Journal of Cleaner Production 126 (2016) 394–408

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

A resource efficiency assessment of the industrial mushroom production chain: the influence of data variability

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ARTICLE INFO

Article history:
Received 28 September 2015
Received in revised form
26 February 2016
Accepted 22 March 2016
Available online 19 April 2016

Keywords:
Sustainability
Exergy analysis
Food industry
Recycling

ABSTRACT

We compare the exergetic performance of a conventional industrial mushroom production chain with a mushroom production chain where part of the compost waste is recycled and reused as raw material. The critical exergy loss points (CEPs) identified are the cooking-out process of the spent mushroom substrate, and the phase I composting process which are related to chemical and physical exergy losses, respectively. The total exergy input requirements for the conventional chain are higher (24 GJ per three flushes of mushrooms) than for the alternative chain (17 GJ per three flushes of mushrooms) since more raw materials are required. The largest exergy losses are due to unclosed material balances, i.e. chemical exergy losses, which represent 69% of the total exergy losses for the conventional chain, and 56% for the alternative production chain. Therefore, it only makes sense to reduce any avoidable physical exergy losses after utilizing all mass streams maximally that translate into chemical exergy flows. Further comparison of exergetic indicators (e.g. specific exergy losses, and exergetic cost) shows that recycling material streams would improve the resource efficiency of the industrial mushroom production chain considerably. The variations in the assumed electricity consumption values for the ventilation in phase I composting and for the ammonia scrubbing process affect greatly the exergetic indicators and the number of critical exergy loss points indicating that any further improvement on the exergetic performance of the mushroom production chain should focus on these two process variables. This study shows that variability in data can influence both quantitatively and qualitatively the outcome of exergetic analyses of food production chains since it can lead to the calculation of different values for the selected indicators as well as to the identification of completely different critical exergy loss points.

1. Introduction

A proper investigation of the resource flows, particularly in the food manufacturing and processing sectors is crucial for achieving a better sustainable food supply system (Martindale et al., 2013). The feasibility of reducing resource consumption and waste in three different food production chains was shown by Lee and Okos (2011) while the potential for designing novel side-stream valorisation strategies into added value products has been discussed by Fava et al. (2013). Several indicators have been developed for assessing the sustainability of food production chains which include economic, social, and environmental aspects (Turi et al., 2014). However, there seems to be no agreement in the scientific community on a standardization procedure for the use of all the available sustainability metrics and footprints (Čuček et al., 2012).

The fundamental laws of thermodynamics for assessing the sustainability of food production are objective beyond dispute, they can be used to identify the causes of inefficiencies in the use of material and energy, and they can help in designing food production chains in a more sustainable manner. An objective tool for assessing the sustainability of food production chains that is based on the second law of thermodynamics is exergy analysis (Apaiah

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http://dx.doi.org/10.1016/j.jclepro.2016.03.066
0959-6526/

Nomenclature

m	mass [kg]
w	moisture content of air [g water/kg dry air]
x	mass fraction of component [-]
N	total number of moles [mol]
a	activity [-]
c_p	heat capacity [MJ/kg/K]
f_s	safety factor [-]
f_b	heater efficiency [%]
f_f	exergy quality factor for natural gas [-]
T	temperature of stream [K]
T_o	environmental reference temperature [K]
R	universal gas constant [MJ/mol/K]
P	pressure [Pa]
Q	thermal energy [MJ]
E	electricity [MJ]
F	fuel chemical energy [MJ]
B	exergy [MJ]
b_o	standard chemical exergy [MJ/kg]
RE	reference environment
WF	water footprint [kg water/kg product]
CEL	cumulative exergy losses [MJ]
SEL	specific exergy losses for the total system [MJ/kg final product]
n	overall rational exergetic efficiency [%]
EC	exergetic cost [MJ total exergy input/MJ product exergy]
SI	sensitivity index [-]
I	indicator (mass, energy, exergy indicators)

Subscripts

m	mass efficiency
ex	exergy efficiency
st	steam
i	stream
j	component
o	environment of reference

et al., 2006; Berghout et al., 2015; Colak et al., 2010; Dincer, 2011; Draganovic et al., 2013; Jankowiak et al., 2014; Zisopoulos et al., 2015a) where all input resources (e.g. raw materials, energy) are considered in terms of useful work (exergy). The main steps for exergetically analysing a food production chain have been summarized in literature (Zisopoulos et al., 2015b). Exergy analysis is useful in identifying *Critical Exergy loss Points* (CEPs) that are defined as locations in the food production chain where most of the input exergy is lost (destroyed and/or wasted). The number of CEPs might vary for different food production chains depending on the number of processing steps that are either exergy intensive by nature (e.g. phase change processes like drying) or exergetically wasteful (e.g. processes where a lot of material, i.e. chemical exergy, is wasted). Therefore, the types of exergy loss (chemical or physical) can influence the decision on selecting an alternative process or chain modification to be assessed.

The determination of a processing step along the chain as a CEP or not can be influenced greatly by the variability of data used during the assessment, and it can affect the final decision for any potential improvement on the food production chain. Therefore, screening for influential variables in the model can be very useful for providing more information on the comparison of the exergetic performance of industrial food production chains, and it should be an integral part of any exergy analysis.

This paper compares the exergetic performance of two industrial mushroom production chains (*Agaricus bisporus*) by taking into consideration the influence of data variability on the identification of CEPs. The conventional mushroom production chain is compared with a production chain design where part of its compost waste is recycled and reused as a raw material. First, both mushroom production chains are analysed by material, energy, and exergy balances. Secondly, the chains are compared based on the cumulative exergy losses, specific exergy losses, exergetic efficiency, and critical exergy points. Finally, a sensitivity analysis is used to screen for the most influencing variables of the model on the identification of CEPs. This study demonstrates that assumptions can have a considerable influence on the identification of CEPs, and, consequently, on the outcome of the assessment.

2. Methods

2.1. General description of the industrial mushroom production chain

The industrial production of fresh white button mushrooms (*A. bisporus*) is studied. The system boundaries and the most relevant input material and energy streams in the industrial production of fresh mushrooms are shown in Fig. 1. In summary, the main parts of the industrial mushroom production chain include: the composting process (mixing, phases I, II and III, and ammonia scrubbing), the casing soil production, and the growing and harvesting of mushrooms (Chen et al., 2000).

The mushrooms are grown on composted organic waste (amongst others horse manure), which is covered by a layer of peaty material, called casing soil. Therefore, both the productions of the compost as well as of the casing soil are considered as integral parts of the industrial mushroom production chain. Compost provides the main nutrients (i.e. carbon and nitrogen) for the fungus while the casing soil has a supportive function and acts as a fast water absorber and slow water releaser for the mycelia to start pinning (Jarial et al., 2005; Nair et al., 1994). The final compost is transported to growers where mushrooms (the final product) are harvested to up to three consecutive flushes (batches), each one with a lower yield due to potential infections. Growers in reality chose their own production plans, however, here it is assumed that all three flushes are produced from a certain amount of compost. The remaining spent mushroom substrate and casing soil, after the harvesting of mushrooms, is called spent mushroom substrate (also known as “champost”), and usually is steamed (“cooked-out”) to become pathogen-free before it is discarded as landfill. In this analysis this side-stream is considered as a waste stream, and its impact on the sustainability of the total chain by potential recycling as a useful raw material is studied.

Clearly, the complexity of the industrial mushroom production chain lies on the multiple sources of data used for the analysis, which come both from literature as well as from personal communication with experts in the field. Therefore, the majority of data used in the analysis are represented in the form of tables. The