *Renewable Energy, 44*, 457-462.

ACCEPTED MANUSCRIPT

Kuzgunkaya, E. H., & Hepbasli, A. (2007). Exergetic evaluation of drying of laurel leaves in a vertical ground-source heat pump drying cabinet. *International Journal of Energy Research*, *31*, 245-258.

Kytzia, S., Faist, M., & Baccini, P. (2004). Economically extended—MFA: a material flow approach for a better understanding of food production chain. *Journal of Cleaner Production*, *12*, 877-889.

La Rocca, V. (2011). Cold recovery during regasification of LNG part two: Applications in an Agro Food Industry and a Hypermarket. *Energy*, *36*, 4897-4908.

Lamnatou, C., Papanicolaou, E., Belessiotis, V., & Kyriakis, N. (2012). Experimental investigation and thermodynamic performance analysis of a solar dryer using an evacuated-tube air collector. *Applied Energy, 94*, 232-243.

Le Pierrès, N., Stitou, D., & Mazet, N. (2007). New deep-freezing process using renewable low-grade heat: From the conceptual design to experimental results. *Energy*, *32*, 600-608.

Lee, W., & Okos, M. R. (2011). Sustainable food processing systems - Path to a zero discharge: reduction of water, waste and energy. *Procedia Food Science*, *1*, 1768-1777.

Leites, I. L., Sama, D. A., & Lior, N. (2003). The theory and practice of energy saving in the chemical industry: some methods for reducing thermodynamic irreversibility in chemical technology processes. *Energy, 28*, 55-97.

Liu, Y., Zhao, Y., & Feng, X. (2008). Exergy analysis for a freeze-drying process. *Applied Thermal Engineering*, *28*, 675-690.

Luis, P. (2013). Exergy as a tool for measuring process intensification in chemical engineering. *Journal of Chemical Technology and Biotechnology*, *88*, 1951-1958.

ACCEPTED MANUSCRIPT

Mady, C. E. K. (2013). Human body exergy metabolism. *International Journal of Thermodynamics, 16*.

Maes, D., & Van Passel, S. (2014). Advantages and limitations of exergy indicators to assess sustainability of bioenergy and biobased materials. *Environmental Impact Assessment Review, 45*, 19-29.

Michalski, M. C., Genot, C., Gayet, C., Lopez, C., Fine, F., Joffre, F., Vendeuvre, J. L., Bouvier, J., Chardigny, J. M., & Raynal-Ljutovac, K. (2013). Multiscale structures of lipids in foods as parameters affecting fatty acid bioavailability and lipid metabolism. *Progress in Lipid Research, 52*, 354-373.

Midilli, A., & Kucuk, H. (2003). Energy and exergy analyses of solar drying process of pistachio. *Energy, 28*, 539-556.

Morosuk, T., Tsatsaronis, G., & Schult, M. (2013). Conventional and Advanced Exergetic Analyses: Theory and Application. *Arabian Journal for Science and Engineering, 38*, 395-404.

Motevali, A., & Minaei, S. (2012). Effects of microwave pretreatment on the energy and exergy utilization in thin-layer drying of sour pomegranate arils. *Chemical Industry & Chemical Engineering Quarterly, 18*.

Moya, C., Domínguez, R., Van Langenhove, H., Herrero, S., Gil, P., Ledón, C., & Dewulf, J. (2013). Exergetic analysis in cane sugar production in combination with Life Cycle Assessment. *Journal of Cleaner Production, 59*, 43-50.

Nazghelichi, T., Aghbashlo, M., & Kianmehr, M. H. (2011). Optimization of an artificial neural network topology using coupled response surface methodology and genetic algorithm for fluidized bed drying. *Computers and Electronics in Agriculture, 75*, 84-91.

Nazghelichi, T., Aghbashlo, M., Kianmehr, M. H., & Omid, M. (2011). Prediction of Energy and Exergy of Carrot Cubes in a Fluidized Bed Dryer by Artificial Neural Networks. *Drying Technology, 29*, 295-307.

Nazghelichi, T., Kianmehr, M. H., & Aghbashlo, M. (2010). Thermodynamic analysis of fluidized bed drying of carrot cubes. *Energy, 35*, 4679-4684.

Nikbakht, A. M., Motevali, A., & Minaei, S. (2013). Energy and exergy investigation of microwave assisted thin-layer drying of pomegranate arils using artificial neural networks and response surface methodology. *Journal of the Saudi Society of Agricultural Sciences*.

