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Review

Environmental assessment of enzyme use in industrial production – a literature review

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ABSTRACT

Enzymatic processes have been implemented in a broad range of industries in recent decades because they are specific, fast in action and often save raw materials, energy, chemicals and/or water compared to conventional processes. A number of comparative environmental assessment studies have been conducted in the past 15 years to investigate whether these properties of enzymatic processes lead to environmental improvements and assess whether they could play a role in moving toward cleaner industrial production. The purpose of this review is to summarize and discuss the findings of these studies and to recommend further developments regarding environmental assessment and implementation of the technology. Life Cycle Assessment (LCA) has been widely used as an assessment tool, while use of the 'carbon footprint' concept and Environmental Impact Assessment (EIA) is limited to a few studies. Many studies have addressed global warming as an indicator and several studies have furthermore addressed other impact categories (acidification, eutrophication, photochemical ozone formation, energy and land use). The results show that implementing enzymatic processes in place of conventional processes generally results in a reduced contribution to global warming and also a reduced contribution to acidification, eutrophication, photochemical ozone formation and energy use to the extent that this has been investigated. Agricultural land has been addressed in few studies and land use savings appear to occur in industries where enzymatic processes save agricultural raw materials, whereas it becomes a trade-off in processes where only fossil fuels and/or inorganic chemicals are saved. Agricultural land use appears to be justified by other considerable environmental improvements in the latter cases, and the results of this review support the hypothesis that enzyme technology is a promising means of moving toward cleaner industrial production. LCA gives a more complete picture of the environmental properties of the processes considered than EIA and carbon footprint studies, and it is recommended that researchers move toward LCA in future studies. Tradition, lack of knowledge and bureaucracy are barriers to implementation of enzymatic processes in industry. Education and streamlining of public approval processes etc. are means of overcoming the barriers and accelerating the harvesting of the environmental benefits.

1. Introduction

The production of daily life products such as paper, textile, food, feed, chemicals and pharmaceuticals consumes large amounts of raw materials and energy, and generates large amounts of waste with an adverse impact on our environment and quality of life (OECD, 2009; European Commission, 2009). The growing global population and improving economies in many countries increase global consumption and thereby the pressure on environment (UNFPA, 2008; UNEP, 2011a) and it is well recognized that there is an urgent need to reduce the impact per produced unit of product to sustain human needs without compromising the natural resource basis (UNEP, 2011b). Industries around the world are thus looking for alternative technologies that can deliver the increasing numbers of products that are in demand every year while consuming fewer resources and having a lesser impact on the environment.

The use of bio-based materials and nature's production processes, known as industrial biotechnology (Kirk et al., 2002; Soetaert and Vandamme, 2010), is one such alternative technology

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which could be used to either replace or supplement conventional technologies in moving toward cleaner production processes (Kirk et al., 2002; Bornscheuer and Buchholz, 2005; OECD, 2009; Haas et al., 2009; Wohlgemuth, 2009).

Among biotechnologies, enzymatic processing is seen as one of the promising and sustainable alternatives to conventional processing (IPTS, 1998; Vigsoe et al., 2002; Thomas et al., 2002; Kirk-Othmer, 2005). Enzymes are proteins produced by all living organisms; they act as a catalyst for numerous biochemical reactions. Apart from being catalysts in vivo, enzymes can also be catalysts in vitro for various reactions, including in industry.

The use of enzymes to produce goods for human consumption dates back at least 2000 years, when microorganisms were used in processes such as leavening bread and saccharification of rice in koji production (Demain and Fang, 2000). The mechanism of the enzymes was unknown until 1877, when Moritz Traube proposed that "protein-like materials catalyze fermentation and other chemical reactions …". Later, the historic demonstration by Buchner in 1897, showing that alcoholic fermentation could be carried out using cell-free yeast extract, appears to be the first application of biocatalysis. The word 'zymase' was coined to describe this cell-free extract (Bornscheuer and Buchholz, 2005; Soetaert and Vandamme, 2010), which was the initial recognition of what is now called an 'enzyme'. There are currently around 5500 known enzymes (BRENDA, 2012), classified based on the type of reaction they catalyze (oxidoreductases, transferases, hydrolases, lyases, isomerases, and ligases). Specific enzyme names refer to the substance on which they act. An enzyme that acts on cellulose, for example, is known as cellulase, and an enzyme that acts on protein is named protease, etc. (IUB, 1961).

Enzymes for industrial use are produced by growing bacteria and fungi in submerged or solid state fermentation. With submerged being the primary fermentation mode, the unit operations in enzyme production involve fermentation followed by cell disruption and filtration. The crude enzyme is further purified by precipitation followed by centrifugation and vacuum drying or lyophilization, collectively known as "downstream processing" (Kim et al., 2009; Soetaert and Vandamme, 2010).

