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Assessment of the energy and exergy efficiencies of *farm to fork* grain cultivation and bread making processes in Turkey and Germany

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Abstract

Energy and exergy efficiencies of the wheat and rye bread and hamburger bun making processes are assessed based on data from Turkey and Germany. Amount of the land required to produce the same amount of wheat in Turkey is 3.34 times of that required in Germany; this ratio is 2.30 for the rye grain. These results show that the efficiency of the conversion of the solar energy into the grain mass is low in Turkey. Cumulative degree of perfection (CDP) for the wheat and the rye grain production is 3.73 and 4.96 in Turkey, and 11.26 and 10.46 in Germany. Specific energy utilization for rye bread production is almost the same in Turkey and Germany; but it is 12 % higher in Turkey for wheat bread and hamburger bun making. Hamburger bun production requires the maximum energy utilization due to the higher weight loss in baking. The rye bread production process requires the minimum energy utilization due to the lower energy input in the agriculture and higher efficiency in the flour production. The maximum exergy destructions occur during the milling and the baking steps.

Keywords: Bread making, energy efficiency, exergy efficiency, carbon dioxide emission

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Highlights

- Agriculture determines the energy and exergy efficiency of bread making
- Conversion efficiency of the solar energy into grain mass is lower in Turkey
- The smallest energy and exergy is needed for the rye bread making
- The largest energy and exergy is needed for the hamburger bun making
- Energy efficiency per mass of bread production is 12 % higher in Germany

Nomenclature

CDP	Cumulative degree of perfection	
CCO_2E	Cumulative carbon dioxide emission	kg/ton or kg/ha
CEnC	Cumulative energy consumption	MJ/ton or MJ/ha
CExC	Cumulative exergy consumption	MJ/ton or MJ/ha
Ex	Specific exergy	MJ/kg
G	Gibbs energy	kJ/kg
H	Enthalpy	kJ/kg
M	Mass	kg
N	Number of the elements atomic groups in molecules	
Q	Heat	kJ
R	Universal gas constant	J/mol K
S	Entropy	kJ/K
T	Temperature	K
W	Work	kJ
Δ_G	Gibbs energy increment of an atomic group	kJ
Δ_H	Enthalpy increment of an atomic group	kJ
μ	Chemical potential	kJ/kmol
X	Molar fraction	
Y	Mass fraction	
Subscripts		
0	Dead state	
Ch	Chemical	
E	Element	
grain	Grain	
I	Element, atomic group or molecular group	
In	Input	
K	Heat source index	
Out	Output	
system	System	
U	Universal	
Superscripts		
O	Standard	

1. Introduction

In the food and most other industries, studies on the energy accounting and efficiency began in the late 1970s, and the pioneering outcomes became available in the early 1980s [1]. These studies had generally been successful, e.g., energy consumption in modern chemical fertilizer factories decreased over the years and approached to the theoretical minimum towards the end of the 1990s [2, 3], in 2006 Ramirez et al [4] reported that the energy efficiency was improving about 1 % every year in the Dutch food industry, from 2006 to 2010 the ratio of the units of the energy utilized in the Taiwanese food industry to the gross domestic production of the country showed a continuous decline [5]. Energy utilization for the food production usually consist a sizeable fraction of the total energy utilization in a country, e.g., towards the end of the first decade of the 21st century 20 % of the total energy use was allocated to the food sector in Sweden [6]. The cold stages of food processing and preservation, such as freezing, cooling and refrigeration depend almost entirely on the use of electricity; natural gas is used directly for most drying (50 %) and cooking (25 %) operations [7]. About 5 to 15% of the energy utilized at each step of food processing is wasted [7]. Because of the very high cost of the energy utilization, e.g., American bakery industry pays more than $ 870 million annually for the energy [8], there is rigorous research in the food industry to find ways to reduce the energy utilization [9, 10].

The first stage of the food production is the cultivation of the plants. The plants convert the energy from the Sun into chemical energy with photosynthesis, and then the chemical energy is used to fuel the biological activities of the plants, including the growth. Only the light, which is in the wavelength range of 400 to 700 nm (which constitutes about 45 % of the total solar energy), may be used in photosynthesis. About 25 % of the referred 45 % may be absorbed by the plants; the rest is lost by various reasons including reflection. Receiving non-optimal levels of radiation reduces the efficiency of photosynthesis further; therefore, only 3 to 6 % of total solar radiation may be used in photosynthesis [11, 12]. Ways to increase the photosynthetic efficiency of the plants is being actively researched to improve their yields, including those of the grain crops [13]. The pollutants such as sulfur dioxide and herbicides (weed killers) inhibit the photosynthesis [14, 15]. The rate of photosynthesis is affected by the temperature, the optimum is reported as 25°C for the winter wheat [16]. Soils deficient in nitrate, magnesium or iron give rise to chlorophyll deficient plants and reduce the rate of photosynthesis [17]. The cropping intensity increases with the balanced use of water, fertilizers, pesticides [18]. The moisture content of the grain wheat is 13.5-15.0 % [19]. Plants may not uptake all of the water and the chemical fertilizers available in the soil [20, 21]. The nitrogen use efficiency decreases with denitrification and the subsequent loss of the gaseous nitrogen from the soil [22]. Fertilizer management practices may reduce energy utilization up to 72 %; consequently, herbicide utilization and pollution also decrease [16, 23, 24, 25]. The use of the appropriate fertilizers in the agriculture systems is also reported to increase the water uptake [20].

In Turkey annually, 101.88 kg/ha of nitrogenous and 72.2 kg/ha of phosphorus chemical fertilizers are used and the crop yield is 2.39 ton/ha [26, 27]. In Germany both the chemical fertilizer use e.g., 145 kg/ha of nitrogenous, 37 kg/ha phosphorus and 41 kg/ha potassium [28] and the crop yield are higher, e.g., 7.98 ton/ha [29]. In Turkey 200 kg/ha of seeds [30], 40 kg/ha nitrogen fertilizer and 50 kg/ha phosphorus fertilizer [31] are used in the agriculture and 2.6 ton/ha [32] of rye grain is produded. In Germany the same amount of seeds are used, 98 kg/ha nitrogen fertilizer and 24 kg/ha phosphorus fertilizer and 44 kg/ha potassium fertilizer [33] are utilized to produce 5.7 ton/ha of rye grain [29].

Bread is a staple food in numerous countries, hamburgers are among the mass produced foods. The fast food industry applies the principles of the factory assembly line to a commercial kitchen to increase the speed, lower the prices and raise the volume of the sales [34]. Energy utilization is accompanied with the emission of the greenhouse gases [35, 36, 37]. Therefore, any improvement in the energy and exergy efficiency pertinent to their production will not only reduce the energy budget only, but also decrease the environmental cost.

The first law of thermodynamics, namely energy balance, is the mostly used while assessing the energy efficiency of a plant or process. However, energy balances do not provide information about the potential work lost in the energy transformation processes [38]. The exergy (availability) of a system is defined as the maximum useful work that brings the system from its original state to the dead state via reversible processes [38, 39]. Exergy analysis may be used to pinpoint the irreversibilities in a process and reduce them to improve efficiency. At the dead state mechanical, thermal and chemical equilibria prevail between the system and the environment. The widespread of the use of the exergy method has led to attempts towards cutting down on energy cost, conservation of the limited energy resources and reduction of the environmental damage. These methodologies have been applied to many industrial systems such as: sugarcane bagasse gasification [40], malt drink [41], and vegetable oil [37], flavored yogurt [42] production. The CDP is the ratio of the exergy of the products to the sum of the exergies of the input materials and the exergies of the non-renewable fuels. Exergy efficiency is the ratio of the exergy of the product to the sum of the exergies of the raw materials and the fuels, regardless of whether the fuels are renewable or not. The CDP is used to assess the degree of the renewability of a process, while the exergy efficiency is not.

The CDP values increase if the non-renewable resources are replaced with the renewable resources in a process. The CDP of bottled vegetable oil production was recently reported to be

0.92 for soybean and 0.98 olive oils, whereas the CDP for the sunflower oil is 2.36. The decrease in diesel consumption, good agricultural applications and supply of biodiesel from the renewable resources would reduce the cumulative exergy and fossil consumption, resulting in the CDP of the olive and the soybean oils rise to 1.6 and that of sunflower oil to 2.9 [37]. Sorgüven and Özilgen [42] reported 0.036 cumulative degree of perfection for the strawberry-flavored yogurt, which rise up to 0.046, if renewable energy resources like hydropower and algal biodiesel are employed instead of fossil fuels. The low value of the CDP observed in the flavored yogurt production process may be attributed to the lesser amount of the renewable energy employment in its production, when compared those of the oils. Considering the large volume of the fast food and baking food industries, the assessment of their energy efficiency and their contribution to the environmental pollution deserves special attention. Detailed information about the recent technology regarding the bakery industry is available in detail in the literature [43, 44, 45, 46, 47]. The main originality sought to be achieved in this of the paper may be outlined as follows:

- Detailed thermodynamic analysis for the wheat and rye bread and hamburger bun making processes in Turkey and Germany will be presented by referring to the energy and exergy balances and carbon dioxide emission.
- Energy utilization to produce several food products had been the subject of some studies in the past. However, the overall *farm to fork* production process of wheat bread, rye bread and hamburger bread will be presented in this study for the first time.
- This paper will present a unique approach, where the energy utilization, the carbon dioxide emission, and the exergy destroyed are calculated for bread products starting with the cultivation of the ingredients in the farm, and ending with the transfer of the final product to the market.