Nishitani, H., & Kunugita, E. (1983). Multiobjective Analysis for Energy and Resource Conservation in an Evaporation System. In *Efficiency and Costing* (Vol. 235, pp. 333-347): AMERICAN CHEMICAL SOCIETY.

Ohlsson, T. (2014). Chapter 43 - Sustainability and Food Production. In Y. Motarjemi & H. Lelieveld (Eds.), *Food Safety Management* (pp. 1085-1097). San Diego: Academic Press.

Ozgener, L. (2007). Exergoeconomic analysis of small industrial pasta drying systems. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 221*, 889-906.

Ozgener, L., & Ozgener, O. (2006). Exergy analysis of industrial pasta drying process. *International Journal of Energy Research, 30*, 1323-1335.

Ozgener, L., & Ozgener, O. (2009a). Exergy Analysis of Drying Process: An Experimental Study in Solar Greenhouse. *Drying Technology, 27*, 580-586.

Ozgener, L., & Ozgener, O. (2009b). Parametric study of the effect of reference state on energy and exergy efficiencies of a small industrial pasta drying process. *International Journal of Exergy, 6*, 477-490.

Özilgen, M., & Sorgüven, E. (2011). Energy and exergy utilization, and carbon dioxide emission in vegetable oil production. *Energy, 36*, 5954-5967.

Palacios-Bereche, R., Mosqueira-Salazar, K. J., Modesto, M., Ensinas, A. V., Nebra, S. A., Serra, L. M., & Lozano, M.-A. (2013). Exergetic analysis of the integrated first- and second-generation ethanol production from sugarcane. *Energy, 62*, 46-61.

Pandey, A. K., Tyagi, V. V., Park, S. R., & Tyagi, S. K. (2012). Comparative experimental study of solar cookers using exergy analysis. *109*, 425-431.

Pandey, S. D., & Nema, V. K. (2011). An experimental investigation of exergy loss reduction in corrugated plate heat exchanger. *Energy, 36*, 2997-3001.

Panwar, N. L., Kaushik, S. C., & Kothari, S. (2012). A review on energy and exergy analysis of solar drying systems. *Renewable and Sustainable Energy Reviews, 16*, 2812-2819.

Pellegrini, L. F., & de Oliveira Junior, S. (2011). Combined production of sugar, ethanol and electricity: Thermoeconomic and environmental analysis and optimization. *Energy, 36*, 3704-3715.

Prommas, R., Keangin, P., & Rattanadecho, P. (2010). Energy and exergy analyses in convective drying process of multi-layered porous packed bed. *International Communications in Heat and Mass Transfer, 37*, 1106-1114.

ACCEPTED MANUSCRIPT

Prommas, R., Rattanadecho, P., & Cholaseuk, D. (2010). Energy and exergy analyses in drying process of porous media using hot air. *International Communications in Heat and Mass Transfer, 37*, 372-378.

Prommas, R., Rattanadecho, P., & Jindarat, W. (2012). Energy and exergy analyses in drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt system (CMCB). *International Communications in Heat and Mass Transfer, 39*, 242-250.

Quijera, J. A., García, A., Alriols, M. G., & Labidi, J. (2013). Heat integration options based on pinch and exergy analyses of a thermosolar and heat pump in a fish tinning industrial process. *Energy*.

Quijera, J. A., & Labidi, J. (2013). Pinch and exergy based thermosolar integration in a dairy process. *Applied Thermal Engineering, 50*, 464-474.

Raghu Ram, J., & Banerjee, R. (2003). Energy and cogeneration targeting for a sugar factory. *Applied Thermal Engineering, 23*, 1567-1575.

Ramirez, C. A. (2005). *Monitoring energy efficiency in the food industry.* University of Utrecht.

Ranjbaran, M., & Zare, D. (2013). Simulation of energetic- and exergetic performance of microwave-assisted fluidized bed drying of soybeans. *Energy, 59*, 484-493.

Rosen, M. A., Dincer, I., & Kanoglu, M. (2008). Role of exergy in increasing efficiency and sustainability and reducing environmental impact. *Energy Policy, 36*, 128-137.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., & Shiina, T. (2009). A review of life cycle assessment (LCA) on some food products. *Journal of Food Engineering, 90*, 1-10.

ACCEPTED MANUSCRIPT

Saidur, R., Ahamed, J. U., & Masjuki, H. H. (2010). Energy, exergy and economic analysis of industrial boilers. *Energy Policy, 38*, 2188-2197.

Sami, S., Etesami, N., & Rahimi, A. (2011). Energy and exergy analysis of an indirect solar cabinet dryer based on mathematical modeling results. *Energy, 36*, 2847-2855.

