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Life Cycle Assessment of Microreaction Technology Versus Batch Technology – a Case Study

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14.1
Introduction to Life Cycle Assessment Methodology

Traditionally, the design of chemical and engineering process applications has focused on economic objectives. Some examples of this are given in Chapter 13. However, over the last two decades, additional criteria of sustainability have become more and more important and have started to be integrated into the decision-making process. Therefore, the sustainable development of products or processes requires tools to measure and compare the impact of human activities. Ecological sustainability, one of the three pillars of sustainability besides economic and social criteria, can be examined using life cycle assessment (LCA). The LCA methodology has been standardized by the International Organization for Standardization (ISO) and is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" [1]. The environmental aspects and potential impacts associated with the product system are assessed by compiling an inventory of relevant inputs and outputs during a so-called life cycle inventory analysis (LCI). Then, the environmental impact associated with those inputs and outputs can be evaluated in the next step, the life cycle impact assessment (LCIA). Here, defined impact categories are used covering a wide range of impacts upon the environment, including the depletion of exhaustible raw materials, the emission of hazardous substances and different types of land use. Finally, the results of the inventory and impact phases have to be interpreted in relation to the objectives of the LCA study [1].

This holistic cradle-to-grave approach avoids the problems otherwise connected with balancing single process stages, which disregard the impact of the respective upstream or downstream processes. Consequently, no problem occurs in shifting from one life cycle stage to another. In addition, the use of a common functional unit allows for the comparison of the environmental impacts of alternative products or processes. Thus, the LCA methodology has gained worldwide acceptance as a useful

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tool in strategic planning, process development, policy-making and a wide range of other decision-making situations.

In the special case of chemical processes, some LCA studies have already been carried out. Examples are the work of Burgess and Brennan [2], Azapagic and Clift [3] and Jödicke *et al.* [4]. In the following, a case study is presented which evaluates the ecological potential of microreaction technology using this LCA methodology.

14.2 Environmentally Relevant Characteristics of Microstructured Devices

Microprocess technology employs a system of reaction devices, mixers, heat exchangers and so on with internal structures on the micrometer scale in at least one spatial dimension. The processing is continuous. Compared to large-scale batch reactors, microstructured devices are orders of magnitude more efficient with regard to heat and mass transfer, because of their small channel sizes and high surface-to-volume ratios [5]. These increased surface-to-volume ratios may lead to lower cooling and heating power requirements. The excellent control of heat transfer can additionally result in improved yield, selectivity, product quality and safety [6]. Especially fast and highly exothermic reactions can be performed in microreactors using defined residence times, thus leading to a reduction in unwanted side-reactions [7].

The advantages of microstructured versus conventional reaction devices have been broadly discussed for laboratory-scale syntheses (e.g. [8]). First comparisons on the production scale have also already been presented. For example, Delsman *et al.* [9] performed a comparative study between microreaction and conventional reaction technology in the case of methanol fuel processing for portable power generation. They demonstrated that the microstructured devices outperform the conventional systems, resulting in smaller and lighter reactor devices. Additionally, Tonkovich *et al.* [10] described the transition from laboratory-scale to industrial-scale chemical processing in microchannels. Specifically, a case study of a commercial-scale hydrogen generation plant based on microchannel technology was discussed in this context.

Due to the characteristics of microstructured devices, a considerable reduction inenvironmental impact is commonly expected from the implementation of microreaction technology in industrial processes [11, 12]. However, the advantages of microreaction technology mentioned above may also be accompanied by disadvantages. As an example, the manufacture of microreactors can be more material and energy consuming than that of conventional equipment. This may especially be the case for microstructured devices made from stainless steel. In addition, microreactors might have shorter lifetimes than, for example, conventional stirred-tank reactors due to fouling (clogging) phenomena in the microchannels.

The pros and cons of microreaction technology were investigated by Kralisch and Kreisel [13, 14] using the LCA methodology. A macroscale semi-continuous batch process was chosen as a reference process and the potential environmental impacts of the two alternative processes were contrasted for two scales of production: the

laboratory scale and the industrial scale. This classification was used to differentiate between the results obtained under the limitations of the existing laboratory equipment and under real production conditions. The two-step synthesis of *m*-anisaldehyde was chosen as a model reaction to compare the alternative technologies. A short introduction to this model reaction is given below, followed by a discussion of selected results of this LCA.