- The exergetically inefficient steps of processes will be detected and points, where technological improvement is needed will be identified.

2. Methods

2.1. System, its boundaries and the streams passing through them

The overall bread production system with its boundary, inputs and outputs is presented in Figure 1. Processes occurring within the system boundaries include agriculture of wheat and rye, flour production (cleaning and milling), dough preparation, dividing, fermentation, baking, cooling, slicing, packaging and the transportation of breads to the market. Fertilizers and pesticides consumed during the agriculture are non-renewable chemicals, and the environmental cost for these raw materials is accounted for. Electricity used in all the processes is generated from fossil fuels. The energy or exergy consumed due to human labor is not accounted for, since it is practically impossible to collect representative data. Transportation of the goods is taken into account: the product delivery trucks are considered to be making one-way trip only. Heavy-duty trucks have the capacity of 10 tons and traveling with the velocity of 90 km/h. The total distance for transportation was assumed to be 550 km. Information regarding the energy utilization and the processing rates of the equipment are obtained from the manufacturer web sites. Data about agriculture of wheat and rye are obtained from the literature to study energy and exergy utilization and carbon dioxide emission. Lal [48] reported that the carbon dioxide emission of the diesel oil is 0.94 kg CO_2/kg of diesel oil. Inputs and outputs of the wheat and rye agriculture in Turkey and Germany are compiled from the literature as given in Table 1 and their mass balances are given in Figures 2-5. Equipment used for bread making and energy utilization in each stage of the wheat bread, rye bread and hamburger bun making processes are given in Table 2. Mass and energy inputs and mass outputs of each processing stage during production of one ton of wheat and rye bread and hamburger bun are given in Table 3. Bread is considered to be marketed in packages made of biodegradable [49] polylactic acid (4 g each).

2.3. Modeling of agriculture and bread and bun making processes

Agriculture is modeled as a continuous process where the non-renewable inputs are chemical fertilizers, water, seed and carbon dioxide, and the outputs are grain and straw [50, 51, 52]. For both wheat and rye agriculture, the same agro-chemicals, i.e., herbicide dicamba, insecticide methomyl and the fungicide thiram [21, 22, 53] and the same amount of seeds, 227.7 kg/ha, are assumed to be used [54] both in Turkey and Germany. It was assumed that all the transportation was carried out with 10 ton capacity heavy-duty trucks traveling at a velocity of 90 km/h and consuming 0.287 L diesel oil/km [55]. Additionaly, 165.6 liter diesel/ha [27] is consumed in wheat agriculture and 124.3 liter diesel/ha is consumed in rye agriculture [56]. The density of diesel oil is about 0.771 kg/L [57] its energy equivalent is 45.7 MJ/L [27] and it has the chemical exergy of 44.4 MJ/kg [43]. In our calculations the rye grain to straw ratio wass 2/1 [58]. Table 6 shows that diesel oil for transportation, seeds production and the chemical fertilizers are the largest energy consumers in agriculture. The total energy and exergy inflow and outflow during the agriculture of the wheat grain and rye grain in Turkey and Germany are calculated with equations 5, 6 and 9.

2.2. Estimation of thermodynamic properties

The temperature of dough during fermentation and the temperature of baking were assumed to be 35ºC and 95ºC, respectively [59]. Most of the thermodynamic data were collected from the literature as given in Table 4. Some of the thermodynamic properties were not readily available in the literature, and estimated with the group contribution method based on the molecular structures (Table 5). In accordance with this method, the molecular structure of a compound is decomposed into a set of smaller molecular substructures [60] and then the sum of the thermodynamic properties of these substructures are added up to estimate that of the structure.

The ideal gas standard enthalpy of formation (Δh^o) of a chemical compound is calculated according to Joback's group contribution method scheme as [61]:

$$\Delta h^o = 68.29 \text{ kJ/mol} + \sum_{i=1}^{n} N_i \Delta_{Hi} \qquad (1)$$

Gibbs free energy of formation is needed to calculate the chemical exergies [61]:

$$\Delta g^o = 53.88 \text{ kJ/mol} + \sum_{i=1}^{n} N_i \Delta_{Gi} \qquad (2)$$

The standard chemical exergy is calculated from the exergy of a reversible formation reaction by following the same procedure as Szargut et al [62]. The chemical exergy of a compound is calculated with the summation of Gibbs free energy of a compound and the chemical exergy additions of each element.

$$ex^o_{ch} = \Delta g^o + \sum_{i=1}^{n} N_i (ex^o_{ch,i}) \qquad (3)$$

The thermodynamic properties of the agro-chemicals methomyl and thiram were calculated with the group estimation methods, as well as starch. Wheat and rye seeds consist of 60-70% starch. It was assumed that the seeds were completely composed of starch and the starch monomer $(C_6H_{10}O_5)_n$ was taken as the repeating unit for the seeds [63]. The calculations are given in Table 5 in detail. The details of the process how the chemical exergies are calculated are presented elsewhere [64, 65].

2.3. Thermodynamic analysis

Mass, energy and exergy balance is performed for each operation.

The governing equations for unsteady – state flow system are:

Mass balance:

$$m_{system} = \sum m_{in} - \sum m_{out} \tag{4}$$

Energy balance:

$$\Delta E_{system} = \sum (mh)_{in} - \sum (mh)_{out} + \sum_k Q_k - W \tag{5}$$

Exergy balance:

$$\Delta Ex_{system} = \sum (mex)_{in} - \sum (mex)_{out} + \sum_k Q_k \left(1 - \frac{T_0}{T_k}\right) - W - Ex_{loss} \tag{6}$$

where *k* is the number of heat sources and *ex* is the flow availability of a stream (neglecting the kinetic and potential energy contribution):

$$ex = h - T_0 s - \sum x_i \mu_i^o \tag{7}$$

The exergy destroyed due to the mixing process is calculated for ideal mixture as in Equation 8:

$$Ex_{loss,\ mixing} = R_u T_o \sum m_i \ln(y_i) \tag{8}$$

The cumulative exergy consumption (CExC) is defined as the sum of exergy of all resources consumed in all the stages of a production process. The 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. 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 [42]:

$$\text{CDP}=\frac{\sum m(\text{ex})_{\text{products}}}{\sum m(\text{ex})_{\text{raw materials}}+\sum m(\text{ex})_{\text{fuels}}} \quad (9)$$

3. Results and Discussion

3.1. Agriculture

Table 6 shows that with the input of 13047 MJ/ha of energy and 11232 MJ/ha of exergy 2388.5 kg/ha of wheat grain in produced in Turkey, whereas 15598 MJ/ha of energy and 12473 MJ/ha of exergy are utilized to produce 7980 kg/ha wheat grain in Germany. In Turkey 9561 MJ/ha of energy and 9193 MJ/ha of exergy are utilized to produce 2590 kg/ha rye grain. In Germany, 12020 MJ/ha of energy and 10031 MJ/ha of exergy are utilzed to produce 5960 kg/ha rye grain. When we substitute numbers to equation (9) from Table 6 we calculate the CDP of the wheat agriculture as 3.73 Turkey and 11.26 in Germany. The CDP of the rye agriculture is 4.96 in Turkey and 10.46 in Germany.

3.2. The bread making process

The initial stages of the bread or bun making are consisting of the flour production from the grains, kneading and dividing the dough (Table 2). Milling is the process of breaking open the grain and releasing the starchy center. Milling facilities receive the grains from the trucks and then clean and dry them. The tougher outer layers of the grains may be removed and used for other purposes, e.g., bran is used for breakfast cereals or animal feed [66]. The cleaning of grains is assumed to utilize 0.6 kWh/ton of energy [67] (Table 2). The level of moisture in the grains was taken as 15%. The grains needs to be moisturized before milling [68], the moisture was taken as 16% after moisturizing. The moisture content decreases to 12% after milling [49, 69]**.** The plant employed in this study had the capacity of milling 60 tons of grains in 24 hours with the utilization of 263 kW of electric power. 79.4% of the wheat grain mass wheat and 89.5% rye converted into flour and 379 MJ of energy is utilized for milling of 1 ton grain (Table 2). A typical flour production plant uses 50 % electric power input for milling and grinding, 30 % of it for pneumatic conveying and 11 % of it for mechanical conveying [70].