Sciubba, E. (2001). Beyond thermoeconomics? The concept of Extended Exergy Accounting and its application to the analysis and design of thermal systems. *Exergy, An International Journal, 1*, 68-84.

Sciubba, E. (2009). Exergy-based ecological indicators - A necessary tool for resource use assessment studies. *Termotehnica, 1*, 11-25.

Seckin, C., Sciubba, E., & Bayulken, A. R. (2013). Extended exergy analysis of Turkish transportation sector. *Journal of Cleaner Production, 47*, 422-436.

Shukuya, M. (2013a). Renewing Our View with the Concept of Exergy. In *Exergy* (pp. 1-15): Springer London.

Shukuya, M. (2013b). Theory for Open Systems. In *Exergy* (pp. 231-364): Springer London.

Sogut, Z., Ilten, N., & Oktay, Z. (2010). Energetic and exergetic performance evaluation of the quadruple-effect evaporator unit in tomato paste production. *Energy, 35*, 3821-3826.

Sorgüven, E., & Özilgen, M. (2012). Energy utilization, carbon dioxide emission, and exergy loss in flavored yogurt production process. *Energy, 40*, 214-225.

Stanek, W., & Gazda, W. (2014). Exergo-ecological evaluation of adsorption chiller system. *Energy, 1*.

Stougie, L., Bart, G. C. J., Boelman, E. C., Asada, H., Infante Ferreira, C. A., van Der Kooi, H. J., Oldenhof, S., & Woudstra, N. (2002). *Energy efficiency and the quality of energy in the food processing industry*: Delft University of Technology.

Stougie, L., & Van Der Kooi, H. J. (2011). The relation between exergy and sustainability according to literature. In *2nd International Exergy, Life Cycle Assessment and Sustainability Workshop & Symposium (ELCAS2)*. Nisyros, Greece.

Syahrul, S., Dincer, I., & Hamdullahpur, F. (2003). Thermodynamic modeling of fluidized bed drying of moist particles. *International Journal of Thermal Sciences, 42*, 691-701.

Syahrul, S., Hamdullahpur, F., & Dincer, I. (2002). Exergy analysis of fluidized bed drying of moist particles. *Exergy, An International Journal, 2*, 87-98.

Szargut, J. (1980). International progress in second law analysis. *Energy, 5*, 709-718.

Szargut, J. (1987). Analysis of cumulative exergy consumption. *International Journal of Energy Research, 11*, 541-547.

Szargut, J. (1988). Exergy losses in the chains of technological processes. *Bulletin of the Polish Academy of Sciences. Technical Sciences, 36*, 513-521.

Szargut, J. (1989). Chemical exergies of the elements. *Applied Energy, 32*, 269-286.

Szargut, J. (2005). Exergy analysis. In *Academia* (Vol. 3, pp. 31-33).

Szargut, J., Morris, D. R., & Steward, F. R. (1988). *Exergy analysis of thermal, chemical, and metallurgical processes*. New York: Hemisphere.

Talens Peiró, L. T., Méndez, G. V., & Durany, X. G. I. (2008). Exergy analysis of integrated waste management in the recovery and recycling of used cooking oils. *Environmental Science and Technology, 42*, 4977-4981.

ACCEPTED MANUSCRIPT

Talens Peiró, L., Lombardi, L., Villalba Méndez, G., & Gabarrell i Durany, X. (2010). Life cycle assessment (LCA) and exergetic life cycle assessment (ELCA) of the production of biodiesel from used cooking oil (UCO). *Energy, 35*, 889-893.

Tambunan, A. H., Manalu, L. P., & Abdullah, K. (2010). Exergy Analysis on Simultaneous Charging and Discharging of Solar Thermal Storage for Drying Application. *Drying Technology, 28*, 1107-1112.

Tiwari, G. N., Das, T., Chen, C. R., & Barnwal, P. (2009). Energy and exergy analyses of greenhouse fish drying. *International Journal of Exergy, 6*, 620-636.

Tsatsaronis, G., & Cziezla, F. (1999). Strengths and limitations of exergy analysis. In *Encyclopedia of Life Support Systems* (Vol. Vol. I): Technical University of Berlin.

Tsatsaronis, G., & Morosuk, T. (2012). Understanding and improving energy conversion systems with the aid of exergy-based methods. *International Journal of Exergy*, *11*, 518-542.

