Energy 40 (2012) 214–225

Contents lists available at SciVerse ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Energy utilization, carbon dioxide emission, and exergy loss in flavored yogurt production process

Esra Sorgüven [a,*], Mustafa Özilgen [b]

[a] Department of Mechanical Engineering, Yeditepe University, 34755 Kayisdagi Istanbul, Turkey
[b] Department of Food Engineering, Yeditepe University, 34755 Kayisdagi Istanbul, Turkey

ARTICLE INFO

Article history:
Received 27 October 2011
Received in revised form
30 January 2012
Accepted 1 February 2012
Available online 4 March 2012

Keywords:
Flavored yogurt
Energy utilization
Carbon dioxide emission
Exergy loss

ABSTRACT

This paper investigates the impact of food production processes on the environment in terms of energy and exergy utilization and carbon dioxide emission. There are three different energy utilization mechanisms in food production: Utilization of solar energy by plants to produce agricultural goods; feed consumption by herbivores to produce meat and milk; fossil fuel consumption by industrial processes to perform mixing, cooling, heating, etc. Production of strawberry-flavored yogurt, which involves these three mechanisms, is investigated here thermodynamically. Analysis starts with the cultivation of the ingredients and ends with the transfer of the final product to the market. The results show that 53% of the total exergy loss occurs during the milk production and 80% of the total work input is consumed during the plain yogurt making. The cumulative degree of perfection is 3.6% for the strawberry-flavored yogurt. This value can rise up to 4.6%, if renewable energy resources like hydropower and algal biodiesel are employed instead of fossil fuels. This paper points the direction for the development of new technology in food processing to decrease waste of energy and carbon dioxide accumulation in the atmosphere.

1. Introduction

Scarcity of energy resources and carbon dioxide concentration in the atmosphere are two major concerns of humanity. Since the beginning of the industrial revolution in 1850's, energy demand is rising, resources are diminishing and carbon dioxide concentration in the atmosphere is increasing. Consequences are publicly blamed for numerous environmental and climatic adverse observations. Increasing thermodynamic efficiency and decreasing CO_2 emission are essential. This paper illustrates the importance of a detailed thermodynamic analysis for a food production process. The strawberry-flavored yogurt production process is selected as an example, since it involves three important stages: agriculture, dairy farming, and industrial processes. Plants take energy from a renewable source, i.e. sun, and perform photosynthesis. The environmental cost for the agriculture is only due to the consumption of non-renewables, such as fertilizers, microelements and diesel consumed by farming machinery. Herbivores take energy from plant-based feed and use this energy for growth, locomotion, heat transfer, etc. In the case of calves, a small part of the intake energy is used for lactation, too. Industrial processes mainly consume fossil fuels; thus, the environmental cost of these operations is rather large. This paper shows the thermodynamical differences between the consumption of renewables and non-renewables by plants through photosynthesis, by calves to synthesize milk, and by industrial processes like mixing, refrigeration, transportation etc.

Energy utilization to produce several food products had been the subject of some studies in the past. However, the overall production process of flavored yogurt had never been a subject of such a study before. The exergy loss and carbon dioxide emission was not a part of previous studies either. This paper presents a unique approach, where the energy utilization, the carbon dioxide emission, and the exergy loss are calculated for a food product starting with the cultivation of the ingredients in the farm, and ending with the transfer of the final product to the market.

2. Methods

Fig. 1 shows the system chosen for the analysis. System boundaries involve milk production in the dairy farm, agriculture of strawberry and sugar beet, industrial processes to produce milk

* Corresponding author. Tel.: +90 216 578 04 98; fax: +90 216 578 04 00.
E-mail addresses: sorguven@yeditepe.edu.tr (E. Sorgüven), mozilgen@yeditepe.edu.tr (M. Özilgen).

0360-5442/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.energy.2012.02.003

Nomenclature

b	Stream availability, kJ/kmol
CDP	Cumulative degree of perfection, –
CCO_2E	Cumulative carbon dioxide emission, kg/ton
CEnC	Cumulative energy consumption, MJ/ton
CExC	Cumulative exergy consumption, MJ/ton
h	Enthalpy, kJ/kmol
m	mass, kg
Q	Heat, kJ
s	Entropy, kJ/(kmol K)
T	Temperature, K
W	Work output from the system, kJ
x	Molar fraction
X	Exergy, kJ

Subscripts

0	Restricted dead state
i	Any species
in	Inlet
k	Index of heat sources
out	Outlet

Superscripts

th	Thermomechanical
ch	Chemical

powder, sugar, jam and flavored yogurt, and recycling and waste management. Hydrosphere, lithosphere, and atmosphere act as water and carbon reservoirs, and are included within the system boundaries. Nutrient rich water consumed during the production is fully recycled. Fertilizers, pesticides, and micronutrients consumed during the agriculture are non-renewable chemicals, and the environmental cost for these raw materials is accounted for. Electricity used in all processes is generated from fossil fuels. The energy or exergy consumed due to human labor is not accounted for, since it was practically impossible to collect representative data. Transportation of goods is also taken into account. Average transportation distances are determined by considering the geographical situation in Turkey. Product delivery trucks are considered to be making one-way trip only, since in practice they usually carry other products on the way back. If trucks return empty, than the distance is multiplied by two to determine the actual distance traveled.

Data about the agriculture of strawberries and sugar beet, dairy farming and transportation are obtained from the literature. Information regarding energy utilization and processing rates of the equipment are obtained from the manufacturer web sites.

Mass, energy and exergy balance is performed for each operation. Exergy (availability) is defined as the maximum work that a system can produce, without violating the laws of thermodynamics, if it is brought to thermal, mechanical, and chemical equilibrium with its surroundings via reversible processes. The governing equations for this steady-flow system are:

Mass balance:

$$\sum (m)_{in} - \sum (m)_{out} = 0 \tag{1}$$

Energy balance:

$$\sum (mh)_{out} - \sum (mh)_{in} = Q - W \tag{2}$$

Exergy balance:

$$\sum (mb)_{in} - \sum (mb)_{out} - \sum_k Q_k \left(1 - \frac{T_0}{T_k}\right) - W = X_{loss} \tag{3}$$

Where k is the number of heat sources and b is the flow availability of a stream. The exergy content of a stream depends on its thermomechanical state (pressure, temperature, composition) and

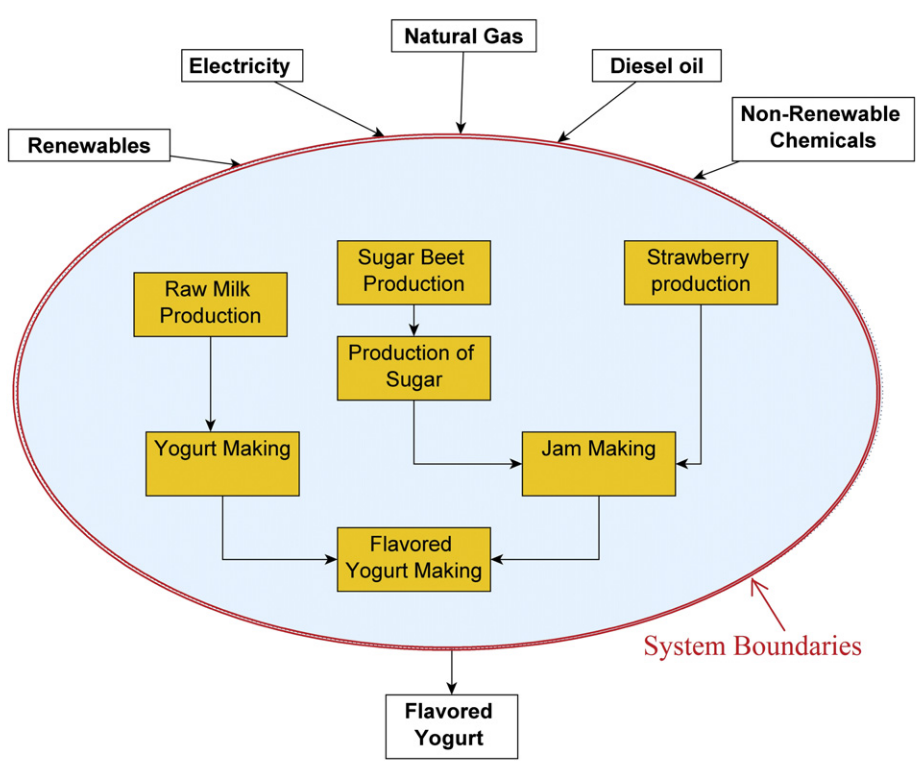

Fig. 1. Overall system.

chemical structure. Accordingly, flow availability is the sum of thermomechanical and chemical availabilities (neglecting the kinetic and potential energy contribution):

$$b = b^{\mathrm{th}} + b^{\mathrm{ch}} \tag{4}$$

Where:

$$b^{\mathrm{th}} = h - T_0 s$$

The chemical availability can be obtained from tables, if available or computed via group contribution method, if the chemical constitution of the compound is known. The group contribution method estimates b^{ch} as the sum of the chemical exergies of the simple chemical groups, which make up the chemical compound. Chemical exergy calculations are given in the Appendix.