Mass balances for flour production and following steps are presented in Tables 7, 8 and 9. Water added to the grains to make their water content to 16 % before milling was equivalent to 0.84 % of the grain mass. The details of the mass and energy balances pertinent to the flour production stages of the wheat and rye bread and the hamburger bun making processes are given in Tables 7, 8 and 9.

The kneading machine had a capacity of 450 kg/h and utilizing 2.2 kW of electric power. In order to produce one ton dough for wheat flour 17.6 MJ work needed to be done. In rye dough, the mixing energy for the production of rye bread is 1/3 times of that of the wheat dough kneading due to the difference in pentosan content [62] (Table 2). The common steps of the dough preparation and dividing are explained in detail by Cauvain and Young [71].

The dough divider has the capacity of cutting and rounding 50 - 850 g of pieces of dough in 7 seconds by utilizing 0.75 kW of energy (Table 2). A 65 g hamburger bun was assumed to be produced with 58.0 g of wheat flour. The dough weight of the dough for making one roll of hamburger bun was 108 g. During the mixing of ingredients in bread formulation, exergy destroyed occurs according to equation 8. The exergy destroyed due to the mixing is 578.1 MJ/ton wheat bread, 921.0 MJ/ton rye bread and 953.4 MJ/ton hamburger buns. Also, total exergy destroyed in dough preparation and dividing is 621.7 MJ/ton wheat bread, 951.4 MJ/ton rye bread and 1114.1 MJ/ton hamburger buns.

After mixing of all ingredients, carbon dioxide and ethanol are produced due to the consumption of glucose by the yeast. During one hour of fermentation, yeast consumes 1.86 g of glucose and produces 0.95 g of ethanol and 0.91 g of carbon dioxide in 1 kg of dough (Table 6) [72]. The energy utilization during fermentation is 9.2 MJ/ton of wheat and rye dough, while this value is 49.0 MJ/ton of for hamburger bun dough (Table 7). In the wheat and rye bread production, the baking oven has the capacity of 100 kg/h and power of 10.8 kW and the energy utilization is 648 MJ/ton bread (Table 7). The duration of baking is assumed as 45 minutes; the wheat and rye breads loss 13% of their weights in the oven during the baking process [73], the weight loss is assumed to be 40% in hamburger buns [6]. After the baking process the loaves are cooled on the racks that allow the air to circulate around them and prevent the crusts from becoming soggy. The cooling machine used in this study has the capacity of 1000 kg/h and utilizes 167 kW of power. The energy consumption is 36 MJ for cooling of 1 ton of bread (Table 7). The wheat and rye bread loaves are assumed as 500 g in weight and sliced in to 15 slices / bread. Wheat bread is made of 59.1% wheat flour, 38.5% water, 1.2% yeast and 1.2% salt. Rye bread formulation consists of 61.7% rye flour, 37.0% water, 0.4% yeast and 0.9% salt. Hamburger bun is composed of 53.5% wheat flour, 34.8% water, 2.1% yeast, 0.7% salt, 6.3% sugar and 2.6% margarine [74, 75]. The hamburgers are sliced in two at the middle of the bun, slicing is done horizontally in a single stroke [76]. The slicing machine has the capacity of 1800 loaves/hour and utilized 2.4 kW of power. The energy consumption for the slicing the wheat or rye bread is 9.6 MJ/ ton and 3 MJ/ton hamburger bun (Table 7). Eight buns are packaged together for shipping to the restaurants. The packaging machine operated at the rate of 1 bag/s with the power requirement of 3.6 kW; and the packaging material was selected as 4 g per package and 4 g each. The energy consumption for the packaging of the wheat bread is 7.2 MJ/ton bread for 1 ton wheat bread and rye bread. The hamburger bun packs contains 8 rolls and the energy consumption is 4.2 MJ/ton hamburger buns.

In Table 7, the energy and exergy balances of baking, cooling, slicing and packaging are given for 1 ton wheat bread. The heat rejected is 1580.5 MJ/ton wheat bread and exergy destroyed is 2777.0 MJ/ton wheat bread. The same values are presented for 1 ton rye bread in Table 8 and for 1 ton hamburger bun in Table 9. The heat loss is 1521.1 MJ/ton rye bread and exergy destroyed is 1463.7 MJ/ton rye bread. The heat loss is 1976.2 MJ/ton hamburger buns and exergy destroyed is 2390.5.

In overall, hamburger bun production has the maximum energy consumption due to the higher weight loss in baking. Rye bread production has the minimum energy consumption due to lower energy consumption in agriculture of rye grain with respect to agriculture of wheat grain, less energy consumption in dough preparation and higher flour production efficiency.

Transportation is the last step of the bread production. Heavy-duty trucks (capacity=10 tons, velocity=90 km/h) utilize 0.287 L/km of fuel [77]. The data of the transportation of grains to the flour factory was calculated in the agriculture as 51 MJ/ton bread and the distance between the farm and flour factory was assumed to be 50 km [37]. Transportation is also needed to deliver the flour to baking factory and to deliver breads to market. The total distance for those was assumed to be 550 km [37]. Therefore, total energy consumption for the transportation is 701 MJ/ton bread and exergy consumption 681 MJ/ton bread.

3.3. The values of CEnC, CExC and CCO_2E

The values of CEnC, CExC and CCO_2E for the wheat and rye grain production both in Turkey and Germany, and the contribution of each ingredient to these sums are given in Table 10. The CEnC of wheat grain production is 5.4 MJ/kg in Turkey and 1.9 MJ/kg in Germany while CExC of wheat grain production is 6.7 MJ/kg in Turkey and 2.7 MJ/kg in Germany. The CCO_2E of wheat grain cultivation is 0.3 kg/kg in Turkey and 0.2 kg/kg in Germany (Table 10). Diesel consumption contributes 57.27 % and 58.88 % of the total CEnC in Turkey and Germany, respectively. The chemical fertilizers produce the highest CEnC 27.87 % of the total in Turkey, and 31.49 % of the total in Germany. The highest contribution to the CExC is made by diesel in both countries: in Turkey 42.84 % and 31.01% in Germany. The most important contributor to carbon dioxide emission was made by the chemical fertilizers: 48.92% in Turkey, and 36.55% in Germany. A high contribution, 36.22%, to CCO_2E was made by irrigation in Germany.

The CEnC of the rye grain produced in Turkey is 3.5 MJ/kg and 1.8 MJ/kg in Germany while CExC of rye grain production 5.4 MJ/kg in Turkey and 2.4 MJ/kg in Germany (Table 10). The CCO_2E is 0.2 kg/kg rye grain in both countries. Diesel consumption comprises 61.58 % and 51.03% of the total CEnC in Turkey and Germany, respectively. The chemical fertilizers make the highest contribution to CEnC by 16.85% and 30.02% in Turkey and Germany, respectively. The highest contribution was made to the CExC by diesel utilization and seed production in both countries. Contribution of diesel to CExC is 36.88% and 35.48% in Turkey and Germany, respectively while contribution of the seeds to the CExC is 26.97% and 25.95% in Turkey and Germany, respectively. The most important contributor to carbon dioxide emission is irrigation in Turkey (30.83%) and the chemical fertilizers (39.44%) in Germany. When we compare the grains, rye agriculture equire lower energy utilization and has lower values of CEnC, CExC and CCO_2E.

The values of CEnC, CExC and CCO_2E are presented for the wheat and rye grain agriculture in Turkey and Germany in Table 10, and for the bread making process in Table 11. The values of CEnC, CExC and CCO_2E were higher during hamburger bun production when compared to those of the wheat and rye bread production processes due to the higher weight loss occurring during the baking process. In both wheat and rye the bread making processes the flour production stage made the highest contribution to the calculated values of CEnC, CExC and CCO_2E, whereas in the hamburger bun production process the flour production had the second highest contribution to the total after that of the dough production (Table 11).

Nylund and Erkkilä [78] after making measurements with 18 to 60 ton capacity trucks running under dynamic load cycles including simulations of transportation at freeway, highway and delivery conditions with the load ranging between 0 to 100 % of the total loading capacity of the trucks, reported that although the fuel consumption increases with the load, fuel consumption per ton of the load per km traveled decreases as the pay load increases. Their results varied substantially with the type of the truck and the engine. Large range of fuel consumption and carbon dioxide emission factor variations were also reported by the other researchers [79, 80] under varying conditions of transportation. Therefore the carbon dioxide emission calculations of this study pertinent to transportation are valid under the conditions they are calculated and subject to change as the type, speed of transportation.