Tyagi, S. K., Tyagi, V. V., Anand, S., Chandra, V., & Diwedi, R. C. (2009). First and second law analyses of a typical solar air dryer system: a case study. *International Journal of Sustainable Energy*, *29*, 8-18.

United Nations. (2013). World population prospects: the 2012 revision. In *Press Release* (13 June 2013 ed.): Department of Economic and Social Affairs.

Valero, A. (1998). Thermoeconomics as a conceptual basis for energy-ecological analysis. In S. Ulgiati (Ed.), *Advances in Energy Studies - Energy Flows in Ecology and Economy* (pp. 415-444).

Van Gool, W. (1980). Thermodynamic aspects of energy conservation. *Energy, 5*, 783-792.

Van Gool, W. (1997). Energy Policy: Fairy Tales and Factualities. In O. D. Soares, A. M. Cruz, G. C. Pereira, I. R. T. Soares & A. P. S. Reis (Eds.), *Innovation and Technology — Strategies and Policies* (pp. 93-105): Springer Netherlands.

Velásquez-Arredondo, H. I., Ruiz-Colorado, A. A., & De Oliveira junior, S. (2010). Ethanol production process from banana fruit and its lignocellulosic residues: Energy analysis. *Energy, 35*, 3081-3087.

Vintila, I. (2012). Mass and heat transfer coefficients assessment, optimisation and validation for multiphase food systems under transient stages. *Trends in Food Science & Technology, 26*, 114-119.

Waheed, M. A., Jekayinfa, S. O., Ojediran, J. O., & Imeokparia, O. E. (2008). Energetic analysis of fruit juice processing operations in Nigeria. *Energy, 33*, 35-45.

Wall, G. (1988). Exergy flows in industrial processes. *Energy, 13*, 197-208.

Wall, G. (1990). Exergy conversion in the Japanese society. *Energy, 15*, 435-444.

Wall, G. (2009). Exergetics. In G. Wall (Ed.). Bucaramanga.

Xiang, J. Y., Calì, M., & Santarelli, M. (2004). Calculation for physical and chemical exergy of flows in systems elaborating mixed-phase flows and a case study in an IRSOFC plant. *International Journal of Energy Research, 28*, 101-115.

Xydis, G., Koroneos, C., & Nanaki, E. (2011). Exergy-based comparison of two Greek industries. *International Journal of Exergy, 8*, 460-476.

Zhu, P., & Feng, X. (2007). Allocation of cumulative exergy in multiple product separation processes. *Energy, 32*, 137-142.

ACCEPTED MANUSCRIPT

Zvolinschi, A., Kjelstrup, S., Bolland, O., & van der Kooi, H. J. (2007). Exergy Sustainability Indicators as a Tool in Industrial Ecology. *Journal of Industrial Ecology*, *11*, 85-98.

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Table 1. Indicative list of forms of exergy and formulas used for their calculation.

Form of exergy	Formulas
Total exergy of a stream	$B_i = B_{i,physical} + B_{i,chemical} + B_{mix}$
Physical exergy of a stream	$B_{i,physical} = B_{i,th} + B_{i,pr} + \cdots + B_{i,e}$
Thermal exergy of a stream	$B_{i,th} = \int_{T_1}^{T_2} \left(1 - \frac{T_o}{T}\right) dQ_i$
Pressure exergy of an incompressible liquid stream	$B_{i,pr} = \int_{P_1}^{P_2} PdV$
Pressure exergy of an gaseous stream	$B_{i,pr} = RT_o ln\left(\frac{P}{P_o}\right)$
Chemical exergy of a stream	$B_{i,chemical} = m_i \sum (b_{o,j} x_j)$
Mixing exergy	$B_{mix} = N_i RT_o \sum \left(x_j \ln(a_j)\right)$

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Table 2. Indicative but not exhaustive list with various exergetic indicators found in literature after the comparison of 134 publications to the best of the authors knowledge.

Indicator	Formula	References
Exergetic efficiency	$n_{exergy} = \frac{\sum B_{out}}{\sum B_{in}} \quad or \quad \left(\frac{\sum B_{product}}{\sum B_{in}}\right)^{1} \quad or \quad \frac{\sum B_{required}}{\sum B_{in}} \quad or \quad \frac{\sum B_{requi}}{\sum B_{provi}}$	Evaporation of tomato paste (Sogut, Ilten, & Oktay, 2010), milk and bread processing (Ho, Wijeysundera, & Chou, 1986), fish drying (Tiwari, Das, Chen, & Barnwal, 2009), extrusion of fish feed (Boyar, Akdeniz, & Hepbasli, 2012), drying of rice

[1]Also known as *cumulative degree of perfection* and its use is demonstrated in the production of yoghurt (Sorgüven & Özilgen, 2012), and vegetable oil (Özilgen & Sorgüven, 2011).