The cumulative exergy consumption, (CExC), is defined as the sum of exergy of all resources consumed in all the steps of a production process [1]. CExC is a function of the pathway that the process follows, and quantifies the total consumption of the exergy, including those of the raw materials, transportation, work, and heat transfer for production. CExC of various fuels and industrial products have been calculated during the last decade [1,2]. Some studies started to appear in the literature focusing on the exergy consumption of a single unit [3–5] or the entire process [6] employed in food plants but the CExC calculations focusing on production of foods from farm to market are rare in the food industry [7].

The cumulative degree of perfection (CDP) is the ratio of the chemical exergy of the product to the sum of the exergies of all the raw materials and the fuel consumed during production [1]:

$$\mathrm{CDP} = \frac{(mb)_{\mathrm{product}}}{\sum (mb)_{\mathrm{raw\ materials}} + \sum (mb)_{\mathrm{fuels}}} \tag{5}$$

Strawberry-flavored yogurt is produced by stirring plain yogurt with strawberry jam. Main ingredients of yogurt are milk and microbial culture. Strawberry jam is produced from strawberries and sugar. Pectin is added to both yogurt and strawberry jam to bind water and improve texture. Although numerous formulations are available for yogurt making [8], only one recipe is considered in this study.

3. Results and discussion

3.1. Milk production

Koknaroglu published a detailed investigation on the annual energy requirements in a diary farm [9]. These data are summarized in Table 1 and are used here as a basis of the energy, exergy and CO_2 emission calculations. Inputs to the raw milk production process are feed and diesel, and the by-products are calves and organic manure. The energy utilized for the transportation includes the transportation of the milk to laboratory for analysis, to the factory for processing and the transportation of the feed from the manufacturer to the dairy farm. The energy utilization for the dairy operations includes those of preparing the feed, feeding, inspection, veterinary care, waste removal, milking, and those of water and direct electric consumption. Each cow gives birth to one calf with an average mass of 40 kg during this period [9].

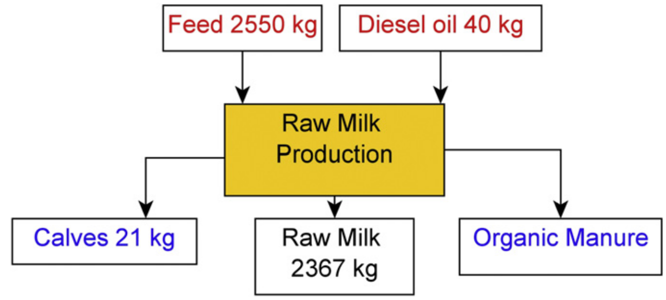

Fig. 2. Flowchart of raw milk production.

Fig. 2 shows the flowchart and the mass flow rates, which are scaled to obtain 1 ton of flavored yogurt at the end of the overall process. The CEnC, CExC and CCO_2E to produce raw milk are calculated by multiplying the scaled mass flow rates of each inlet stream shown in Fig. 2, with the specific values listed in the Table A1. Calculation of the specific CEnC, CExC and CCO_2E values are explained in the Appendix.

Results show that 9442.8 MJ of energy and 49824.9 MJ of exergy is consumed to produce 2367.0 kg of raw milk. The corresponding CO_2 emission is 625.6 kg (Table 2).

3.2. Non-fat yogurt production

Fig. 3 shows the steps of non-fat yogurt making from raw milk. First, fat is removed from raw milk with a skimming machine. The skimming machine MSM200 produced by Wenshou Topsky Enterprice, China has a capacity of 15–20 tons/h and an energy utilization of 6 MJ/h. If MSM200 is employed for skimming, than about 0.94 MJ of electricity is used, which corresponds to 3.95 MJ of exergy consumption and 0.13 kg of CO_2 emission.

About 60% of the skim milk is converted to milk powder. The average process specific energy consumption for milk powder production with spray drying is 11.1 GJ/ton of milk powder [10]. We assumed that only electric energy is used in this process to calculate the values in Table 3. The spray drying is an exergetically inefficient process, where 72% of the total exergy input is lost.

About 3% microbial culture is required to produce yogurt. On 20% non-fat dry milk media (1% fat, 35% proteins, 52% lactose and balance water) 5.0 10^9 cfu/mL of *Lactobacillus delbrueckii subspecies bulgaricus* and 1.1 10^9 cfu/mL of *Streptococcus thermophilus* are grown in 400 min [11]. Each cfu (colony forming unit) is about 9.5×10^{-13} g, and about 20% of non-cellular fermentation solids accompany the bacterial cells. Therefore, the wet weight of the starter culture is calculated to be 7.0 g/L. Electrical energy requirement to run an unaerated fermentor is around 100 J/L per meter of reactor diameter [12]; implying that in a 1 m diameter fermentor, the electrical power requirement is 0.1 MJ/kg of culture. When the fermentor is sterilized with steam produced from natural

Table 1
Annual energy utilization and milk yield in a dairy farm [9].

Feed	13,596 MJ/cow
Dairy operations	2322 MJ/cow
Transportation	1035 MJ/cow
Machinery	1017 MJ/cow
Average lactation	4498.6 kg milk/cow

Table 2
Energy and exergy consumed and CO_2 emitted to produce one ton of raw milk.

Activity	Energy utilization/ton of product (MJ/ton)	CExC/ton of product (MJ/ton)	CO_2 emission/ton of product (kg/ton)
Feed	3017.0	20,149.4	248.4
Diesel oil	972.3	900.4	15.9
Total	3989.4	21,049.8	264.3

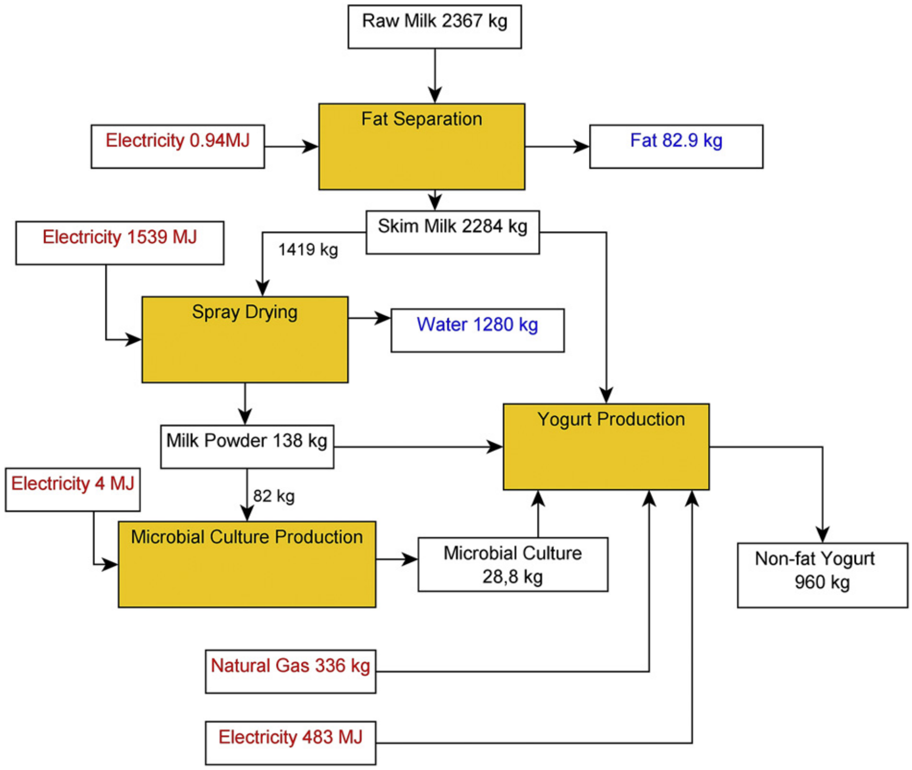

Fig. 3. Flowchart of yogurt production.

gas, the energy utilization for sterilization is negligible compared to that of running the fermentor. Therefore, calculations are performed only for the growth media. Results show that 4 MJ of energy and 16.8 MJ of exergy are consumed and 0.56 kg of CO_2 is emitted during microbial culture production. 47% of the consumed exergy is lost during this process.

One of the ingredients of yogurt is pectin. Recently developed technology makes it possible to produce pectin from residues of apple, citrus fruit, and sugar beet processing plants [13]. These residues are processed to reduce energy utilization for waste removal, and have a positive contribution to the energy balance of the plants. Therefore, the energy and exergy utilization and the carbon dioxide emission associated with pectin utilization in the flavored yogurt production will not be considered as a separate entry in our calculations. Our decision is also justified by the very small percentage, e.g., 1%, of pectin utilization in the yogurt formulation.

Table 3
Energy and exergy consumed and CO_2 emitted during the stages of the yogurt making process.