It is stated in Tables 7, 8 and 9 that exergy destruction during production of one ton of wheat bread, rye bread and hamburger buns is 6269.5 MJ/ton wheat bread, 4726.6 MJ/ton rye bread and 6687.9 MJ/ton hamburger buns. Tsatsarones [81] while discussing the definitions and nomenclature in exergy analysis states that the thermodynamic inefficiencies of a system, associated with the irreversibilities (entropy generation) cause exergy destruction within the system boundaries. The exergy destruction results in the transfer of exergy (through material and energy streams) to the surroundings.

3. Conclusions

Table 12 shows that the amount of the land required to produce the same amount of wheat in Turkey is 3.34 times of that required in Germany, this ratio is 2.30 with rye pointing the lower efficiency of the conversion of the solar energy into the grain mass in Turkey. The ratio of the values of the CDPs achieved in Germany to those achieved in Turkey was 3 with the wheat grain and 2 with the rye grain indicating the higher level of renewability of the German agriculture. The ratio of the values of the CExCs and CEnCs (Table 10) achieved in Turkey to those achieved in Germany was 2.8 with the wheat grain and 2.25 with the rye grain indicating that in Turkey more than two times of the exergy and energy utilized in Germany was needed to produce the same amounts of grains. The ratio of the values of the CCO_2Es (Table 10) achieved in Turkey to those achieved in Germany was 1.5 with the wheat grain and 1.0 with the rye grain indicating that in Turkey 1.5 times of the carbon dioxide of that of Germany was emitted to produce the same amount of wheat grains, while it was the same with rye in both countries.

Specific energy utilization for rye bread production is almost the same in Turkey and Germany; but it is 12 % higher in Turkey for wheat bread and hamburger bun making processes (Table 12). Hamburger bun production requires the maximum energy utilization due to the higher weight loss in baking. Maximum amount of exergy, 6687.9 MJ, is destroyed during production of one ton hamburger buns (Tables 7, 8 and 9).

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Figure Captions

Figure 1. The overall bread production system with its boundary, inputs and outputs

Figure 2. Mass balance of the wheat agriculture in Turkey

Figure 3. Mass balance of the wheat agriculture in Germany

Figure 4. Mass balance of the rye agriculture in Turkey

Figure 5. Mass balance of the rye agriculture in Germany

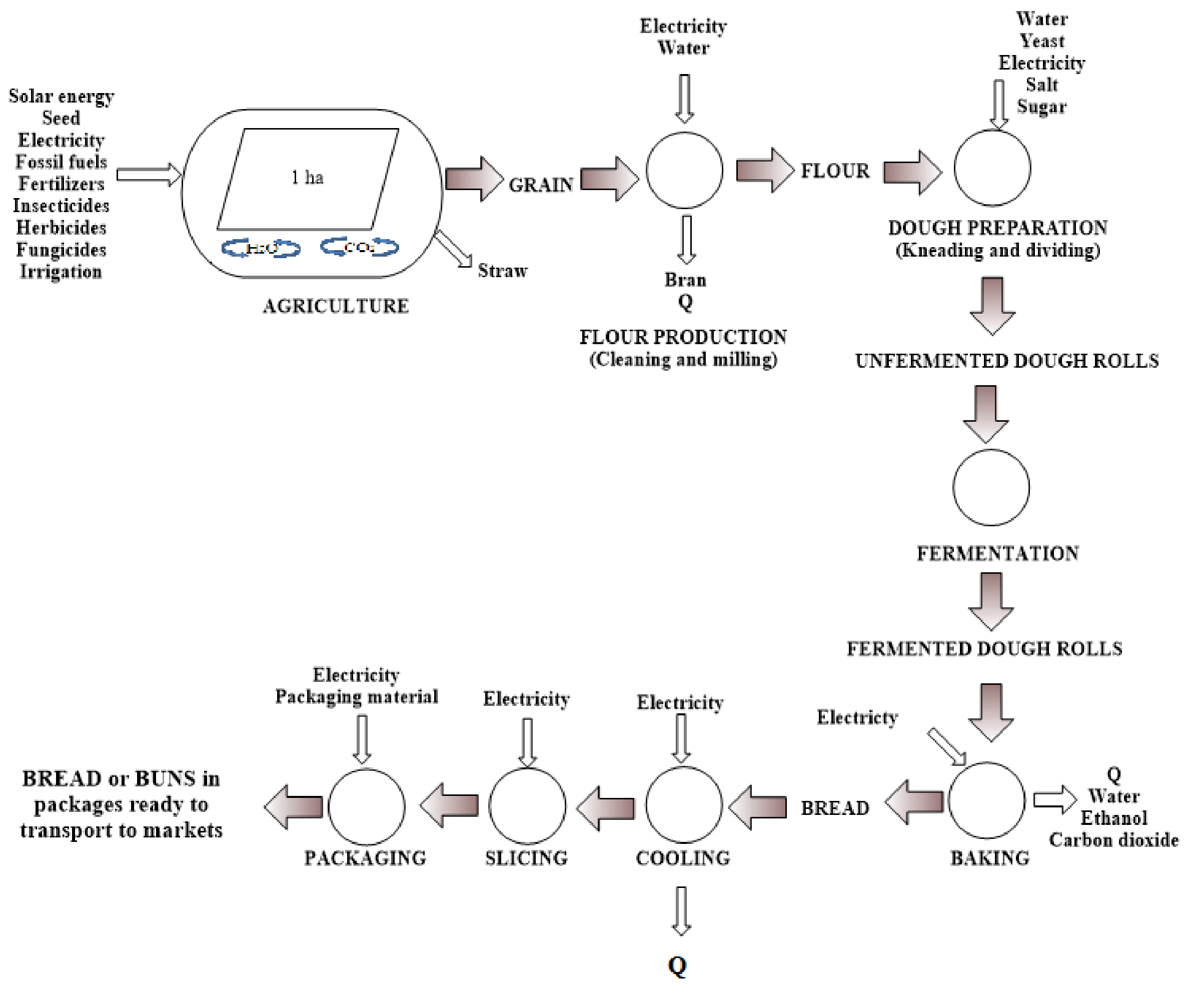
Solar energy
Seed
Electricity
Fossil fuels
Fertilizers
Insecticides
Herbicides
Fungicides
Irrigation
1 ha
AGRICULTURE
Straw
GRAIN
Electricity
Water
Bran
Q
FLOUR PRODUCTION
(Cleaning and milling)
FLOUR
Water
Yeast
Electricity
Salt
Sugar
DOUGH PREPARATION
(Kneading and dividing)
UNFERMENTED DOUGH ROLLS
FERMENTATION
FERMENTED DOUGH ROLLS
Electricty
Q
Water
Ethanol
Carbon dioxide
BAKING
BREAD
Electricity
COOLING
Q
Electricity
SLICING
Electricity
Packaging material
PACKAGING
BREAD or BUNS in
packages ready to
transport to markets

Figure 1.

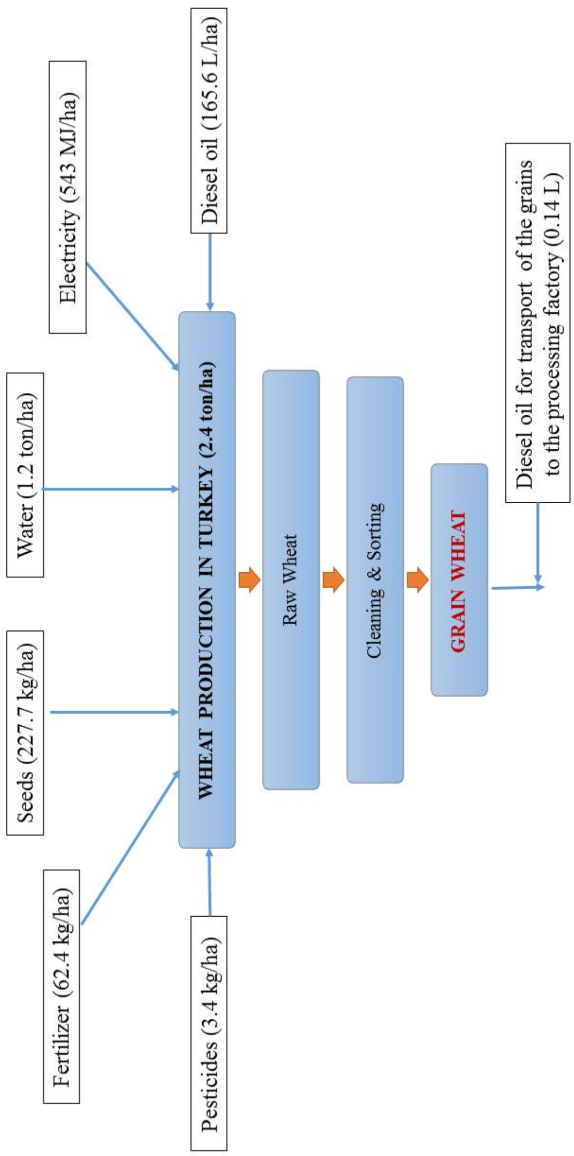
Fertilizer (62.4 kg/ha)
Seeds (227.7 kg/ha)
Water (1.2 ton/ha)
Electricity (543 MJ/ha)
Pesticides (3.4 kg/ha)
Diesel oil (165.6 L/ha)
WHEAT PRODUCTION IN TURKEY (2.4 ton/ha)
Raw Wheat
Cleaning & Sorting
GRAIN WHEAT
Diesel oil for transport of the grains to the processing factory (0.14 L)

Figure 2.