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		(Pandey, Tyagi, Park, & Tyagi, 2012), carrot cubes (Nazghelichi, Kianmehr, & Aghbashlo, 2010), cereal grains (Amantéa, Fortes, Martins, & Ferreira, 2013), red pepper (Akpinar, 2004), mulberry (Akbulut & Durmuş, 2010), coroba slices (Corzo, Bracho, Vásquez, & Pereira, 2008a, 2008b), corn (Bolaji, 2011;

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		Fortes, Martins, Amantéa, & Ferreira, 2009; Syahrul, Dincer, & Hamdullahpur, 2003), wheat (Assari, Basirat Tabrizi, & Najafpour, 2013; Fortes, 2004; Fortes & Ferreira, 2004; Inaba, 2007), carrot (Aghbashlo, Kianmehr, & Arabhosseini, 2009), pistachio (Midilli & Kucuk, 2003), coffee (Fissore, Pisano, & Barresi, 2014; Hernández-Díaz,

		Hernandez-Campos, Vargas-Galarza, Rodríguez-Jimenes, & García-Alvarado, 2013), chili (Sami, Etesami, & Rahimi, 2011), olive leaves (Celma & Cuadros, 2009; Erbay & Icier, 2009a; Erbay & Icier, 2011), beef (Liu, Zhao, & Feng, 2008), mint leaves (Akpinar, 2010a; Boulemtafes-Boukadoum & Benzaoui, 2011;

		Colak, Kuzgunkaya, & Hepbasli, 2008), parsley leaves (Akpinar, 2011), jackfruit leather (Chowdhury, Bala, & Haque, 2011), multilayer porous media (Prommas, Keangin, & Rattanadecho, 2010), solar greenhouse drying (Ozgener & Ozgener, 2009a), solar air drying (Tyagi, Tyagi, Anand, Chandra, & Diwedi, 2009),

		steam production (Saidur, Ahamed, & Masjuki, 2010), co-generation in sugar production (Kamate & Gangavati, 2009), ethanol production (Palacios-Bereche, et al., 2013), milling of cereals (Akinoso, Lawal, & Aremu, 2013), pasta (Ozgener, 2007; Ozgener & Ozgener, 2006; Ozgener & Ozgener, 2009b), cheese powder

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		(Erbay, Koca, Kaymak-Ertekin, & Ucuncu, 2014), ethanol production from banana and its residues (Velásquez-Arredondo, Ruiz-Colorado, & De Oliveira junior, 2010)
Exergy losses	$\sum B_{lost} = \sum B_{in} - \sum B_{out} = \sum B_{destroyed} + \sum B_{wasted}$	Drying of potato (Aghbashlo, Kianmehr, & Arabhosseini, 2008; Akpinar, Midilli, & Bicer, 2005), pumpkin (Akpinar, Midilli, & Bicer, 2006), apple (Akpinar,

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		2005b), apricot (Akpinar & Sarsilmaz, 2004), strawberry (Akpinar, 2007), pomegranate (Motevali & Minaei, 2012), wheat (Syahrul, Hamdullahpur, & Dincer, 2002), multilayer porous media (Prommas, Rattanadecho, & Cholaseuk, 2010), non-hygroscopic porous media (Prommas, Rattanadecho, & Jindarat, 2012), eggplant (Akpinar, 2005a),

		plants (Gungor, Erbay, & Hepbasli, 2011c)
Improvement potential	$IP = \left(1 - n_{exergy}\right) \sum B_{lost}$	Drying of broccoli (Colak, et al., 2010; Icier, Colak, Erbay, Kuzgunkaya, & Hepbasli, 2010), pasta (Colak, Erbay, & Hepbasli, 2013), cheese powder (Erbay & Koca, 2012a), plums (Hepbasli, Colak, Hancioglu, Icier, & Erbay, 2010; Hepbasli, Erbay, Colak, Hancioglu,

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		& Icier, 2010), green olives (Colak & Hepbasli, 2007), fruits and vegetables (Gungor, Erbay, & Hepbasli, 2011a, 2011b), laurel leaves (Kuzgunkaya & Hepbasli, 2007), tinning of fish (Quijera, García, Alriols, & Labidi, 2013)
Entropy generation	$$\sum B_{destroyed} = T_o\left(S_{final\ staet}^{system} - S_{initial\ state}^{system} + S_{generated}^{senvironment}\right)$$	Pasteurization and concentration of orange juice (Balkan, et al., 2005; Waheed, Jekayinfa,