Activity	Main product	CEnC (MJ)	CExC (MJ)	CCO_2E (kg)
Raw milk production	2367 kg raw milk	9442.8	49,824.9	625.60
Fat separation	2284 kg skim milk	0.9	4.0	0.13
Spray drying	138 kg milk powder	1538.9	6417.0	215.44
Microbial culture production	28.8 kg microbial culture	4.0	16.8	0.56
Yogurt production	960 kg non-fat yogurt	17,283.6	18,392.3	1075.70
Total	960 kg unpacked non-fat yogurt (90% milk, 3% microbial culture, 6% skim milk powder and 1% pectin)	28,270.2	74,655.0	1917.43

Natural gas is used in heating and electricity is used in cooling stages of the yogurt making process. Mikiki and Rizet [14] reported that in France a factory, which produces 106,000 tons of yogurt annually, utilizes 53.4 10^6 MJ of electric power and 37,100 tons of natural gas in one year. Based on these data, energy consumption during yogurt production process is calculated as 17,283.6 MJ, exergy consumption as 18,392.3 MJ and CO_2 emission as 1075.70 kg. The plain yogurt making is the process with the highest energy input requirement, where 87% of the total consumed energy and 85% of the consumed exergy originates from fossil fuels; 89% of the total input exergy is lost, and only 11% of the input exergy is converted into the chemical exergy of yogurt.

3.3. Strawberry agriculture

Plants uptake CO_2 and convert it into organic compounds using the solar energy. The environmental effect of photosynthesis is quite different from lactation or industrial processes, since a vast portion of the input energy comes from a renewable source. Nonetheless, some non-renewable resources like fertilizers and microelements are used up during photosynthesis. Besides, fossil fuels and electricity are consumed to run agricultural machines or to transport agricultural goods. Mass flow rates of the non-renewable inputs required to agriculture strawberry are listed in Table 4 [15]. Since seed to crop ratio is very small, the energy and exergy utilization, and the carbon dioxide emission associated with seed production is neglected.

Fig. 4 shows the flowchart of strawberry production. Raw strawberries, which are harvested very early in the morning, are put into the reusable plastic crates, and transported with no cooling. We assumed that heavy-duty trucks with 10 ton capacity are employed to transport raw strawberries from the farm to a cleaning facility, which is 30 km away. The strawberry cases are unloaded from the trucks manually and stems are removed on the sorting

Table 4
Inputs to produce strawberry with a yield of 64.2 ton/(ha year) [15].

Fertilizer		3369.2 kg/(ha year)
Nitrogenous (NH_4NO_3)	18%	
Phosphorus (P_2O_5)	55%	
Potasium (K_2O)	27%	
Microelements		51.0 kg/(ha year)
Fe	92%	
B	2%	
Mn	4%	
Zn	2%	
Pesticides		42.9 kg/(ha year)
Herbicides	33%	
Insecticides	33%	
Funghicides	33%	
Diesel oil consumed during agriculture		10,976.1 kg/(ha year)
Electricity consumed during agriculture		11,076.4 MJ/(ha year)

Table 5
Energy and exergy consumed and CO_2 emitted to produce one ton of strawberry.

Activity	CEnC (MJ/ton)	CExC (MJ/ton)	CCO_2E (kg/ton)
Consumption of chemical fertilizers	1540.0	598.7	516.6
Consumption of chemicals (pesticides, etc)	132.8	215.4	3.4
Diesel consumption	9822.4	9095.5	136.4
Electric power consumption	172.5	719.5	24.2
Transportation of the strawberries to the factory	41.2	38.1	0.6
Cleaning machinery	5.4	22.5	0.8
Sorting machinery	1.1	4.6	0.2
Recycling of the strawberries	23.0	88.3	3.2
Total	11,738.4	10,782.6	685.4

table. Strawberry cleaning machine (Model JY X700, Zhengzhou Jun Yu Trade Co., Ltd. China, capacity = 500 kg/h) utilizes 5.4 MJ of electricity per ton of strawberries. The sorting machine (Jiadi, China, Model JD-JG-5, capacity = 5 ton/h) utilizes 1.1 MJ of electricity per ton of strawberries.

About 5% of the strawberries, which are inappropriate for processing, are ground in an industrial waste grinder (Tsingtao Donghao Plastics Machinery Co., Ltd., China, capacity = 500–2000 kg/h, energy utilization = 324 MJ/h) and recycled to the fields in 50 g polylactic acid bags as fertilizer.

Energy and exergy consumed, and CO_2 emitted during the agriculture of strawberry are listed in Table 5. About 86% of the total energy and 92% of the total exergy consumed during the strawberry production originates from fossil fuels; the rest is contributed by non-renewable chemicals (fertilizers, pesticides, and micronutrients). 17% of the input exergy is converted into useful product, and 83% of exergy is lost.

3.4. Sugar beet agriculture

Mass flow rates of the non-renewable inputs for sugar beet production are listed in Table 6 [16] and the flowchart is shown in Fig. 5. Calculations are performed the same way as the strawberry agriculture, assuming that 5% of the sugar beet is found inappropriate for processing, therefore ground, and recycled to the field as fertilizer. Sugar beets are transported to the factory at an average distance of 60 km with heavy-duty trucks [17]. Since the trucks are empty, or carrying the recycled beets only, while going back to the fields, calculations are performed for the two way trip. Results are summarized in Table 7.

The diesel and the chemical fertilizers have large shares in the energy and the exergy utilization of agriculture of both strawberry and sugar beet (Tables 5 and 7). The diesel utilization may be reduced by using energy efficient trucks and optimizing delivery plans. The energy consumption decreased in modern chemical fertilizer factories over the years and approached to the theoretical minimum [18,19]. Providing the fertilizers from the energy efficient plants may contribute to energy savings. The chemical fertilizer use in agriculture is generally not based on soil analysis, and much more than the actual need [20]. Introducing some microorganisms to the soil may stimulate nitrogen fixation, solubilize insoluble minerals, and reduce the need to produce and transport large amounts of chemical fertilizers [21]. Successful fertilizer management practices may reduce energy utilization up to 72%, consequently herbicide utilization and pollution also decrease [22–25].

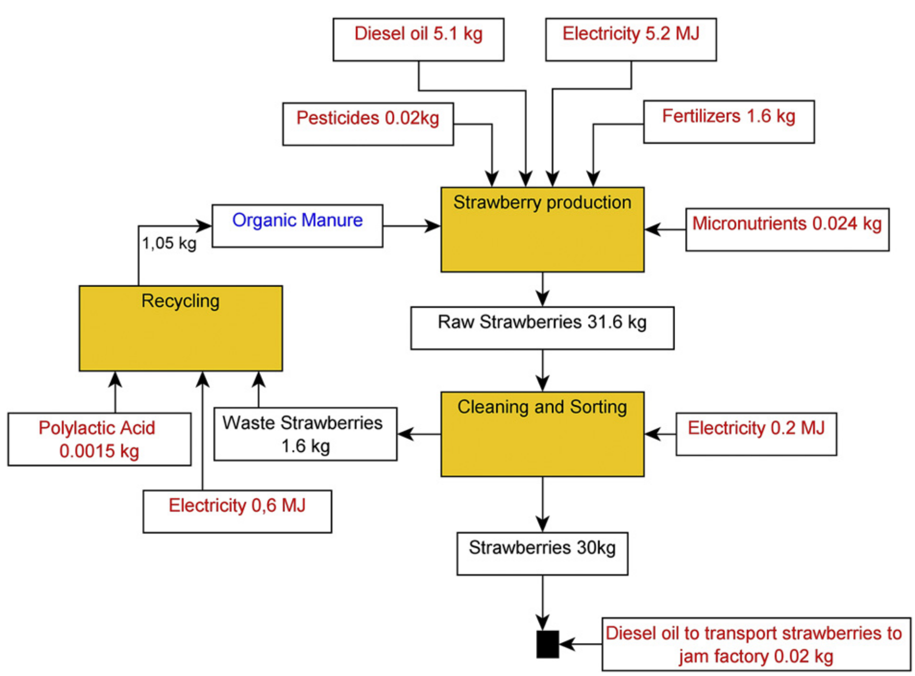

Fig. 4. Flowchart of strawberry agriculture.

Table 6
Inputs to produce sugar beet with a yield of 60.8 ton/(ha year) [16].

Fertilizer		480.3 kg/(ha year)
Nitrogenous (NH_4NO_3)	53%	
Phosphorus (P_2O_5)	33%	
Potasium(K_2O)	13%	
Organic manure		9100.0 kg/(ha year)
Hemicellulose	21%	
Cellulose	25%	
Lignin	13%	
Protein	12%	
Ash	9%	
Pesticides		0.60 kg/(ha year)
Herbicides	18%	
Insecticides	25%	
Funghicides	57%	
Diesel oil consumed during agriculture		141.9 kg/(ha year)
Electricity consumed during agriculture		1884.8 MJ/(ha year)

3.5. Sugar production

The data on the sugar production is based on a sugar manufacturing plant (capacity = 3000 tons of sugar beet/day) located in Erzurum, Turkey [26]. The energy utilization is calculated as 666 MJ/ton of sugar beet. Half of this energy is assumed to be provided from electricity and the other half is provided from natural gas. CDP of the process (Eqn. (5)), which is the ratio of the sum of exergies of useful products to the input exergy (i.e. sum of the exergy of the reactants, fuel, work and the heat transfer) is 3.28% when the chemical exergies of pulp and sugar are not taken into account; otherwise it is 68.4%.