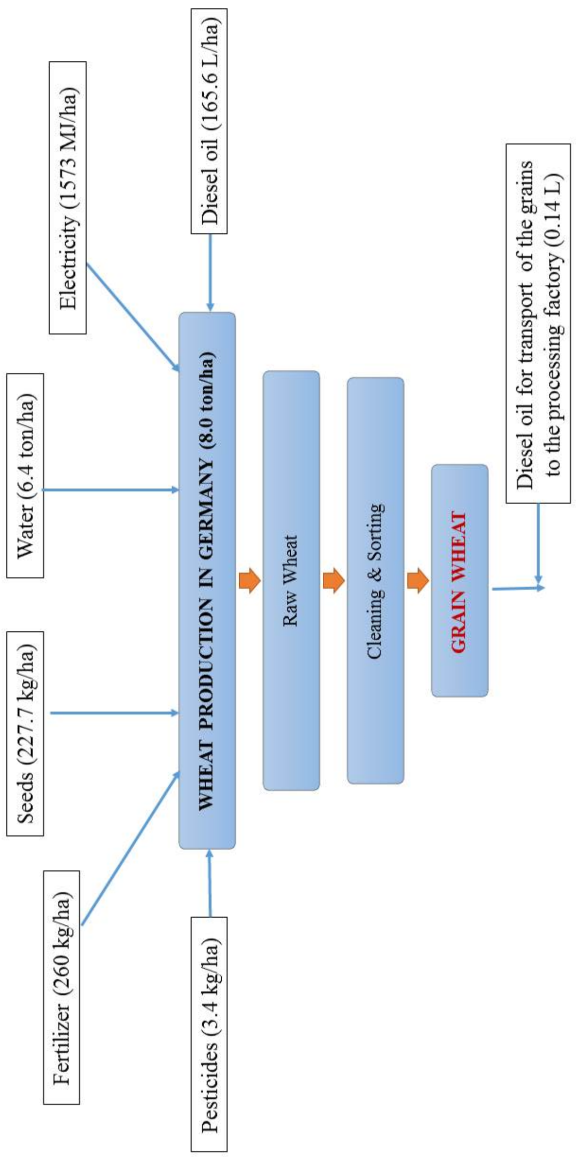
Fertilizer (260 kg/ha)
Pesticides (3.4 kg/ha)
Seeds (227.7 kg/ha)
Water (6.4 ton/ha)
Electricity (1573 MJ/ha)
Diesel oil (165.6 L/ha)
WHEAT PRODUCTION IN GERMANY (8.0 ton/ha)
Raw Wheat
Cleaning & Sorting
GRAIN WHEAT
Diesel oil for transport of the grains to the processing factory (0.14 L)

Figure 3.

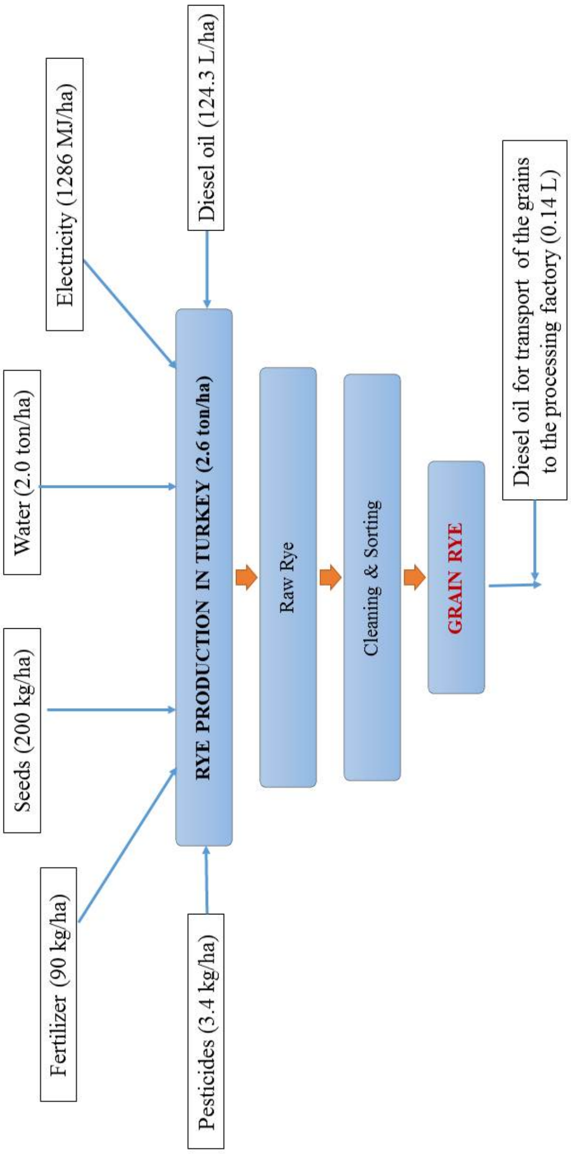
Electricity (1286 MJ/ha)
Diesel oil (124.3 L/ha)
Water (2.0 ton/ha)
Seeds (200 kg/ha)
Fertilizer (90 kg/ha)
Pesticides (3.4 kg/ha)
RYE PRODUCTION IN TURKEY (2.6 ton/ha)
Raw Rye
Cleaning & Sorting
GRAIN RYE
Diesel oil for transport of the grains to the processing factory (0.14 L)

Figure 4.

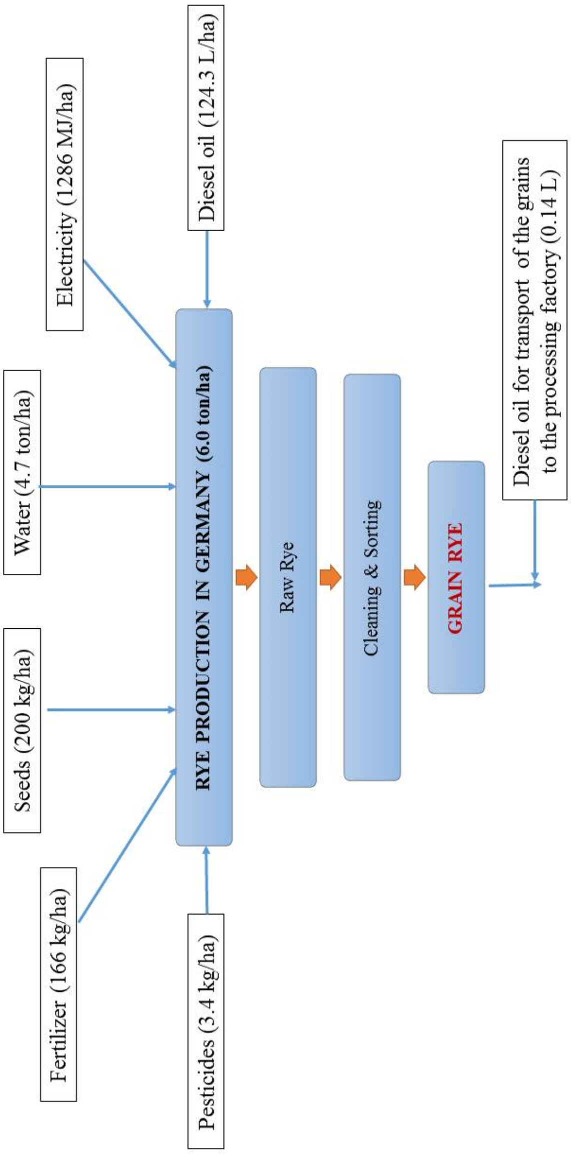
Fertilizer (166 kg/ha)
Seeds (200 kg/ha)
Water (4.7 ton/ha)
Electricity (1286 MJ/ha)
Diesel oil (124.3 L/ha)
Pesticides (3.4 kg/ha)
RYE PRODUCTION IN GERMANY (6.0 ton/ha)
Raw Rye
Cleaning & Sorting
GRAIN RYE
Diesel oil for transport of the grains to the processing factory (0.14 L)