		Ojediran, & Imeokparia, 2008), spray drying of milk powder (Jin & Chen, 2011), spray drying microencapsulation of fish oil (Aghbashlo, Mobli, Madadlou, & Rafiee, 2012; Aghbashlo, Mobli, Rafiee, & Madadlou, 2012a, 2012b, 2012c), waste heat utilization for frying potato (Aneke, Agnew, Underwood, & Menkiti, 2012),

		solar drying of fruits and vegetables (Lamnatou, Papanicolaou, Belessiotis, & Kyriakis, 2012)[2]
Exergy destruction ratio	$D_p = \frac{\sum B_{destroyed}}{\sum B_{in}} = 1 - n_{exergy}$	Drying of soybeans (Ranjbaran & Zare, 2013), plums (Erbay & Hepbasli, 2013), olive leaves (Erbay, Icier, & Hepbasli, 2010), cheese powder spray drying (Erbay & Koca, 2012a), sugar

[2]Use of the *entropy generation number* N_s which is calculated based on the ratio of the thermal energy of the product over the solar energy absorbed, and it indicates the entropy produced during the conversion of solar to thermal energy.

		production (Bapat, Majali, & Ravindranath, 2013)
Sustainability index	$$SI = \frac{1}{D_p}$$	Fruits and vegetables cultivation (Hepbasli, 2011), drying of laurel (Erbay & Hepbasli, 2014), cheese powder spray drying (Erbay & Koca, 2012b)
Cumulative exergy consumption	$$CEC = \sum B_{input}$$	Sugar production (Moya, et al., 2013; Raghu Ram & Banerjee, 2003), fish feed formulation (Draganovic, et

		al., 2013), recycling of used cooking oil (Talens Peiró, Méndez, & Durany, 2008; Talens Peiró, Lombardi, Villalba Méndez, & Gabarrell i Durany, 2010), general agricultural production (Hoang & Rao, 2010; Wall, 1990), vegetable oil production (Özilgen & Sorgüven, 2011)

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Cumulative exergy losses	$$CEL = CEC - \sum B_{useful}$$	Sugar production (Raghu Ram & Banerjee, 2003), societal chains that include the agricultural sector (Gong & Wall, 1997; Wall, 1990).
Exergetic factor	$$f = \frac{B_{fuel\ consumed\ at\ process\ i}}{\sum B_{fuel\ input}}$$	Drying of plums (Hepbasli, Erbay, et al., 2010), olive leaves (Erbay, et al., 2010), laurel (Erbay & Hepbasli, 2014), cheese powder spray drying (Erbay & Koca, 2012b)

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Specific exergy destruction	$SED = \frac{\sum B_{destroyed}}{m_{produced}}$	General chilling process (Ducoulombier, et al., 2007)
Relative irreversibility	$RI = \frac{B^{i}_{destroyed}}{\sum B_{destroyed}}$	Drying of olive leaves (Erbay, et al., 2010), of laurel (Erbay & Hepbasli, 2014), cheese powder spray drying (Erbay & Koca, 2012b)
Productivity lack	$\xi_i = \frac{B^{i}_{destroyed}}{\sum B_{product}}$	Cheese powder spray drying (Erbay & Koca, 2012b)
Exergetic renewability	$\alpha = \frac{B_{renewable}}{\sum B_{in}}$	Sugar production (Bapat, et al., 2013)[3] (Moya, et

[3]Defined as *exergy renewability ratio*: $ERR = \frac{\sum B_{evaporation} + \sum B_{product}}{\sum B_{in}}$

		al., 2013)[4], fruits and vegetables cultivation (Hepbasli, 2011)
Renewability performance indicator	$\lambda = \frac{\sum B_{product}}{\sum B_{fossil} + \sum B_{destroyed} + \sum B_{deactivation} + \sum B_{emissions}}$	Ethanol production from banana and its residues (Velásquez-Arredondo, et al., 2010), production of sugar and ethanol (Pellegrini & de Oliveira Junior, 2011)
Eco-exergy	$B_{eco} = \sum_{i=0}^{n} (B_{chemical}\, \beta_i)$	Fish feed formulation (Draganovic, et al., 2013)

[4]The *non-renewable fraction* can also be calculated as: $\alpha = \frac{B_{non-renewable}}{\sum B_{in}}$