Enzymes are highly specific and they usually act under milder reaction conditions than traditional chemicals. Furthermore, they are readily biodegradable and usually lead to reduced or no toxicity when they reach the environment after use in industrial production (Kirk-Othmer, 2005; Soetaert and Vandamme, 2010). These properties allow manufacturers to produce the same or sometimes even better quality products with less raw material, chemical, water and/or energy consumption and with less problematic waste generation than traditional processes (Thomas et al., 2002; Soetaert and Vandamme, 2010). Industrially produced enzymes are used in a broad variety of production processes, such as pulp and paper production (Jiménez et al., 1999; Nguyen et al., 2008), leather production (Dayanandan et al., 2003; Saravanabhavan et al., 2004; Valeika et al., 2009; Kandasamy et al., 2012), textile production (Aly et al., 2004; Vankar et al., 2007; Chen et al., 2007; Zhou et al., 2008), detergent production (Hemachander and Puvanakrishnan, 2000; Saeki et al., 2007), food production (Minussi et al., 2002; Ramos and Malcata, 2011), beverage production (Grassin and Fauquembergue, 1996; Okamura-Matsui et al., 2003), animal feed production (Gado et al., 2009; Zhu et al., 2011), pharmaceuticals production (Bonrath et al., 2002; Woodley, 2008), fine chemicals production (Panke et al., 2004; Gavrilescu and Chisti, 2005), cosmetics production (Sim et al., 2000; Lods et al., 2001) and biodiesel production (Kumari et al., 2007; Hernández-Martín and Otero, 2008).

The environmental benefits of enzymatic processes over conventional processes in various industries have been discussed in several books, articles and reports over the past decade (Falch, 1991; Sime, 1999; Wandrey et al., 2000; Zaks, 2001; Kirk et al., 2002; Sijbesma, 2003; Olsen, 2008; Kirk-Othmer, 2005; Gavrilescu and Chisti, 2005; Herbots et al., 2008; Haas et al., 2009; OECD, 2009; Kanth et al., 2009; Soetaert and Vandamme, 2010; Mahmoodi et al., 2010). All agree that enzymatic processes are favorable to the environment compared with the traditional processes. However, these are only based on qualitative judgments, and a concrete justification is needed as it cannot be excluded that the production of enzymes (Nielsen et al., 2007; Kim et al., 2009) and any helping agents for the enzymatic processes requires more energy and raw materials than it saves. Quantitative environmental impact assessments are therefore necessary in order to assess the actual environmental benefits of enzymatic processing.

LCA and EIA are versatile tools for quantitatively assessing the environmental impacts of products and systems (Wenzel et al., 1997; Guinée, 2002; ILCD, 2010). Comparative LCA and EIA of enzymatic processes versus conventional processes began in the late 1990s (OECD, 1998). It became increasingly used during the first decade of this century (Kallioinen et al., 2003; Fu et al., 2005; Nielsen and Wenzel, 2006), when concepts, databases, tools and standardizations were sufficiently developed, and have been used extensively since then. Results are published in many different reports and journals in various fields and it has long been difficult to gather all the information and draw the first more general conclusions on enzymatic processes as a means of achieving cleaner industrial production. The purpose of the present review is therefore: 1) to provide an overview of LCA and EIA studies reported so far comparing enzymatic processes with conventional processes; 2) to summarize the main results of the studies; 3) to draw the first more general conclusions on whether and to what extent enzymatic or enzyme-assisted processes are environmentally favorable as alternatives to conventional technology; and 4) to recommend further development of environmental assessment of enzymatic processes and implementation of enzyme technology in industry.

2. Methods and scope

This study focuses on industrial processing and addresses cases ranging from lab-scale to full-scale production where conventional production technology is partially or fully replaced with enzyme-assisted production technology (Fig. 1A) by means of industrially produced enzymes.

Replacement of conventional materials with bio-based materials is outside the scope of the study, even if one or more enzymatic processes may have been involved (Fig. 1B). The reason is that a review of environmental assessments of bio-based materials is a comprehensive subject in itself (González-García et al., 2011; Álvarez-Chávez et al., 2012; Weiss et al., 2012) and we find it meaningful to distinguish between the material-oriented studies of biomaterials and the process-oriented studies of enzyme technology.

The review is based on literature from the entire world, and since the subject is still in development we have included not only comparative LCA and EIA studies reported in peer-reviewed journals but also studies reported in technical journals, books, conference proceedings and publically available reports.

Studies published in technical journals and books, etc. are often summaries of comprehensive background reports with third-party external review according to standards such as ISO 14040. Use of standards and reviews is important when evaluating the credibility of the results, and the name of the standard and type of review has been investigated (in some cases by contacting authors) and reported in a summary table (Table 1).