Figure 5

Table1. Inputs and outputs of the wheat and rye agriculture in Turkey and Germany

	Agriculture of wheat in Turkey	Agriculture of wheat in Germany	Agriculture of rye in Turkey	Agriculture of wheat in Germany
Inputs				
Diesel oil (L/ha)	165.6 [27]	165.6 [27]	124.3 [56]	124.3 [56]
Nitrogen fertilizer (kg/ha)	101.88 [26]	145 [28]	40 [31]	98 [33]
Phosphorus fertilizer (kg/ha)	72.2 [26]	37 [28]	50 [31]	24 [33]
Potassium fertilizer (kg/ha)	-	41 [28]	-	44 [33]
Herbicide (kg/ha)	1.12 [53]	1.12 [53]	1.12 [53]	1.12 [53]
Insecticide (kg/ha)	0.56 [82]	0.56 [82]	0.56 [82]	0.56 [82]
Fungicide (kg/ha)	1.69 [83]	1.69 [83]	1.69 [83]	1.69 [83]
Seed (kg/ha)	227.7 [26]	227.7 [26]	200 [26]	200 [26]
Irrigation water (kg/ha)	1195 [19]	6350 [19]	1982 [19]	4731 [19]
Transportation (L diesel /km)	0.287 [55]	0.287 [55]	0.287 [55]	0.287 [66]
Outputs				
Grain (kg/ha)	2388.5 [26]	7980 [29]	2590 [32]	5960 [29]
Straw (kg/ha)	223.6 [26]	3990 [29]	1295 [32]	2980 [29]

Table 2. Energy utilization in each stage of the wheat bread, rye bread and hamburger bun making processes

Stage of processing	Energy utilization
Cleaning of the grains (0.6 kWh) [67]	2.2 MJ/ton grain
Shijiazhuang Hongdefa (China) flour milling plant (60 t/24h, 263 kW, 79.4% wheat flour extraction and 89.5% rye flour extraction)	379 MJ/ton grain
Dough preparation with Meiying (China), model HWY75, dough kneading machine capacity 450 kg/h, power 2.20 kW for the wheat flour and 0.73 kW for the rye flour	Wheat bread: 17.6 MJ/ton dough Rye bread: 5.9 MJ/ton dough Bun: 17.6 MJ/ton dough
Dividing the dough with Haidier (China), model HDR-2000 divider, power 1.5 kW, dividing rate 7s/piece, each piece weighs 50-850 g	Wheat bread: 21.0 MJ/ton dough Rye bread: 21.0 MJ/ton dough Bun: 97.2 MJ/ton dough
Fermentation in Berg (China), model XF-16FC, bread proofer equipped with 16 trays in 620 mm x 970 mm x 2100 mm dimensions, power 0.85 kW	Wheat bread 9.2 MJ/ton dough Rye bread: 9.2 MJ/ton dough Bun: 49.0 MJ/ton dough
Baking in Zhengzhou Ditai (China), model 239-YXDF60 oven, capacity 60 kg/h, power 10.8 kW	648 MJ/ton bread
Cooling in Hebei Aocno (China), model ACN-C 1000 bread cooler, operating at cooling capacity of 500 kg/20 min, power 15 kW	36 MJ/ton bread
Slicing with Atlas slicer (Taiwan), slicing capacity 1800 loaves/h, slicing thickness 12 mm, power 2.4 kW)	Wheat bread: 9.6 MJ/ton bread Rye bread: 9.6 MJ/ton bread Bun: 3.0 MJ/ton bread
Packaging with Dachuan, model DF-450W packaging capacity 1 bag/s, power 3.6 kW)	Wheat bread: 7.2 MJ/ton bread Rye bread: 7.2 MJ/ton bread Bun: 4.2 MJ/ton bread

Table 3. Mass and energy inputs and mass outputs of each processing stage during production of one ton of wheat and rye bread and hamburger bun

	INPUT	Wheat	Rye	Hamburger Bun	OUTPUT	Wheat	Rye	Hamburger bun
Flour production	Grain	834 kg	772 kg	935 kg	Flour	668 kg	697 kg	749 kg
	Water	7.0 kg	7.0 kg	8.0 kg	Bran	173 kg	82 kg	194 kg
	Electricity for cleaning	0.6 kWh	0.6 kWh	0.6kWh				
	Electricity for milling	263 kW	263 kW	263 kW				
Dough preparation	Flour	668 kg	697 kg	749 kg	Dough	1130 kg	1130 kg	1400 kg
	Water	434 kg	418 kg	487 kg				
	Yeast	14 kg	5 kg	29 kg				
	Salt	14 kg	10 kg	10 kg				
	Sugar	-	-	88 kg				
	Margarine	-	-	36 kg				
	Electricity for kneading	2.20 kW	0.73 kW	2.20 kW				
	Electricity for dividing	1.50 kW	1.50 kW	1.50 kW				
Fermentation	Unfermented dough	1130 kg	1130 kg	1400 kg	Fermented dough	1130 kg	1130 kg	1400 kg
	Electricity	0.85 kW	0.85 kW	0.85 kW				
Baking	Dough	1130 kg	1130 kg	1400 kg	Bread	1000 kg	1000 kg	1000 kg
	Electricity	10.8 kW	10.8 kW	10.8 kW	Ethanol	0.95 kg	0.95 kg	0.95 kg
Cooling	Electricity	15 kW	15 kW	15 kW	Carbon dioxide	0.91 kg	0.91 kg	0.91 kg
Slicing	Electricity	2.4 kW	2.4 kW	2.4 kW	Water	128.14 kg	128.14 kg	398.14 kg
Packaging	Polylactic acid	8 kg	8 kg	5 kg	Bread in packages	1000+16 kg	1000+8 kg	1000+5 kg
	Electricity	3.6 kW	3.6 kW	3.6 kW				

Table 4. Thermodynamic data

	Δh_f^o		ex_{ch}^o		Specific CEnC		Specific CExC		Specific CCO_2E	
Diesel oil	45.7 MJ/kg	[27]	44.4 MJ/kg	[42]	57.5 MJ/kg	[100]	53.2 MJ/kg	[62]	0.94 kg/kg	[48]
Nitrogen fertilizer	66.1 MJ/kg	[56]	3.68 MJ/kg	[92]	78.2 MJ/kg	[101]	32.7 MJ/kg	[62]	7.11 kg/kg	[4]
Phosphate fertilizer	12.4 MJ/kg	[56]	10.5 MJ/kg	[37]	17.5 MJ/kg	[101]	7.5 MJ/kg	[103]	2.7 kg/kg	[4]
Potassium fertilizer	11.2 MJ/kg	[56]	0.26 MJ/kg	[92]	13.8 MJ/kg	[101]	4.6 MJ/kg	[104]	25.0 kg/kg	[4]
Herbicide (dicamba)	2.3 MJ/kg	[84]	18.4 MJ/kg	[93]	198.8 MJ/kg	[100]	368.0 MJ/kg	[105]	6.3 kg/kg	[65]
Insecticide (methomyl)	1.4 MJ/kg	[61]	23.2 MJ/kg	[94]	198.8 MJ/kg	[100]	344.0 MJ/kg	[105]	5.1 kg/kg	[65]
Fungicide (thiram)	0.9 MJ/kg	[84]	27.9 MJ/kg	[94]	198.8 MJ/kg	[100]	256.0 MJ/kg	[105]	3.9 kg/kg	[65]
Seed	15.7 MJ/kg	[85]	19.8 MJ/kg	[94]	2.8 MJ/kg	[102]	18.7 MJ/kg	[106]	0.23 kg/kg	[42]
Water	0.10 MJ/kg	[61]	0.05 MJ/kg	[92]	0.06 MJ/kg	[61]	0.25 MJ/kg	[62]	0.085 kg/kg	[109]
Electricity from fossil fuel			1 MJ/MJ	[95]	1.0 MJ/MJ	[61]	4.17 MJ/MJ	[62]	0.14 kg/MJ	[110]
Electricity used in agriculture	228 MJ/ton grain	[86]								
Wheat grain	14.7 MJ/kg	[51]	17.6 MJ/kg	[96]	3.65 MJ/kg		4.7 MJ/kg		0.25 kg/kg	
Rye grain	14.7 MJ/kg	[26]	17.6 MJ/kg	[96]	2.65 MJ/kg		3.9 MJ/kg		0.20 kg/kg	
Straw	12.5 MJ/kg	[26]	2.1 MJ/kg	[97]						
Flour	15.2 MJ/kg	[87]	18.4 MJ/kg	[61]	17.9 MJ/kg	[42]	17.5 MJ/kg	[42]		
Bran	6.0 MJ/kg	[87]	3.1 MJ/kg	[61]						
Salt	7.0 MJ/kg	[88]	0.24 MJ/kg	[92]	0.357 MJ/kg	[62]	0.297 MJ/kg	[62 107]		
Sugar	7.1 MJ/kg	[61]	16.7 MJ/kg	[98]	16.0 MJ/kg	[42]	26.0 MJ/kg	[42]		
Yeast	5.4 MJ/kg	[61]	21.4 MJ/kg	[61]	41 MJ/kg	[62]	171 MJ/kg	[108,109]	5.74 kg/kg	[62,108]
Margarine	2.1 MJ/kg	[89]	39.9 MJ/kg	[37]	39 MJ/kg	[42]	39.6 MJ/kg	[42]		
Carbon dioxide	8.9 MJ/kg	[89,90]	0.5 MJ/kg	[62]						
Ethanol	0.5 MJ/kg	[61, 91]	30.4 MJ/kg	[99]						
Wheat bread	9.6 MJ/kg	[87]	10.0 MJ/kg	[61]	18.9 MJ/kg		29.1 MJ/kg		1.5 kg/kg	
Rye bread	10.1 MJ/kg	[87]	10.7 MJ/kg	[61]	12.8 MJ/kg		22.6 MJ/kg		1.8 kg/kg	
Hamburger bun	11.5 MJ/kg	[87]	14.5 MJ/kg	[61]	23.4 MJ/kg		38.5 MJ/kg		1.1 kg/kg	
Polylactic acid	3.4 MJ/kg	[61]	21.5 MJ/kg	[61]	54.0 MJ/kg	[42]	78.0 MJ/kg	[42]	1.8 kg/kg	[42]