14.3 The Model Reaction

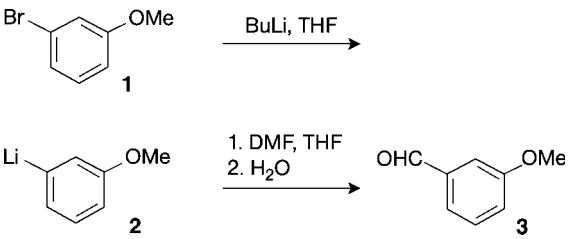
The two-step synthesis of *m*-anisaldehyde (**3**) is a very exothermic lithium–organic reaction (Scheme 14.1). In a macroscale batch reactor, this synthesis can only be carried out with extensive safety precautions and with high energetic effort for operating the cooling system. In contrast, the improved heat transfer in the microscale system allows the reaction to be run isothermally at more moderate temperatures.

In stage I of the synthesis, *m*-bromoanisole (**1**) and *n*-butyllithium are converted via bromine–lithium exchange in order to obtain *m*-anisolelithium (**2**) and *n*-bromobutane. In stage II, the reaction mixture is treated with dimethylformamide, then the reaction is quenched using 3 M hydrochloric acid. Tetrahydrofuran is used as the solvent at both synthetic stages.

14.4 Evaluation of Alternative Systems

14.4.1 Laboratory-scale Synthesis

The realization of the comparison between macroscale semi-continuous batch and a continuous microscale process on the laboratory scale was carried out for several reasons. First, it was of marked interest whether ecological improvements can be expected for the chosen model reaction performed in microstructured devices. Such improvements were the premise for the transfer of this model reaction to the



Scheme 14.1 Model reaction.

production scale. Additionally, the influence of the lifetime of the microstructured devices and the expenditure on the peripheral equipment needed to be estimated in order to limit the effort of the ecological balance on the industrial production scale. In the following, the synthesis procedure for *m*-anisaldehyde on the laboratory scale will be described in detail.

The reference (batch) experiment was conducted in a 10-L double-walled reactor (manufacturer: QVF). A temperature of 223 K was maintained using a thermostat. After dissolution of *m*-bromoanisole (**1**) in tetrahydrofuran, the other starting materials were dosed successively. The two reaction steps and the first work-up step were carried out in the apparatus mentioned above. The organic phase was distilled *in vacuo* after phase separation. In order to obtain pure *m*-anisaldehyde, the residue was subjected to two further distillation steps after removing the low-boiling solvents. This procedure resulted in a yield of 60% of *m*-anisaldehyde. It should be noted that the reaction can hardly be controlled under laboratory conditions in reactors of a larger capacity (e.g. 50 L) due to the extremely exothermic nature of this reaction. Additionally, the reaction outcome depended strongly on the batch size in so far as the yield of *m*-anisaldehyde is reduced in larger reactors [7].

In continuous mode, the two-step synthesis was conducted at 273 K in two Cytos-Lab-System modules connected in series. The Cytos microreactor is characterized by dimensions of $100 \times 150 \times 10$ mm with a channel width of less than 0.1 mm, a weight of 1.2 kg and an internal volume of 1.1 mL (reactant side, after mixing) and 12 mL (heat exchanger). It is made from stainless steel, a common material for microstructured devices. Apart from the reactor, the Cytos-Lab-System also includes control elements and pumps. A personal computer was used to control the overall set-up and to achieve a constant product flow of $0.06\,\mathrm{kg\,h^{-1}}$. The work-up of the reaction mixture was carried out again by phase separation and successive distillation. In this reaction mode, the yield amounted to 88% of the theory. When transferred to a continuous microscale set-up, the increased surface-to-volume ratio allows improved control of the heat supply and removal and the reaction can be conducted isothermally. The outcome of this was a decreased energy demand for cooling processes and an increase in yield. These phenomena can be attributed to the short residence time and the narrow residence time distribution of the unstable lithium-containing intermediate (**2**) (a few seconds) before being submitted to stage II of the reaction. The short residence time of the intermediate (relative to its rate of decomposition) leads to a higher yield in comparison with the laboratory-scale batch process. In the latter instance, several hours for the dosage of the *n*-butyllithium are necessary, depending on the batch size.