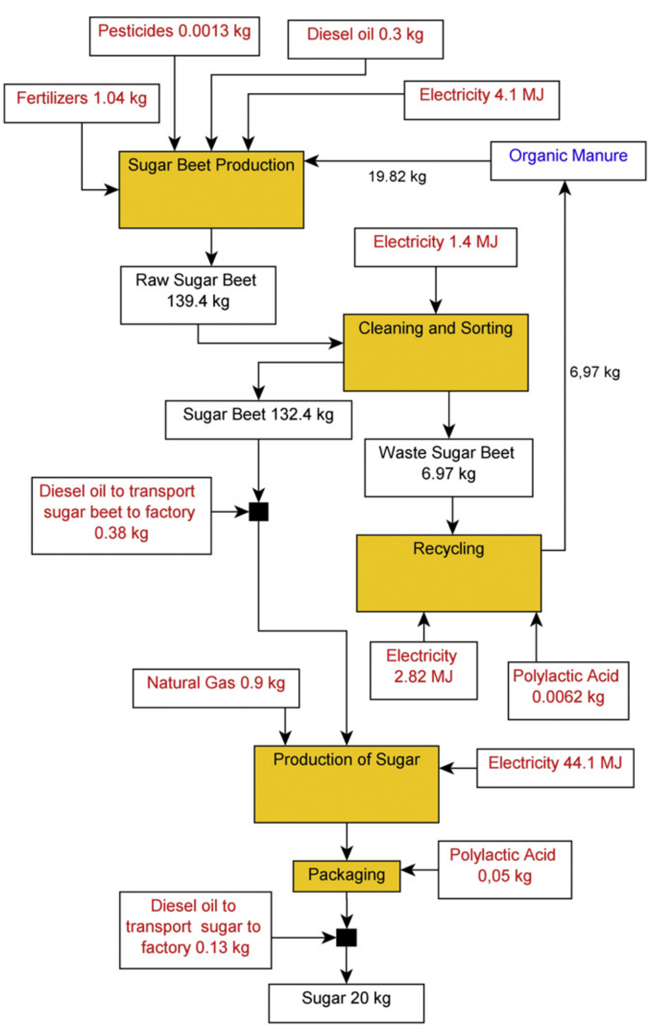

Fig. 5. Flowchart of sugar beet agriculture and sugar production.

Table 7
Energy and exergy consumed and CO_2 emitted to produce one ton of sugar beet.

Activity	CEnC/ton of sugar beet (MJ/ton)	CExC/ton of sugar beet (MJ/ton)	CCO_2E/ton of sugar beet (kg/ton)
Consumption of chemical fertilizers	387.2	161.2	62.5
Consumption of chemicals (pesticides and manure)	2.0	3.0	0.0
Diesel consumption	134.1	124.2	1.9
Electric power consumption	31.0	129.3	4.3
Transportation of the sugar beet to the sugar factory	164.6	152.4	2.4
Cleaning, sorting and recycling of the sugar beet	34.3	135.5	4.7
Total	753.2	705.6	75.8

7100 kg of sugar is obtained from 47 tons of sugar beet [27]. Hence, the total CEnC, CExC and CCO_2E values of Table 7 is multiplied with 47/7.1 to determine the thermodynamic cost of the sugar beet consumed to produce 1 ton of sugar.

50 kg of sugar is packed in 100 g polylactic acid bags, 20 bags are placed on a pellet then covered with 500 g shrink-wrap polylactic acid cover. The sugar is transported to 200 km to go to the jam factory. Results are summarized in Table 8. About 70% of the total energy and 49% of the total exergy consumed during the sugar production (including the sugar beet agriculture) originates from diesel, natural gas and electricity. The rest is the non-renewable chemicals (fertilizers, pesticides, and organic manure). 84% of the input exergy is converted into useful product, and 16% is lost.

3.6. Strawberry jam production

The strawberry jam is made from 60% strawberries and 40% sugar (Fig. 6). Strawberries are ground in a pulper (Jiadi Machinery China, Model JD-DJ-5, capacity = 5000 kg/h, power utilization = 39.6 MJ/h). Strawberry pulp and sugar are blended together for 15 min in a tank (Jiadi Machinery China, capacity = 2000 L, power utilization = 27.0 MJ/h). The strawberry jam is concentrated to have 50% strawberries and 50% sugar in the final product by evaporating 200 kg water/ton of strawberry-sugar blend. An evaporator with a capacity of removing 5300 kg water/h is employed (Jiadi Machinery China, electric power utilization rate = 684 MJ/h, steam utilization rate = 2120 kg/h). An aseptic filling machine (Jiadi Machinery China, model JD-WJGZ-1, filling capacity = 1000 kg jam/h) utilizes 16.2 MJ/h of electric power and 100 kg/h of steam.

250 kg of strawberry jam is packed in a 50 g polylactic acid bag placed in a reusable steel drum (thickness = 1.2 mm, body weight = 20 kg, lid weight = 3 kg [28]), and four drums are placed

Table 8
Energy and exergy consumed and CO_2 emitted to produce one ton of sugar.

Activity	CEnC/ton of sugar (MJ/ton)	CExC/ton of sugar (MJ/ton)	CCO_2E/ton of sugar (kg/ton)
Production of sugar beet	4985.9	4670.8	501.8
Production of sugar	4408.7	11,341.3	443.5
Packaging material	135.0	195.0	4.5
Transportation to the jam factory	274.3	254.0	4.0
Total	9803.9	16,461.1	953.8

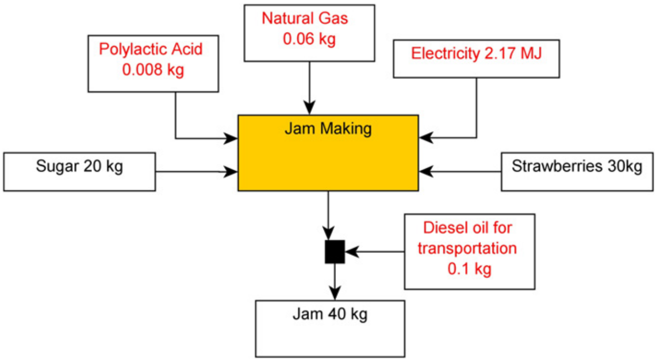

Fig. 6. Flowchart of strawberry jam production.

on one reusable pallet. Strawberry jam is transported to the flavored yogurt factory (distance = 100 km) with heavy-duty trucks. Results of the jam production process are summarized in Table 9. Jam making is one of the efficient operations in the flavored yogurt process, where only 3% of the total input exergy is lost. This is because jam making is mostly a mixing process, and most of the exergy loss occurs during evaporation.

3.7. Flavored yogurt production

Strawberry-flavored yogurt is produced by blending the plain yogurt (96%) and the strawberry jam (4%) for 3 min in a tank (Jiadi Machinery China, capacity = 2000 L, power utilization = 27.0 MJ/h). Only electricity is consumed for blending (Fig. 7 and Table 10). The final blending step is the most efficient operation, where only 0.2% of the total input exergy is lost.

3.8. Primary and secondary packaging

High-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS) and polylactic acid (PLA) are the most preferred primary packaging polymers. The weight of 1 kg yogurt pot is about 6 g. Therefore, the energy utilization for making the containers for one ton of yogurt may vary between 5.4 and 324.0 MJ/ton (Table 10) depending on the packaging polymer.

PLA is regarded as an environment-friendly polymer, since it is biodegradable, but it requires the highest energy utilization and causes the highest CO_2 emission (Table A1). On the contrary, since the amount of non-renewable raw material required to produce PLA is lower than those of its alternatives, the CExC for PLA is lower

Table 9
Energy and exergy consumed and CO_2 emitted to produce one ton of strawberry jam.

