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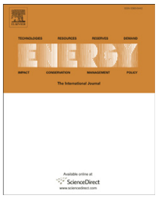

The use of enzymes for beer brewing: Thermodynamic comparison on resource use

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ABSTRACT

The exergetic performance of beer produced by the conventional malting and brewing process is compared with that of beer produced using an enzyme-assisted process. The aim is to estimate if the use of an exogenous enzyme formulation reduces the environmental impact of the overall brewing process. The exergy efficiency of malting was 77%. The main exergy losses stem from the use of natural gas for kilning and from starch loss during germination. The exergy efficiency of the enzyme production process ranges between 20% and 42% depending on if the by-product was considered useful. The main exergy loss was due to high power requirement for fermentation. The total exergy input in the enzyme production process was 30 times the standard chemical exergy of the enzyme, which makes it exergetically expensive. Nevertheless, the total exergy input for the production of 100 kg beer was larger for the conventional process (441 MJ) than for the enzyme-assisted process (354 MJ). Moreover, beer produced using enzymes reduced the use of water, raw materials and natural gas by 7%, 14% and 78% respectively. Consequently, the exergy loss in the enzyme production process is compensated by the prevention of exergy loss in the total beer brewing process.

1. Introduction

Brewing is a traditional process, which can still be further optimized with respect to environmental impact [1]. Several sustainability analyses have been performed on the process [2–4] and studies have been aimed at the re-use or prevention of by-product streams to minimize water and raw material losses and energy use [5–9]. Even though it does not take into account every aspect of sustainability, exergy analysis is based on the second law of thermodynamics and, therefore, is considered as an objective method to compare material and energy losses occurring in a system both quantitatively and qualitatively [10]. As formulated by Szargut, exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of its surrounding nature by means of reversible processes, involving interaction only with the components of nature [11]. Exergy analysis has been used to analyse, optimize, and compare various food processes and food production chains in terms of their resource use efficiency [12]. An improvement of the exergetic or thermodynamic efficiency of a process reflects a reduction on its overall use of resources and hence its environmental impact [13]. Exergy analysis can be applied to many different food production chains to identify improvements, and to compare the thermodynamic performance of existing processes to potential alternatives. This was done for example in vegetable oil (/and protein) production [14,15], in a fish-oil microencapsulation process [16], dairy processing [17], an isoflavone extraction process [18], and the use of plant based ingredients for fish feed [19] amongst others. The analysis shows if the use of an alternative process is in fact more efficient.

The outcome of an exergy analysis can be influenced by the system boundaries, which are chosen by the analyst, i.e. wider system boundaries imply a more complex but also a more complete analysis [20]. Besides, the allocation of the exergetic content of the streams will also influence the outcome of the analysis. In this paper, these aspects will be demonstrated when describing the exergetic production costs, or cumulative exergy consumption (CExC), of enzymes.

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Nomenclature/list of symbols

m	mass [kg]
x	mass fraction of component [−]
h	Enthalpy [kJ/mol]
Q	heat [kJ]
W	work performed by the system
Ex	exergy [kJ]
c_p	specific heat capacity [kJ/kg K]
T_0	reference temperature [K]
T	temperature [K]
R	ideal gas constant [kJ/mol K]
m_x	average molar mass of the stream [kg/mol]
P_0	reference pressure [Pa]
P	pressure [Pa]
b_0	standard chemical exergy [kJ/kg] for which the values can be found in Table 3
x_i	mass fraction of component i [−]

The conventional brewing process has 3 main process stages. The first stage is malting, during which enzymes are synthesized in the barley kernel. In this stage the endosperm is modified: cell walls are broken down to render the protein and starch inside the cells more accessible. The second stage is mashing, during this stage the enzymes hydrolyse starch into fermentable sugars and proteins into amino acids. The third stage is fermentation, during which yeast ferment the sugars into alcohol. Brewing with unmalted barley grains more attention because of the economic advantages and its potential for water and energy savings. Additionally, material losses due to respiration are prevented [21]. In this paper, we analyse the both beer brewing processes with exergy analysis.