14.4.2 Life Cycle Inventory on the Laboratory Scale

After characterizing the model reaction, the reaction conditions and the system itself, the basis of the evaluation will be introduced in the following. The system boundary of an LCA study comprises a number of preselected modules (life cycle stages). In this special case, the system boundary included the earlier life cycle stages of the

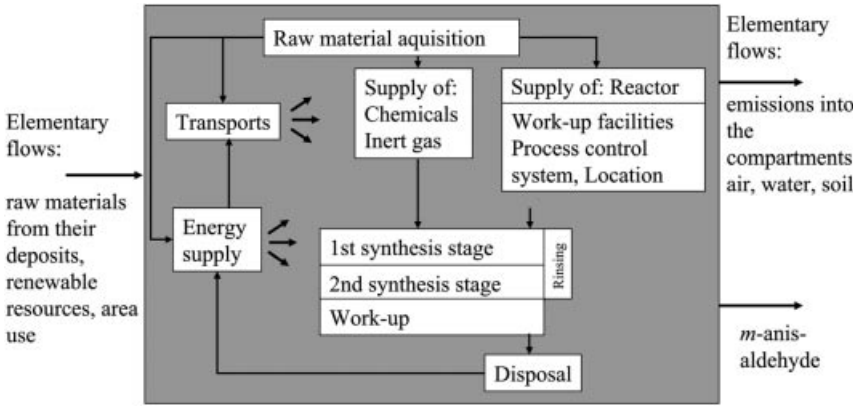


Figure 14.1 System boundary of the LCA – laboratory scale [14].

chemicals used, the supply of energy and inert gas, the realization of the model reaction, work-up and transport to the disposal of wastes (Figure 14.1).

All processes within this system's boundaries were involved in the balance. Also, the dependence of the additional expenditure of materials and energy necessary on the choice of the reactor (stainless-steel microreactor versus borosilicate glass double-walled reactor) was investigated. This aspect was analyzed with the help of different case scenarios. In order to provide a holistic view on its influence, the peripheral equipment such as the reaction vessels, control elements, thermostats and distillation equipment was also included in the balance (Figure 14.1).

As opposed to laboratory glassware made of borosilicate glass, there is no statistically proven knowledge about the lifetime of microstructured stainless-steel appliances. The reasons for this lies in the novelty of such reaction devices in chemical process engineering and the strong dependence on the area of application, chemical resistance and breakage safety. In case of "fouling" phenomena within the microchannels, an immediate exchange of the microstructured devices may be necessary. In order to elucidate the range of possible exchange cycles with respect to the resulting potential for environmental impact, four scenarios were envisaged. The "worst case scenario" (Conti Sc wc) prescribes a lifetime of 1 week as a minimum prerequisite. In order to allow for a comparison of the two synthetic methods, the presumed "best case" (Conti Sc 3) is based on a lifetime equal to that of the double-walled glass reactor, which is 10 years on average. Scenarios 1 (Conti Sc 1) and 2 (Conti Sc 2) represent lifetime expectancies of 3 months and 3 years, respectively, thus ranging between the worst and the best case scenarios. A comprehensive assessment of the influence of the supply of the Cytos reactors on the overall result is thus feasible.

14.4.3
Selected Results of the Life Cycle Impact Assessment on the Laboratory Scale

During the stage of life cycle impact assessment, results generated in a life cycle inventory are condensed and assigned to potential environmental effects. The aim is

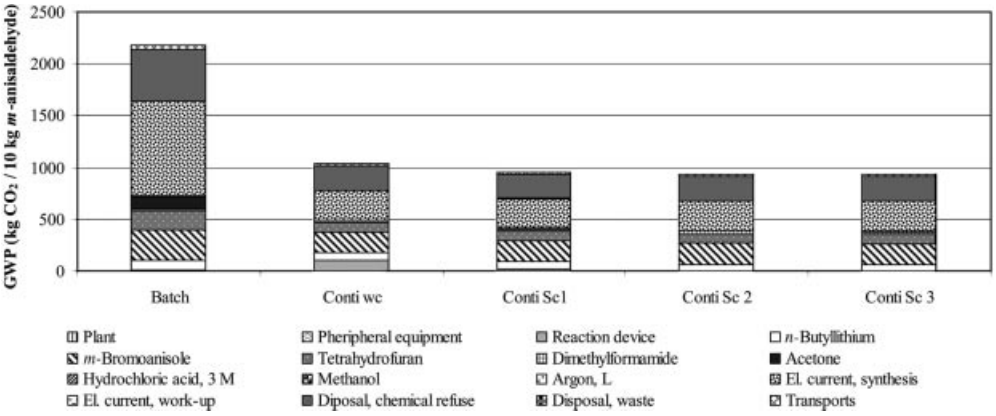


Figure 14.2 Laboratory scale ($Y_{batch} = 60\%$, $Y_{conti} = 88\%$, FU = 10 kg *m*-anisaldehyde) – comparison of the global warming potential.