Activity	Main product	CEnC (MJ)	CExC (MJ)	CCO_2E (kg)
Strawberry production	750 kg strawberry	8803.8	8086.9	514.1
Sugar production	500 kg sugar	4902.0	8230.6	476.9
Pulping	Strawberry pulp	5.5	22.9	0.8
Blending	Strawberry-sugar blend	6.8	28.2	1.0
Concentrating	1 ton strawberry jam	90.0	170.2	7.6
Total	1 ton unpacked strawberry jam	13,808.0	16,538.8	1000.3
Aseptic filling	–	22.3	73.5	2.6
Polylactic acid bags	–	10.8	15.6	0.4
Transportation to the yogurt factory	–	137.2	127.0	2.00
Total	1 ton bulk packed strawberry jam	13,978.3	16,754.9	1005.3

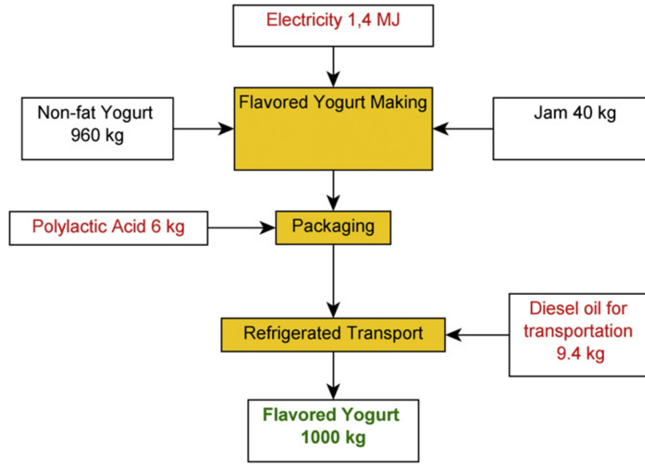

Fig. 7. Flowchart of flavored yogurt production.

than those of the other packaging materials, e.g., 1.6 kg of fossil fuel is used to produce 1 kg of PLA, whereas 2.2 kg of fossil fuel is required to produce the same amount of PE [29].

Thermoform yogurt container machine (BETA-PAK, Turkey; model 26/37, capacity = 5 boxes/min, power utilization = 54 MJ/h) may be used to make the containers and a filling machine (KROMEL, Turkey; capacity = 700 units/h, power utilization = 18 MJ/h) may be employed to fill them. When one ton of flavored yogurt is filled into 500 g containers, the energy and exergy utilization and the carbon dioxide emission during the primary packaging are estimated to be 1851.4 MJ/ton, 7720 MJ/ton, and 259.2 kg CO_2/ton, respectively.

The yogurt containers are delivered to the markets in 100% recyclable plastic baskets, which can make about 250 trips; therefore, basket making is not investigated [30].

The energy utilization for the transportation of the yogurt in the refrigerated trucks is equivalent to 8.3 and 10.4 g of diesel utilization/kg of yogurt in Greece and France, respectively [14]. Employing the average of these numbers, we estimate the energy utilization for the refrigerated transportation of the final product as 636.2 MJ/ton, CExC as 589.12 MJ/ton and the CO_2 emission as 8.9 kg CO_2 per ton of yogurt.

3.9. Storage, transportation and retailing of flavored yogurt

Yogurt is maintained at 10 °C until reaching the consumer [8]. Reusable baskets eliminate the need for secondary packaging in transportation. We assumed that the refrigeration system consumes 5.4 MJ/ton of yogurt in both the factory and the retail market [31] to calculate the energy utilization for yogurt storage. The corresponding CExC and emission are calculated to be 22.5 MJ/ton of yogurt and 0.8 kg CO_2/ton of yogurt. The exergy lost during packaging and transportation is about 8500 MJ/ton of flavored yogurt. About 74% of the total exergy input is lost during packaging and refrigerated transport to the market.

3.10. Waste management

About 80% of the post-consumer plastic waste is sent to landfill, 8% is incinerated, and 7% is recycled [28]. When 0.2 ton of waste/ton of flavored yogurt is produced in the factory and transported to the distribution center (distance = 50 km, trucks come back empty), the total energy and exergy utilization and the CO_2 emission of the transportation are calculated as 32.4 MJ/ton, 30 MJ/kg of yogurt and 0.4 kg CO_2/ton of yogurt.

Table 10
Energy and exergy consumed and CO_2 emitted to produce one ton of strawberry-flavored yogurt.

Activity		Energy utilization/ton of product (MJ/ton)	CExC/ton of product (MJ/ton)	CO_2 emission/ton of product (kg/ton)
960 kg unpacked non-fat yogurt (90% milk, 3% microbial culture, 6% skim milk powder and 1% pectin)		28,270.2	74,655.0	1917.43
40 kg bulk packed strawberry jam		559.1	670.2	40.2
Blending plain yogurt and strawberry jam		1.4	5.8	0.2
Unpacked flavored yogurt (96% plain yogurt 4% strawberry jam)		28,830.7	75,331.0	1957.8
Primary packaging	HDPE	19.2	516.0	2.7
	PP	10.8	511.2	1.5
	PS	5.4	551.4	0.8
	PLA	324.0	468.0	45.4
Container making and filling machinery		1851.4	7720.3	259.2
Waste transport		32.4	30.0	0.4
Storage		5.4	22.5	0.8
Transport to store		636.2	589.1	8.9
Retail air conditioning		5.4	22.5	0.8
Total (flavored yogurt packaged in PLA containers)		31685.5	84183.4	2273.3

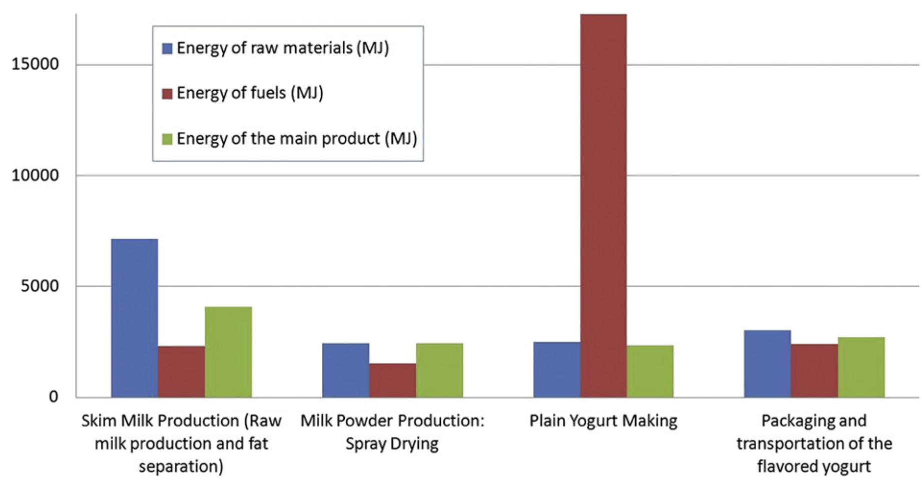

Fig. 8. Energy balance for each step (skim milk production involves raw milk production and fat separation stages).

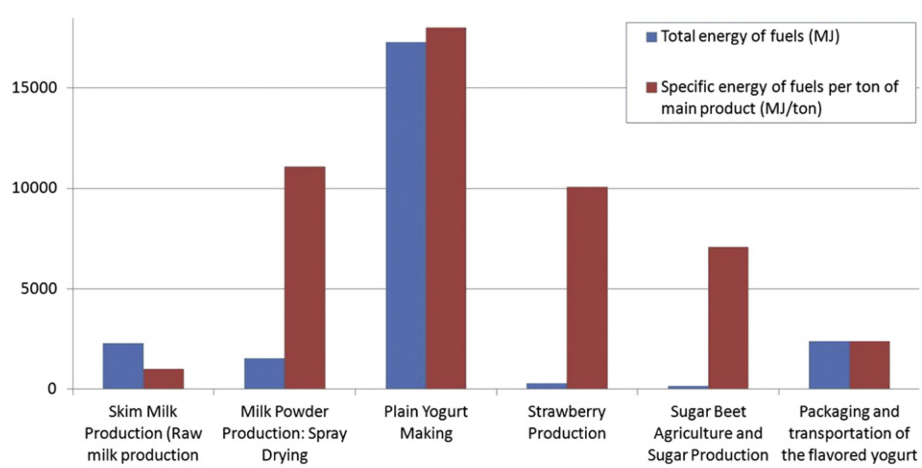

Fig. 9. Comparison of the specific energy consumed at each step (MJ/ton of main product at each step) and the total energy consumed at each step (MJ) to produce 1 ton of flavored yogurt. (Skim milk production involves raw milk production and fat separation stages. Sugar production involves the agriculture and processing of the sugar beet to obtain sugar.)