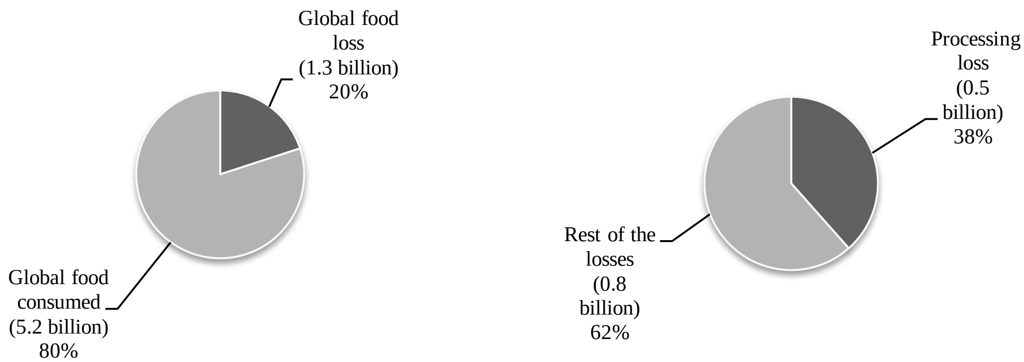

Figure 1. Left: Global food losses in relation to the total global food production. Right: Food processing losses in relation to the total global food losses. The values used for the estimations were adapted from the report of Gustavsson et al. (2011).

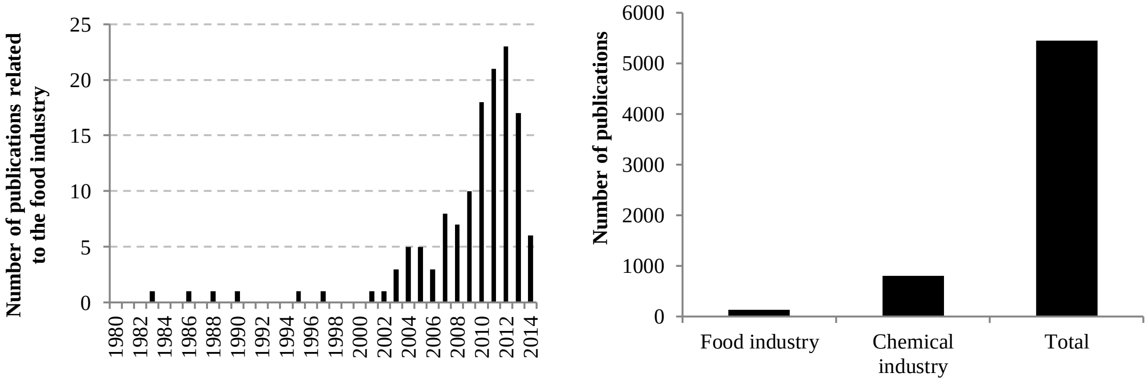

Figure 2.a Number of published papers related to exergy analysis applied in the food industry. The results are obtained after the comparison of 134 publications to the best of the authors knowledge. Figure 2.b Total number of exergy analysis publications related to the chemical industry as shown by Luis (2013), and to the food industry.

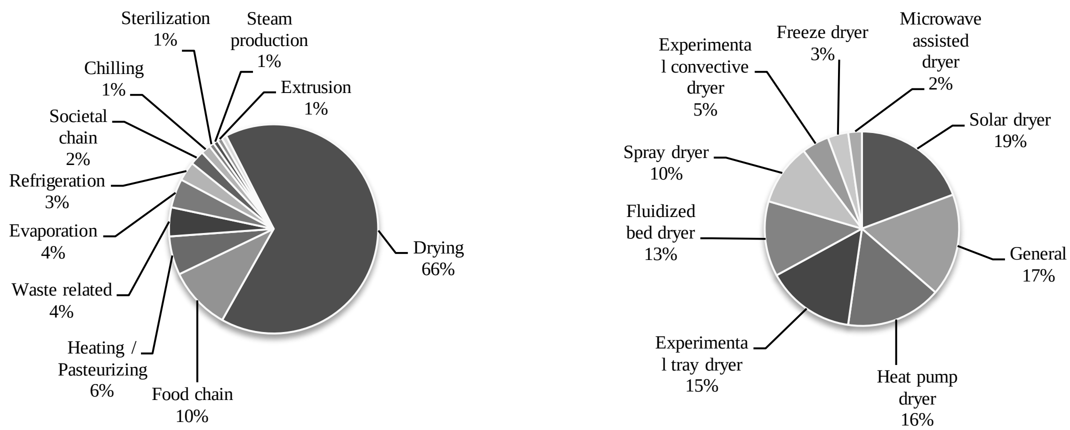

Figure 3. Publications of *ExA* applied in the food industry which show: figure 3.a. the main type of processes researched, and figure 3.b: the main drying technologies researched. The results are obtained after the comparison of 134 publications to the best of the authors' knowledge.