to generate a manageable number of impact categories and thus increase the comparability of the data. Within each impact category, a reference compound is defined. All material and energy flows are related to this reference using an equivalence factor. According to CML [15], the following impact categories were considered in this specific LCA: abiotic resource depletion potential (ADP), global warming potential (GWP), ozone depletion potential (ODP), photochemical ozone creation potential (POCP), acidification potential (AP) and nutrification potential (NP). Additionally, an assessment of the human toxicity potential (HTP), fresh aquatic eco-toxicity potential (FAETP), marine aquatic eco-toxicity potential (MAETP) and terrestrial eco-toxicity potential (TETP) was taken into account.

Selected results of the LCIA on the laboratory scale are presented in Figures 14.2 and 14.3 considering the impact categories GWP and HTP as examples. The GWP is calculated from the sum of the global warming potential of different greenhouse gases. They enhance radiative forces, causing the temperature at the Earth's surface to rise [16]. The equivalence factor of this impact category is related to the impact of the greenhouse gas carbon dioxide. The impact category HTP includes the human intake of toxic compounds by inhalation of contaminated air and also from drinking water and from food. Risk values such as the ratio of the predicted effect level (PEC) to the predicted no-effect level (PNEC) are used for the determination of the HTP [17]. Here, the initial emission compartments air, fresh water and sea water and, furthermore, agriculturally used areas are taken into account. The equivalence factors of this impact category are related to the environmental impact of 1,4-dichlorobenzene.

All calculations on the laboratory scale refer to a production of 10 kg of *m*-anisaldehyde as functional unit (FU). The results represent the variation of environmental impact potentials as a consequence of the change from the macroscale batch to the microreaction mode. Thus, four scenarios regarding the lifetime of the microstructured devices are considered. In order to analyze the influence of single

modules on the overall result, the environmental impacts are assigned to single units of the process chain.

The results of the impact category GWP illustrate the great influence of both the supply of chemicals and the energy demand for synthesis and work-up during the whole process chain (Figure 14.2).

The supply of the production unit plays only a minor role within this impact category, and the supply of the peripheral equipment has almost no effect. The results of the GWP on the laboratory scale highlight the fact that the transfer of the model reaction from batch to continuous mode in a microstructured reactor leads to significant reductions in greenhouse gases. Therefore, the lifetime of the microscale set-up plays a subordinate role. Similar results were obtained for the majority of impact categories considered.

In this context, the human toxicity potential and partly also some eco-toxicity potentials (FAETP, TETP) have to be considered as exceptions.

The results of the impact category HTP are based on the toxicity potentials of heavy metals and inorganic and organic compounds. Figure 14.3 indicates that the HTP is increased by 47% for the "worst case" scenario of the continuous process (lifetime of the microreactor: 1 week) as opposed to the batch mode. This effect mainly results from the emission of chromium and nickel during stainless-steel production. However, this can be counteracted by a longer lifetime of the microreactor. Realistically, longer lifetimes of the Cytos microreactor lead to a significant reduction in the HTP by up to 46%. Similar results were obtained for FAETP and TETP, whereas MAETP was decreased in the continuous production mode in each scenario considered. A summary of all variations within the impact categories resulting from the change from the macroscale batch to the microreaction system is given in Figure 14.4.