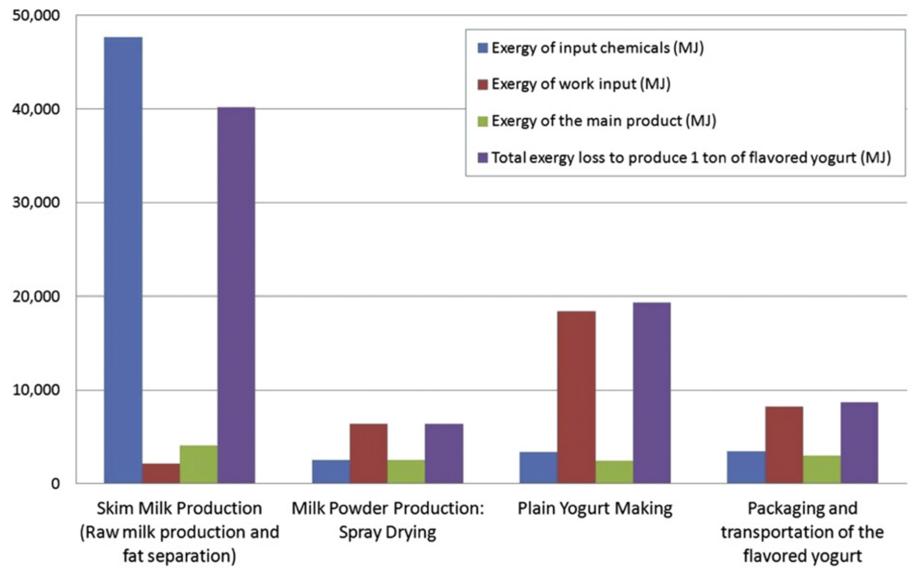

Fig. 10. Exergy of the raw materials and fuels (diesel, natural gas and electricity); exergy loss and the exergy of the main product. (Skim milk production involves raw milk production and fat separation stages.)

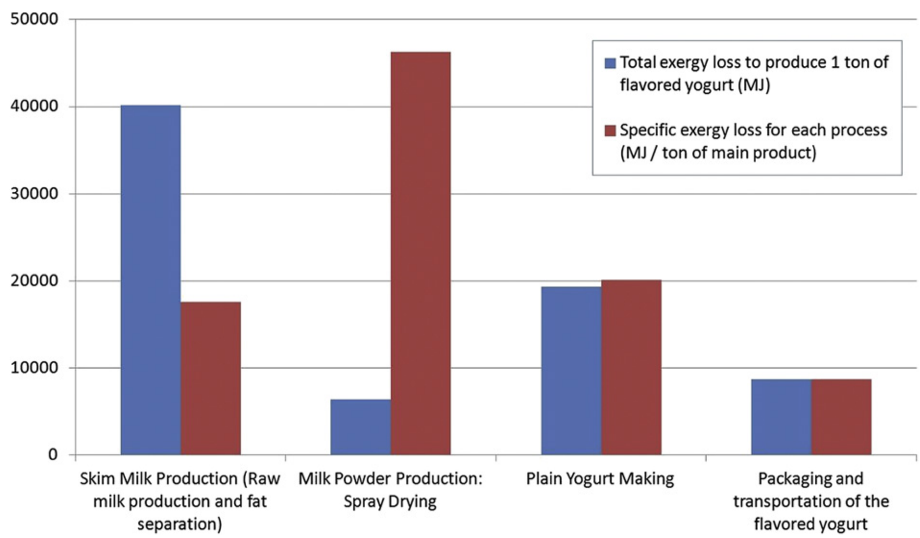

Fig. 11. Specific exergy loss in each process and the total exergy loss while producing one ton of flavored yogurt. (Skim milk production involves raw milk production and fat separation stages.)

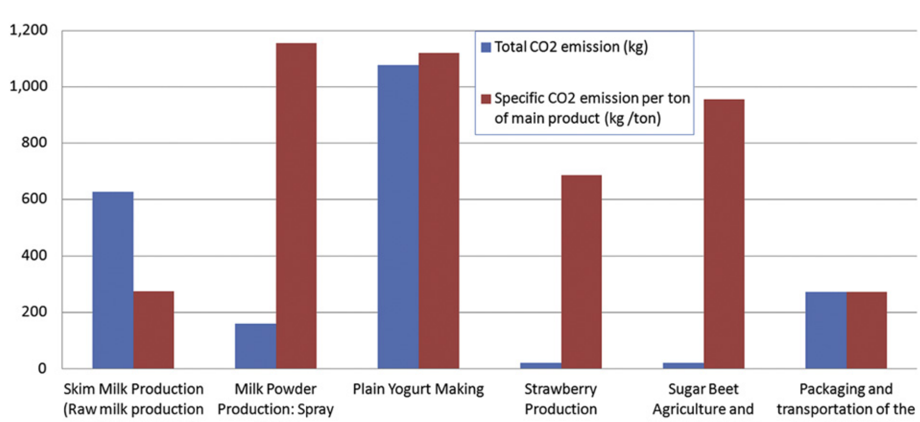

Fig. 12. The carbon dioxide emission. (skim milk production involves raw milk production and fat separation stages. Sugar production involves the agriculture and processing of the sugar beet to obtain sugar.)

The methodology followed in this study is indeed necessary and at the same time sufficient to lead to "new technology in food processing to decrease waste of energy and carbon dioxide accumulation". If any process is not feasible thermodynamically, it can never be used in the real world; however, thermodynamic feasibility does not imply the immediate use of the process either. If the limits offered in thermodynamic analysis cannot be attained immediately with the present technology, they may still be used to understand the area where new technology is needed [2]. Exergy is the maximum energy content that can be extracted from a system without violating the laws of thermodynamics. In the last few decades, numerous studies are published on exergy analysis [52–56]. Especially in the assessment of renewable energy sources, where we need to weigh various processes and fuels with respect to their ability to produce useful work and to identify their impact on environment, exergy analysis provide a fair tool for comparison. Since carbon dioxide emission, is closely related with energy consumption any decrease in energy consumption will also lead to decrease in carbon dioxide emission. Inefficient use of energy and high levels of waste in the food industry is drawing public attention as recently discussed in [57].

4. Conclusions

Energy intensity has been decreasing to approach the theoretical minimum in most subsectors [32]. If the energy utilization trends reported by Nuibe [33] continue over the next five years, at least 5% more decline can be expected in all the processes employed in this study. In some countries, the strawberries are cultivated in greenhouses. Hepbasli [34] described a method to compare exergy efficiency of the greenhouse heating options, which may help to reduce the exergy utilization during the production of the strawberries. Abdel-Dayem et al. [35] and Al-Soud et al. [36] described solar energy using equipment with potential to be used in a dairy factory. Production of biogas from municipal waste [37] and manure [38,39] and wastewater [40] are also described in the literature. It is possible to implement results of these and similar studies in the flavored yogurt production to improve both the energy efficiency and share of the renewable energy utilization in the process. About 15% deviation may be expected between the equipment produced by different manufacturers, deviation in different agricultural practices may be larger. The energy and exergy consumption and the CO_2 emission estimates are subject to change with the scenario. The energy consumption may increase, as the equipment gets older. Therefore, about $\pm 20\%$ error may be expected in the values we report, but the relative amounts of the energy utilization and the carbon dioxide production associated with products, e.g., raw milk, pasteurized milk, plain yogurt and the flavored yogurt is not expected to change as much.

Figs. 8 and 9 visualize the energy balance for the processes. During the milk production, 99% of the consumed energy comes from the animal feed. The energy input of the consumed diesel is negligibly small. Milk production is an inefficient process from the thermodynamics point of view. About 19% of the total exergy consumed is converted into useful products: milk, manure and calves (Fig. 10). The chemical exergy of raw milk, organic manure and calves contribute to 74.5%, 24.3% and 1.2% of the total exergy output, respectively. About 81% of the exergy is lost. However, only 24% of the consumed energy and 4% of the consumed exergy comes from fossil fuel. A large portion of the input energy and exergy comes from renewable resources, i.e. plants fed to the animals. This makes the process highly renewable. The total chemical exergy of the products is 4.5 times larger than the CExC of irrenewables consumed during the process.

Most of the work (79.5% of the total work input) is consumed during plain yogurt making, where large amounts of electric power and natural gas are consumed. Spray drying to produce milk powder requires a high energy input, but since the amount of used milk powder is low, its contribution to the total work input is only 7% (Fig. 11). The process with the highest CO_2 emission per ton of main product is the spray drying, but since the amount of milk powder used to produce 1 ton of flavored yogurt is only 139 kg, its contribution to the total CO_2 emission is 7% (Fig. 12). The amounts of strawberry and sugar used are even less; i.e. 30 kg and 20 kg, respectively. Therefore their contributions to the total CO_2 emission are 1.6% and 1.5%, respectively. The largest contribution to the CO_2 emission comes from the plain yogurt making (50%) and milk production process (29%).

The total exergy loss is 75791.6 MJ/ton of flavored yogurt. The exergy of the dispensible by-products (like fat thrown away during the fat separation process and water wasted in all of the process) makes up 3030 MJ/ton of flavored yogurt. Exergetically most inefficient process is the milk production, since the energy and the exergy of the feed are mainly used for the metabolic activities of the animals. Only a small part of energy and exergy are used to produce milk, calves and manure. 53% of the total exergy loss occurs at this step.

Aside from the milk production, processes with the highest fossil fuel consumption have the lowest exergetic efficiencies. During the plain yogurt making, where large amounts of electricity and natural gas are consumed, 26% of the total exergy loss occurs. The exergy loss during the packaging and refrigerated transport of the flavored yogurt accounts for the 12% of the total exergy loss.