A disadvantage of brewing with unmalted barley is the low amount of available endogenous enzymes present in the native kernel. Therefore the addition of enzyme formulations is necessary. These formulations usually contain a combination of α-amylase, pullulanase, proteases, lipase, β-glucanase, and xylanase. The effectiveness of these formulations has been investigated and documented in various reports. No negative effect on beer quality was found when 50% or up to 100% of the malt was replaced by unmalted barley [21–24].

One should take into account that the production of an enzyme formulation also requires resources and produces waste. This raises the question if the use of enzymes requires less resources compared to the malting process. In many studies the standard chemical exergy of purified ingredients like enzymes, protein isolates or other isolated or purified ingredients is used in exergetic assessments, neglecting the CExC of these components. The aim of this paper therefore is two-fold. It assesses the exergetic performance of traditional beer brewing by the conventional malting and brewing process, and compares it to an enzyme-assisted brewing process. It also estimates the CExC of the enzyme formulation used in the enzyme-assisted brewing process.

2. General description of the brewing production chain

To analyse the brewing process and the enzyme production process, we first defined the process operations of the process. Subsequently we did the mass flow analysis, then the energy analysis, and finally the exergy analysis.

2.1. System boundaries

In the brewing process, the malting process was taken into account when malt was used, while enzyme production was considered in the enzyme-assisted brewing process. The compositions of the various streams in both processes are listed in Table 1. The process configurations of the analysed processes are shown in Fig. 1. The production of the growth medium used in the enzyme production process is not considered in the analysis, which means that only the chemical exergy for the ingredients present in the medium was taken into account. The same counts for glycerol, as this product is currently produced as a by-product of biodiesel. All exergy input for this process was attributed to the biodiesel and not to the glycerol used in the enzyme formulation.

Data collection for every process step is usually quite cumbersome (e.g. because they are hard to measure, because they are not readily available or because they might be confidential etc.). Therefore we had to make several assumptions in order to calculate the exergy destruction in these processes. Some assumptions, like assuming an adiabatic process, are simplifying the situation, as heat losses do occur in reality. The data and assumptions made for the enzyme production process, malting process and brewing process and the associated references are listed in Table 2.

2.2. Exergy analysis

Mass and energy balances were calculated with Eq. (1) and Eq. (2),

$$\sum m_{in} - \sum m_{out} = 0 \tag{1}$$

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

The exergy was categorised into the chemical exergy (Eq. (6)) (the chemical exergy relates to the actual chemical exergy of a flow or a stream based on its composition and difference in chemical potentials in relation to the environment of reference) and the physical exergy (Eq. (3)) composed of the thermal and pressure exergy (Eq. (4) and Eq. (5)). The exergy loss was defined as the difference between the total exergy input and the total exergy output (Eq. (7)), and consisted of both the wasted exergy (i.e. theoretically usable but lost to the environment) and destroyed exergy (irreversibly lost) (Eq. (8)). Exergy wasted could be any stream, material or immaterial, which contains exergy (useful work) that could be available but is wasted to the environment due to, e.g. inadequate heat insulation, or mismanagement (i.e. food losses and food waste). The universal efficiency is described as 1-exergy_destroyed/exergy_in. Chemical exergy is very important to consider in an exergy analysis of a food production chain simply because they are usually much larger than physical exergy flows [18,36]The chemical exergy efficiency of a process chain was therefore defined as the total output chemical exergy over the total input exergy (Eq. (9)) (also known as the cumulative degree of perfection [37]). The rational exergy efficiency was defined as the useful chemical exergy output over the total exergy input (Eq. (10)). The two different definitions of exergy efficiency we provided have an allocation function in order to differentiate between the exergy outputs that are usually considered as useful, and the total exergy outputs of the chain. In this way it is possible to estimate the potential for improvement. Dry enzyme, malt and beer were considered useful exergy output. It was debatable whether the fertilizer and enzyme formulation are to be considered as useful; we will discuss this in the results section. The cumulative exergy consumption (CExC) is related to the total cumulative exergy