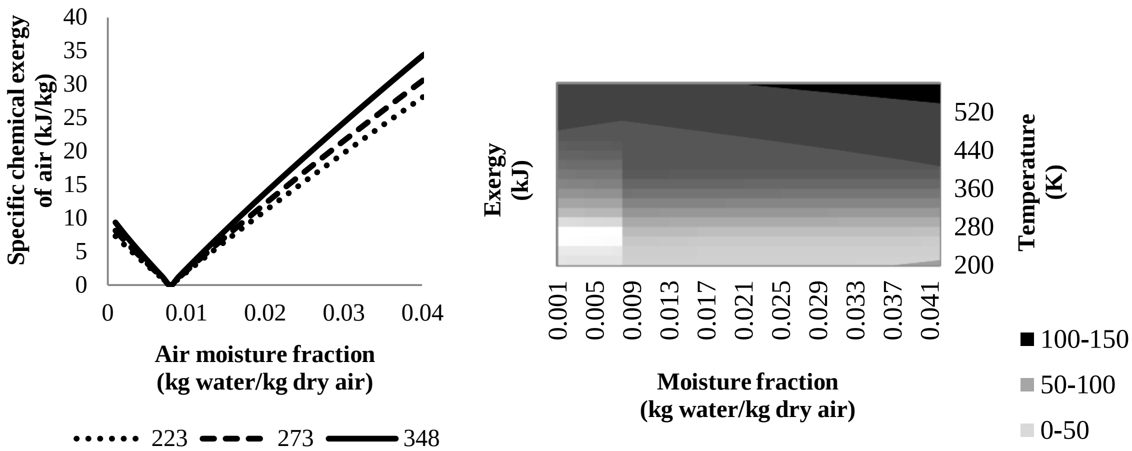

Figure 4.a. Chemical exergy of 1 kg of moist air as a function of its moisture content at a constant environmental moisture content (0.008 kg water/kg dry air) and at different environmental temperatures. Figure 4.b. Contour plot of the total exergy of 1 kg of moist air as a function of its moisture content (kg water/kg dry air) and its temperature (K) at constant environmental moisture content (0.008 kg water/kg dry air) and at constant environmental temperature (298 K).

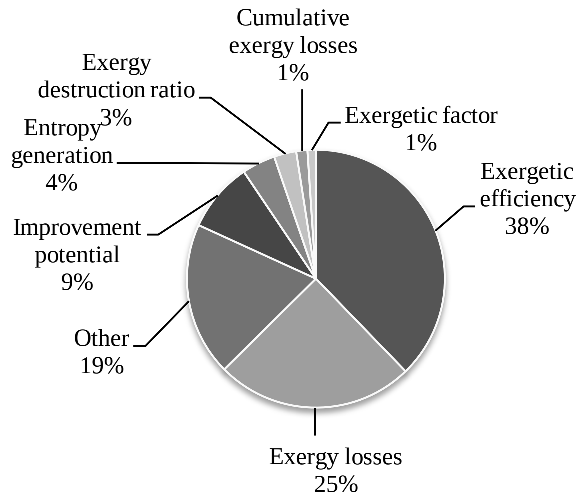

Figure 5. Main exergetic indicators used in industrial food processes and food chains. The results are obtained after the comparison of 134 publications to the best of the authors knowledge.

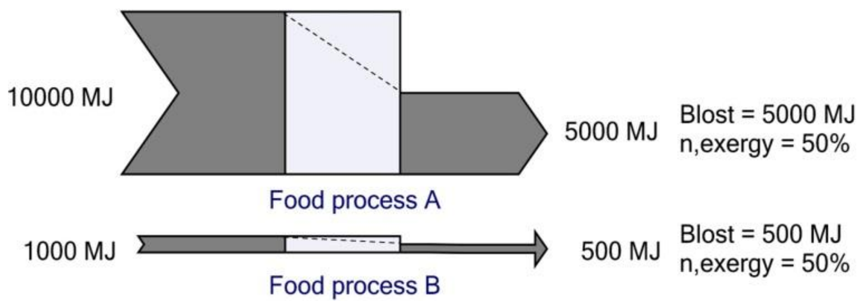

Figure 6. *Grassmann* diagrams of two different food processes that have the same exergetic efficiency.