The calculated CDP for the flavored yogurt is 3.6%. Two major inputs of the flavored yogurt production process are electricity and diesel. If the manufacturers should substitute diesel (CExC = 53.2 MJ/kg) with biodiesel obtained from renewable resources (CExC = 8.8 MJ/kg) as described by Sorgüven and Özilgen [2], the total exergy loss would decrease to 73328 MJ/ton of flavored yogurt and the CDP would rise to 3.7%. Additionally, if the electric power would be obtained from hydraulic resources instead of fossil fuel, the CExC for electricity would decrease from 4.2 MJ/MJ to 0.006 MJ/MJ, which results in a total exergy loss of 56919 MJ/ton and increases the CDP to 4.6%. These values represent substantial improvement toward more environment-friendly production.

Processes with negligibly low contributions to the total energy and exergy requirements, e.g. sugar, strawberry, jam, microbial culture and flavored yogurt production, are omitted in Figs. 8–12. The last three processes mentioned are also omitted from the CO_2 emission figure (Fig. 12), since their contribution to the total CO_2 emission is less than 0.1%.

During the recent decade, food companies targeted substantial reductions in their energy expenditures and major progress has been achieved. Considering the extremely high exergy losses accounted in this study, reducing the exergy losses appears to be realistic target for the next decade.

Appendix

CEnC, CExC, and CCO_2E values of the input and output materials are listed in Table A1. Most of the data are taken from literature. Carbon dioxide emission of during the feed preparation is calculated assuming that 45% of the energy for the feed production comes from electricity, 30% from diesel oil, and 25% from natural gas.

Earlier works reported rather low CExC values for pesticide production (e.g., 32.7 MJ/kg herbicide [1], 7.5 MJ/kg insecticide [41] and 4.6 MJ/kg fungicide [42]). Brehmer [43] draw attention to the noticeable variation based on the active ingredients and showed that the CExC values are between 172 and 564 MJ/kg for the

Table A1
Specific energy and exergy consumption and CO_2 emission for each input.

		Specific CEnC			Specific CExC			Specific CCO_2C		
Renewable inputs										
Feed		2.8	MJ/kg	[9]	18.7	MJ/kg	[44]	0.23	kg/kg	a
Non-renewable inputs										
Fertilizers										
Nitrogenous (NH_4NO_3)		78.2	MJ/kg	[45]	32.7	MJ/kg	[1]	7.11	kg/kg	[18]
Phosphorus (P_2O_5)		17.5	MJ/kg	[45]	7.5	MJ/kg	[41]	2.7	kg/kg	[18]
Potasium(K_2O)		13.8	MJ/kg	[45]	4.6	MJ/kg	[42]	25.0	kg/kg	[18]
Micronutrients		119.2	MJ/kg	[15]						
Fe		–			6.7	MJ/kg	[1]	–		
B		–			58.1	MJ/kg	[1]	–		
Mn		–			8.8	MJ/kg	[1]	–		
Zn		–			5.2	MJ/kg	[1]	–		
Pesticides		198.8	MJ/kg	[15]						
Herbicides		–			368.0	MJ/kg	[43]	6.3 ± 2.7	kg/kg	[46]
Insecticides		–			344.0	MJ/kg	[43]	5.1 ± 3.0	kg/kg	[46]
Funghicides		–			256.0	MJ/kg	[43]	3.9 ± 2.2	kg/kg	[46]
Diesel		57.5	MJ/kg	[15]	53.2	MJ/kg	[1]	0.94	kg/kg	[46]
Natural gas		50.0	MJ/kg	[1]	48.7	MJ/kg	[1]	0.06	kg/MJ	[31]
Electricity		1.0	kJ/kJ	[1]	4.17	kJ/kJ	[1]	0.14	kg/MJ	[31]
HDPE		3.2	MJ/kg	[47]	86.0	MJ/kg	[48]	0.45	kg/kg	b
PP		1.8	MJ/kg	[47]	85.2	MJ/kg	[48]	0.25	kg/kg	b
PS		0.9	MJ/kg	[47]	91.9	MJ/kg	[48]	0.12	kg/kg	b
PLA		54.0	MJ/kg	[49]	78.0	MJ/kg	c	1.8	kg/kg	[49]
Products										
Calves										
Fat	3%	39.0	MJ/kg	[50]	39.6	MJ/kg	d,e	–		
Protein	19%	23.8	MJ/kg	[50]	25.4	MJ/kg	d,e	–		
Organic manure		0.30	MJ/kg	[16]						
Hemicellulose	21%	–			16.56	MJ/kg	d	–		
Cellulose	25%	–			18.54	MJ/kg	d	–		
Lignin	13%	–			25.00	MJ/kg	[51]	–		
Protein	12%	–			25.35	MJ/kg	d,e	–		
Flavored yogurt										
Carbohydrate	7%	17.9	MJ/kg	[50]	17.5	MJ/kg	[1] e	–		
Protein	4%	23.8	MJ/kg	[50]	25.4	MJ/kg	d,e	–		
Fat	0.2%	39.0	MJ/kg	[50]	39.6	MJ/kg	d,e	–		
Sugar	2%	16.0	MJ/kg	[50]	26.0	MJ/kg	[1]	–		

[a] Calculated assuming that 45% of the energy for the feed production comes from electricity, 30% from diesel oil and 25% from natural gas.
[b] Calculated assuming that only electric energy is used for this process.
[c] Calculated based on the data given by Swaan Arons et al. [29].
[d] Calculated based on the group additivity method with the data presented in Szargut et al. [1].
[e] Proteins are assumed to be polymers of alanine, fats are assumed to be polymers of oleic acid, and carbohydrates are predominantly lactose; here all of the milk carbohydrate is assumed to be beta-lactose.

Table A2
Group contributions for standard chemical exergy of some organic compounds [1].

Group	b_0^{ch} (kJ/mol)	Number of the group in alanine	Number of the group in oleic acid
$-\overset{\vert}{\underset{\vert}{\mathrm{CH}}}$	545.27	1	
$-\overset{\vert}{\mathrm{CH_2}}$	651.46		14
$-\mathrm{CH_3}$	752.03	1	1
$=\overset{\vert}{\mathrm{CH}}$	569.95		2
$-\overset{\vert}{\mathrm{C{=}O}}$	281.36	1	
$-\overset{\mathrm{O}}{\overset{\Vert}{\mathrm{C}}}-\mathrm{OH}$	155.11		1
$-\overset{\vert}{\mathrm{NH}}$	195.56	1	
Alanine: $-(N-CH(CH_3)-CO)-$		b_0^{ch} (kJ/mol)=	174.22
		b_0^{ch} (kJ/g)=	25.35
Oleic Acid: $H_3C-(CH_2)_7-CH=CH-(CH_2)_7-COOH$		b_0^{ch} (kJ/mol)=	11167.48
		b_0^{ch} (kJ/g)=	39.54

herbicides, 21–667 MJ/kg for the insecticides and 38–474 MJ/kg for the fungicides. Here the averages of these ranges are used.

The CExC value of electricity depends on the method chosen to generate the electricity. Calculations are performed assuming that electricity is generated from fossil fuel and the CExC is 4.2 MJ/MJ [1].

Chemical energy and exergy of organic compounds are calculated based on their composition. Proteins are assumed to be polymers of alanine, fats are assumed to be polymers of oleic acid and carbohydrates are assumed to be predominantly lactose. All of the milk carbohydrate is assumed to be beta-lactose and its enthalpy of devaluation and standard chemical exergy are taken from the corresponding table in [1]. The group contribution method is used to calculate the chemical exergies of proteins and fats. Table A2 lists the standard chemical exergy of the organic groups in alanine and oleic acid. Carbon dioxide emission of organic compounds is neglected.

References

[1] Szargut J, Morris DR, Steward FR. Exergy analysis of thermal, chemical, and metallurgical processes. New York: Hemisphere; 1988.
[2] Sorgüven E, Özilgen M. Thermodynamic assessment of algal biodiesel utilization. Renew Energy 2010;35:1956–66.
[3] Gungor A, Erbay Z, Hepbasli A. Exergetic analysis and evaluation of a new application of gas engine heat pumps (GEHPs) for food drying processes. Appl Energy 2011;88:882–91.
[4] Gungor A, Erbay Z, Hepbasli A. Exergoeconomic analyses of a gas engine driven heat pump drier and food drying process. Appl Energy 2011;88:2677–84.