Table 5. Estimation of the thermodynamic properties which are not readily available in the literature.

a) Atomic group contributions employed for estimating Δh° and Δg° of methomyl and thiram [61]

Atomic group	Occurrence	Δ_H (kJ/mol)	Δ_G (kJ/mol)
methomyl			
$-CH_3$	3	-76.45	-43.96
-S-	1	41.87	33.12
-C=	1	83.99	92.36
=N-	1	23.61	-
-O-	1	-132.22	-105.00
-C=O	1	-133.22	-120.50
-NH-	1	53.47	89.39
		$\sum h^o$ = -223.56 kJ/mol	$\sum g^o$ = -88.63 kJ/mol
thiram			
$-CH_3$	4	-76.45	-43.96
- N-	2	123.34	163.16
-C=	2	83.99	92.36
-S-	2	41.87	33.12
=S	2	-17.33	-22.99
		$\sum h^o$ = -226.23 kJ/mol	$\sum g^o$ = 409.34 kJ/mol

b) Increments to be added for the estimation of the standard chemical exergy [86]

Molecule	$ex_{ch,element}$ /molecule (kJ/mol)
C	410.25
H_2	236.10
O_2	3.97
N_2	0.72
S	607.05

c) Estimated standard chemical exergies of methomyl, thiram and the seed

	$\sum n_i ex_{ch,element}$ (kJ/mol)	Chemical exergy ex_{ch}^o (kJ/mol)
Methomyl	3844.0	3755.4
Thiram	6307.0	6716.3
Seed	3652.0	4313.0

Table 6. Total energy and exergy input and output during the agriculture of the wheat grain and rye grain in Turkey and Germany as calculated with equations 5, 6 and 9

	TURKEY		GERMANY	
	Energy inflow (MJ/ha)	Exergy inflow (MJ/ha)	Energy inflow (MJ/ha)	Exergy inflow (MJ/ha)
What grain inputs				
Diesel oil	5842	5675	5842	5675
Nitrogen fertilizer	2694	150.0	3834	213
Phosphate fertilizer	269	227.6	89	117
potassium fertilizer	-	-	46	1
Herbicide	2.60	20.6	2.60	20.6
Insecticide	0.78	12.8	0.78	12.8
Fungicide	1.01	34.5	1.01	34.5
Seed	3575	4508	3575	4508
Irrigation	120	60	635	318
Electricity	543	543	1573	1573
TOTAL	$\sum(mh)_{in}$: 13047	$\sum(mex)_{in}$: 11232	$\sum(mh)_{in}$: 15598	$\sum(mex)_{in}$: 12473
Wheat grain outputs				
Grain	35037	41950	117306	140448
Straw	2795	474	49875	8379
TOTAL	$\sum(mh)_{out}$: 37832	$\sum(mex)_{out}$: 42424	$\sum(mh)_{out}$: 167181	$\sum(mex)_{out}$: 148827
		CDP_{grain}: 3.73		CDP_{grain}: 11.26
Rye grain inputs				
Diesel oil	4378	4255	4378	4255
Nitrogen fertilizer	1058	58.9	2593	144.3
Phosphate fertilizer	186	157.6	89	75.7
potassium fertilizer	-	-	51	1.14
Herbicide	2.60	20.6	2.60	20.6
Insecticide	0.78	12.8	0.78	12.8
Fungicide	1.01	34.5	1.01	34.5
Seed	3140	3960	3140	3960
Irrigation	198	99	473	237
Transportation	6	3.65	6	3.65
Electricity	591	591	1286	1286
TOTAL	$\sum(mh)_{in}$: 9561	$\sum(mex)_{in}$: 9193	$\sum(mh)_{in}$: 12020	$\sum(mex)_{in}$: 10031
Rye grain outputs				
Grain	38073	45584	87612	104896
Straw	16188	2745	37250	6258
TOTAL	$\sum(mh)_{out}$: 54261	$\sum(mex)_{out}$: 48329	$\sum(mh)_{out}$: 12862	$\sum(mex)_{out}$: 111154
		CDP_{grain}: 4.96		CDP_{grain}: 10.46

Table 7. Energy and exergy balances for the flour production, dough preparation and diving, fermentation**,** baking, cooling, slicing, packaging and transportation during production of one ton of wheat bread

	INPUTS	Total energy inflow (MJ)	Total exergy inflow (MJ)	OUTPUTS	Total energy outflow (MJ)	Total exergy outflow (MJ)
Flour production	Grain	12259.8	14678.4	Flour	10153.6	12291.2
	Water	0.6	0.4	Bran	1038.0	536.3
	Electricity for cleaning	1.7	1.7	Heat rejected	1389.7	-
	Electricity for milling	319	319	Exergy destroyed		2172.2
Dough preparation and diving	Flour	10153.6	12291.2	Unfermented dough	10414.2	12037.8
	Water	43.4	21.7			
	Yeast	75.6	299.6			
	Salt	98.0	3.4			
	Electricity for kneading	19.9	19.9			
	Electricity for dividing	23.7	23.7			
				Exergy destroyed due to mixing		578.1
				Total exergy destroyed		621.7
Fermentation	Unfermented dough	10414.2	12037.8	Fermented dough	10424.6	12037.8
	Electricity for fermenter	10.4	10.4			
				Exergy destroyed		10.4
Baking	Fermented dough	10424.6	12037.8	Bread	9600	10000
	Electricity for oven	732	732	Water	12.8	9.0
Cooling	Electricity for cooler	36.0	36.0	Carbon dioxide	8.2	0.5
Slicing	Electricity for slicer	9.6	9.6	Ethanol	0.7	28.9
				Heat rejected	1580.5	
				Exergy destroyed		2777.0
Packaging	Bread	9600	10000	Bread in packages and delivered	10335.4	10172.0
	Polylactic acid	27.2	172.0			
	Electricity for packaging	7.2	7.2			
Transportation	Packaged bread	701	681			
				Exergy destroyed		688.2

Table 8. Energy and exergy balances for the flour production, dough preparation and diving, fermentation**,** baking, cooling, slicing, packaging and transportation during production of one ton of rye bread