[5] Murr R, Thieriot H, Zoughaib A, Clodic D. Multi-objective optimization of a multi water-to-water heat pump system using evolutionary algorithm. Appl Energy; 2011. doi:10.1016/j.apenergy.2011.04.013.
[6] Pellegrini LF, de Oliveira Jr S. Combined production of sugar, ethanol and electricity: thermoeconomic and environmental analysis and optimization. Energy 2011;36:3704–15.
[7] Özilgen M, Sorgüven E. Energy and exergy utilization and carbon dioxide emission in vegetable oil production. Energy; 2011. doi:10.1016/j.energy.2011.08.020.
[8] Tamime AV, Robinson RK. Yogurt science and technology. Cambridge: CRC Press; 1999.
[9] Koknaroglu H. Cultural energy analyses of dairy cattle receiving different concentrate levels. Energy Convers Manage 2010;51:955–8.
[10] Ramirez CA, Patel M, Blok K. From fluid milk to milk powder: energy use and energy efficiency in the European dairy industry. Energy 2006;31:1984–2004.
[11] Ozen S, Özilgen M. Effects of substrate concentration on growth and lactic acid production by nixed cultures of *Lactobacillus delbrueckii subspecies bulgaricus* and *Streptococcus thermophilus*. J Chem Technol Biotechnol 1992;54:57–61.
[12] Ruggeri B, Tommasi T, Sassi G. Energy balance of dark anaerobic fermentation as a tool for sustainability analysis. Int J Hydrogen En 2010;35:10202–11.
[13] Doran-Peterson J. Pectin-rich biorefinery for production of ethanol and specialty chemicals. Ethanol Prod Mag, http://www.ethanolproducer.com/articles/1254/pectin-rich-biorefinery-for-production-of-ethanol-and-specialty-chemicals/; April 2003 [accessed on 8.05.10].
[14] Mikiki F, Rizet C. Energy consumption in the yogurt supply chain. Presented in COST meeting, Arcueil, Paris, France, May 19, 2005. http://cost355.inrets.fr/cdrom/WG1/SG3/Abstract/C.R.%20Energy%20consumption%202.pdf visited on October 12; 2010.
[15] Banaeian N, Omid M, Ahmadi H. Energy and economic analysis of greenhouse strawberry production in Tehran province of Iran. Energy Convers Manage 2011;5:1020–5.
[16] Erdal G, Esengun K, Erdal H, Gunduz O. Energy use and economic analysis of sugar beet production in Tokat province of Turkey. Energy 2007;32:35–41.
[17] Roy P, Nei D, Okadome H, Nakamura N, Orikasa T, Shiina T. Life cycle inventory analysis of fresh tomato distribution systems in Japan considering the quality aspects. J Food Eng 2008;86:225–33.
[18] Kongshaug G. Energy consumption and greenhouse gas emissions in fertilizer production. Paper presented at IFA Technical Conference, Marrakech, Morocco, 28 September – 1 October, 1998.
[19] Anundskas A. Technical improvements in mineral nitrogen fertilizer production. In: Harvesting energy with fertilizers. Brussels: European Fertilizer Manufacturers Association; 2000.
[20] Esengun K, Erdal G, Gunduz O, Erdal H. An economic analysis and energy use in stake-tomato production in Tokat province of Turkey. Renew Energy 2007;32:1873–81.
[21] Aslantas R, Cakmakci R, Sahin F. Effect of plant growth promoting rhizobacteria on young apple tree growth and fruit yield under orchard conditions. Sci Hortic 2007;111:371–7.
[22] Hülsbergen KJ, Feil B, Biermann S, Rathke GW, Kalk WD, Diepenbrock W. A method of energy balancing in crop production and its application in a long-term fertilizer trial. Agric Ecosyst Environ 2001;86:303–21.
[23] Snyder CS, Bruulsema TW, Jensen TL, Fixen PE. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric Ecosyst Environ 2009;133:247–66.
[24] Ren T, Christie P, Wang J, Chen Q, Zhang F. Root zone soil nitrogen management to maintain high tomato yields and minimum nitrogen losses to the environment. Sci Hortic 2010;125:25–33.
[25] Clements DR, Weise SF, Brown R, Stonehouse DP, Hume DJ, Swanton CJ. Energy analysis of tillage and herbicide inputs in alternative weed management systems. Agric Ecosyst Environ 1995;52:119–28.
[26] Tekin T, Bayramoglu M. Exergy loss minimization analysis of sugar production process from sugar beet. Trans IChemE 1998;76:149–54.
[27] Cederberg C, Mattsson B. Life cycle assessment of milk production – a comparison of conventional and organic farming. J Clean Prod 2000;8:49–60.
[28] RIPA. Reusable packaging association web site, http://www.reusablepackaging.org/greenhou.cfmhttp://www.reusablepackaging.org/greenhou.cfm; 2008 [accessed on 16.01.11].
[29] de Swaan Arons J, van de Kooi H, Sankaranarayanan K. Efficiency and sustainability in the energy and chemical industries. Marcel Dekker; 2004.
[30] Hurst T. Could high-tech plastic pallets mean the end for disposable wooden pallets?. Available at: http://earthandindustry.com/2010/09/is-the-pallet-of-the-future-made-out-of-plastic/; 2010.
[31] PAS 2050. How to assess the carbon footprint of goods and services. London: Department of for Environment food and Rural Affairs; 2008.
[32] Boardman B, Palmer J. Consumer choice and carbon consciousness for electricity. European Commission Altener Program final report. United Kingdom: Environmental Challenge Institute; 2003.
[33] Nuibe T. Energy intensity in industrial subsectors. Japan: The Energy Conservation Center; 2007.
[34] Hepbasli A. A comparative investigation of various greenhouse heating options using exergy analysis method. Appl Energy; 2011. doi:10.1016/j.apenergy.2011.05.022.
[35] Abdel-Dayem AM, Meyer-Pittro R, Russ W, Mohamad MA. How to select collector? Appl Energy 1999;64:159–64.
[36] Al-Soud MS, Abdallah E, Akayleh A, Abdallah S, Hrayshat ES. A parabolic solar cooker with automatic two axes sun tracking system. Appl Energy 2010;87:463–70.
[37] Rao MS, Singh SP, Singh AK, Sodha MS. Bioenergy conversion studies of the organic fraction of MSW: assessment of ultimate bioenergy production potential of municipal garbage. Appl Energy 2000;66:75–87.
[38] Gelegenis J, Georgakakis D, Angelidaki I, Christopoulou N, Maria Goumenaki M. Optimization of biogas production from olive-oil mill wastewater by codigestion with diluted poultry-manure. Appl Energy 2007;84:646–63.
[39] Ogejo JA, Li L. Enhancing biomethane production from flush dairy manure with turkey processing wastewater. Appl Energy 2010;87:3171–7.
[40] Ramasamy EV, Abbasi SA. Energy recovery from dairy waste-waters: impacts of biofilm support systems on anaerobic CST reactors. Appl Energy 2000;65:91–8.
[41] Wittmus H, Olson L, Lane D. Energy requirements for conventional versus minimum tillage. J Soil Water Conserv 1975;3:72–5.
[42] Pimentel D. Ethanol fuels: energy, security, economics, and the environment. J Agr Environ Ethics 1991;4:1–13.
[43] Brehmer B. Chemical biorefinery perspectives: the valorisation of functionalised chemicals from biomass resources compared to the conventional fossil fuel production route. Netherlands: Wageningen University; 2008.
[44] Jorgensen SE, Ladegaard N, Debeljak M, Marques JC. Calculation of exergy for organism. Ecol Model 2005;185:165–75.
[45] Helsel ZR. Energy and alternatives for fertilizer and pesticide use. In: Fluck RC, editor. Energy in farm production, 6. New York: Elsevier; 1992. p. 177–201.
[46] Lal R. Carbon emission from farm operations. Environ Int 2004;30:981–90.
[47] Gielen D, Tom C. Proposal for energy and CO2 emission indicators in the petrochemical sector. Available at: http://www.iea.org/Textbase/work/2006/petrochemicals/Indicators_Discussion_Paper.pdf; 2010.
[48] Dewulf J, van Langenhove H. Thermodynamic optimization of the life cycle of plastics by exergy analysis. Int J Energy Res 2004;28:969–76.
[49] Vink ETH, Rabago KR, Glassner DA, Gruben PR. Applications of life cycle assessment to NatureWorks™ polylactide (PLA) production. Polym Degrad Stab 2003;80:403–19.
[50] Moran MJ. Availability analysis: a guide to efficient engineering use. New Jersey: Prentice Hall; 1982.
[51] Klass DL. Biomass for renewable energy and fuels. In: Cleveland CJ, editor. Encyclopedia of energy. Elsevier; 1998.
[52] Rakopoulos CD, Giakoumis EG. Second-law analyses applied to internal combustion engines operation. Prog Energy Combust Sci 2006;32:2–47.
[53] Caton JA. A review of investigations using the second law of thermodynamics to study internal combustion engines, SAE paper no: 2000-01-1081. Warrendale, PA: Society of Automotive Engineers Inc.; 2000.
[54] Ayres RU. Eco-thermodynamics: economics and the second law. Ecol Econ 1998;26:189–209.
[55] Ayres RU. The second law, the fourth law, recycling and limits to growth. Ecol Econ 1999;29:473–83.
[56] Talens L, Villalba G, Gabarrell X. Exergy analysis applied to biodiesel production. Resour Conserv Recycl 2007;51:397–407.
[57] Cuéllar AD, Webber ME. Wasted food wasted energy: the embedded energy in food waste in the United States. Environ Sci Technol 2010;44:6464–9.