<table>
<tr><th></th><th>INPUTS</th><th>Total energy inflow (MJ)</th><th>Total exergy inflow (MJ)</th><th>OUTPUTS</th><th>Total energy outflow (MJ)</th><th>Total exergy outflow (MJ)</th></tr>
<tr><td rowspan="4">Flour production</td><td>Grain</td><td>11348.4</td><td>14308.8</td><td>Flour</td><td>10685.6</td><td>12015.2</td></tr>
<tr><td>Water</td><td>0.7</td><td>0.4</td><td>Bran</td><td>738</td><td>381.3</td></tr>
<tr><td>Electricity for cleaning</td><td>1.7</td><td>1.7</td><td>Heat rejected</td><td>466.2</td><td></td></tr>
<tr><td>Electricity for milling</td><td>293</td><td>293</td><td>Exergy destroyed</td><td></td><td>1612.9</td></tr>
<tr><td rowspan="6">Dough preparation and dividing</td><td>Flour</td><td>10685.6</td><td>12015.2</td><td rowspan="6">Unfermented dough</td><td rowspan="6">10854.8</td><td rowspan="6">11224.5</td></tr>
<tr><td>Water</td><td>41.8</td><td>20.9</td></tr>
<tr><td>Yeast</td><td>27</td><td>107</td></tr>
<tr><td>Salt</td><td>70</td><td>2.4</td></tr>
<tr><td>Electricity for kneading</td><td>6.7</td><td>6.7</td></tr>
<tr><td>Electricity for dividing</td><td>23.7</td><td>23.7</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Exergy destroyed due to the mixing</td><td></td><td>921.0</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Total exergy destroyed</td><td></td><td>951.4</td></tr>
<tr><td>Fermentation</td><td>Unfermented dough</td><td>10854.8</td><td>11224.5</td><td rowspan="2">Fermented dough</td><td rowspan="2">10865.2</td><td rowspan="2">11224.5</td></tr>
<tr><td></td><td>Electricity for fermenter</td><td>10.4</td><td>10.4</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Exergy destroyed</td><td></td><td>10.4</td></tr>
<tr><td>Baking</td><td>Fermented dough</td><td>10865.2</td><td>11224.5</td><td>Bread</td><td>10100.0</td><td>10700.0</td></tr>
<tr><td></td><td>Electricity for oven</td><td>732</td><td>732</td><td>Water</td><td>12.8</td><td>9.0</td></tr>
<tr><td>Cooling</td><td>Electricity for cooler</td><td>36</td><td>36</td><td>Carbon dioxide</td><td>8.2</td><td>0.5</td></tr>
<tr><td>Slicing</td><td>Electricity for slicer</td><td>9.6</td><td>9.6</td><td>Ethanol</td><td>0.7</td><td>28.9</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Heat rejected</td><td>1521.1</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td>Exergy destroyed</td><td></td><td>1463.7</td></tr>
<tr><td rowspan="3">Packaging</td><td>Bread</td><td>10100.0</td><td>10700.0</td><td rowspan="4">Bread in packages and delivered</td><td rowspan="4">10835.4</td><td rowspan="4">10872.0</td></tr>
<tr><td>Polylactic acid</td><td>27.2</td><td>172.0</td></tr>
<tr><td>Electricity for packaging</td><td>7.2</td><td>7.2</td></tr>
<tr><td>Transportation</td><td>Packaged bread</td><td>701</td><td>681</td></tr>
<tr><td></td><td></td><td></td><td></td><td>Exergy destroyed</td><td></td><td>688.2</td></tr>
</table>

Table 9. Energy and exergy balances for the flour production, dough preparation and diving, fermentation**,** baking, cooling, slicing, packaging and transportation during production of one ton of hamburger buns

	INPUTS	Energy inflow (MJ)	Exergy inflow (MJ)	OUTPUTS	Energy outflow (MJ)	Exergy outflow (MJ)
Flour production	Grain	13744.5	16456.0	Flour	11384.8	13781.6
	Water	0.8	0.4	Bran	1164.0	601.4
	Electricity for cleaning	1.9	1.9	Heat rejected	1552.6	
	Electricity for milling	354	354	Exergy destroyed		2429.5
Dough preparation and dividing	Flour	11384.8	13781.6	Unfermented dough	12510.3	16001.8
	Water	48.7	24.4			
	Yeast	156.6	620.6			
	Salt	70	2.4			
	Sugar	616	1258.4			
	Margarine	73.5	1396.5			
	Electricity for kneading	24.6	24.6			
	Electricity for dividing	136.1	136.1			
				Exergy destroyed due to the mixing		953.4
				Total exergy destroyed		1114.1
Fermentation	Unfermented dough	12510.3	16001.8	Fermented dough	12578.9	16001.8
	Electricity for fermenter	68.6	68.6			
				Exergy destroyed		68.6
Baking	Fermented dough	12578.9	16001.8	Hamburger buns	11500.0	14500.0
	Electricity for oven	907	907	Water	39.8	27.9
Cooling	Electricity for cooler	36	36	Carbon dioxide	8.2	0.5
Slicing	Electricity for slicer	3.0	3.0	Ethanol	0.7	28.9
				Heat rejected	1976.2	
				Exergy destroyed		2390.5
Packaging	Hamburger buns	11500.0	14500.0	Hamburger buns delivered in packages	12375.2	14607.5
	Polylactic acid	17.0	107.5			
	Electricity for packaging	4.2	4.2			
Transportation	Hamburger buns	701	681			
				Exergy destroyed		685.2

Table 10. The values of the CEnC, CExC and CCO_2E as calculated for wheat and rye grain agriculture in Turkey and Germany

	TURKEY			GERMANY		
Wheat grain						
	CEnC (MJ/kg)	CExC (MJ/kg)	CCO_2E (kg/kg)	CEnC MJ/kg)	CExC (MJ/kg)	CCO_2E (MJ/kg)
Wheat grain	5.4 MJ/kg	6.7 MJ/kg	0.3 kg/kg	1.9 MJ/kg	2.7 MJ/kg	0.2 kg/kg
Contribution of each input to the total (%)						
Diesel	57.27	42.84	17.00	58.88	31.01	8.13
Chemical fertilizers	27.87	9.43	48.92	31.49	9.12	36.55
Chemicals (pesticides)	5.18	4.86	1.75	4.29	3.52	0.84
Seed	4.97	26.83	7.35	4.12	19.42	3.51
Irrigation	0.56	1.88	14.31	2.46	7.24	36.22
Electricity	4.23	14.16	10.67	10.16	29.69	14.77
Rye grain						
	CEnC (MJ/kg)	CExC (MJ/kg)	CCO_2E (kg/kg)	CEnC (MJ/kg)	CExC (MJ/kg)	CCO_2E (kg/kg)
	3.5	5.4	0.2	1.8	2.4	0.2
Contribution of each input to the total (%)						
Diesel	61.58	36.88	16.48	51.03	35.48	8.72
Chemical fertilizers	16.85	10.80	28.15	30.02	9.41	39.44
Chemicals (pesticides)	7.41	5.57	2.28	6.14	5.36	1.21
Seed	6.24	26.97	8.39	5.17	25.95	4.45
Irrigation	1.34	3.57	30.83	2.63	8.21	38.84
Electricity	6.58	16.21	13.87	5.01	15.59	7.34

Table 11. The values of the CEnC, CExC and CCO_2E as calculated for the white bread and rye bread and hamburger bun production processes, and the percentage of contribution of each stage of the processes to the total

	Wheat bread			Rye bread			Hamburger bun		
	CEnC (MJ/kg)	CExC (MJ/kg)	CCO_2E (kg/kg)	CEnC (MJ/kg)	CExC (MJ/kg)	CCO_2E (kg/kg)	CEnC (MJ/kg)	CExC (MJ/kg)	CCO_2E (kg/kg)
	9.7	16.6	0.9	7.2	14.7	0.7	13.6	25.2	1.1
Contribution of each stage of the processes to the total (%)									
Agriculture	31.4	23.6	24.2	28.5	20.5	22.3	25.1	17.4	22.3
Flour making	40.0	31.6	29.6	32.7	28.9	28.3	27.8	23.3	27.0
Dough making	6.7	16.2	14.4	9.1	18.3	10.0	30.9	37.5	22.0
Fermentation	0.1	0.3	0.1	0.1	0.3	0.1	0.5	1.1	1.0
Baking	7.5	18.4	11.9	10.2	20.8	14.7	6.7	15.0	12.1
Cooling	0.4	0.9	0.6	0.5	1.0	0.7	0.3	0.6	0.5
Slicing	0.1	0.2	0.1	0.1	0.3	0.1	0.0	0.1	0.0
Packaging	4.5	3.8	1.7	6.1	4.3	2.2	2.0	1.6	1.0
Transportation	9.4	5.1	17.3	12.7	5.7	21.5	6.7	3.3	14.2

Table 12. Land, energy and exergy utilization per ton of wheat and rye bread and hamburger bun production in Turkey and Germany

	Wheat bread production in Turkey	Wheat bread production in Germany	Rye bread production in Turkey	Rye bread production in Germany	Hamburger bun production in Turkey	Hamburger bun production in Germany
Land utilization (ha/ton)	0.326	0.098	0.301	0.137	0.367	0.110
Energy utilization (MJ/ton)	18,200	15,300	15,400	14,100	21,400	18,100
Exergy utilization (MJ/ton)	20,500	17,900	18,500	17,100	25,800	22,900