The decrease within the majority of the environmental impact categories can be related to the savings in energy consumption, the reduction in solvent use and the increase in the reaction yield achieved in the microscale laboratory set-up. These

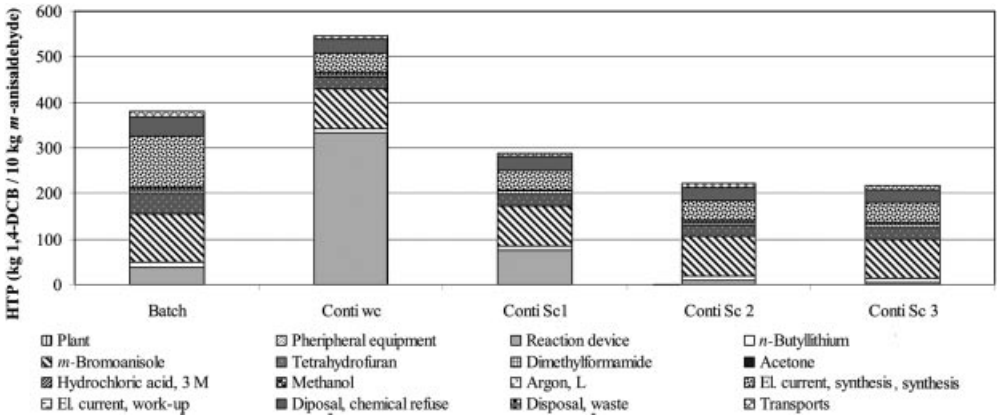


Figure 14.3 Laboratory scale ($Y_{batch} = 60\%$, $Y_{conti} = 88\%$, FU = 10 kg *m*-anisaldehyde) – comparison of the human toxicity potential.

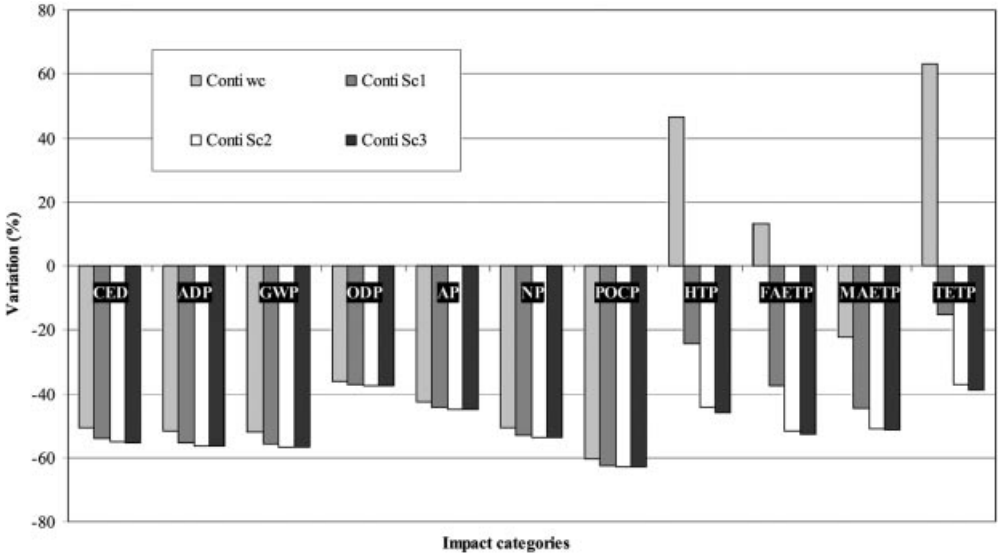


Figure 14.4 Laboratory scale ($Y_{batch} = 60\%$, $Y_{conti} = 88\%$, FU = 10 kg *m*-anisaldehyde) – variation of environmental impact potentials as a consequence of the change from the macroscale batch (0%) to microreaction mode; four scenarios regarding the lifetime of the microstructured devices (Conti wc, 1 week; Conti Sc1, 3 months; Conti Sc2, 3 years; Conti 3, 10 years) [14].

results clearly indicate the possibility of significant ecological advantages associated with continuous synthesis in the microreactor. That is why the investigations were extended to the industrial production scale in microstructured devices. The results of the evaluation on this scale are discussed in the next section.

14.4.4 Industrial-scale Synthesis

On the industrial scale, the comparison is based on the synthesis of *m*-anisaldehyde in a 400-L stainless-steel vessel, cooled to 193 K by a cryogenic system, and alternatively in the continuous Cytos Pilot System at 273 K. The cryogenic system for cooling of the extremely exothermic reaction works with ammonia as primary and nitrogen as secondary cooling medium. Per synthesis cycle, 23 kg of *m*-anisaldehyde were produced.

The Cytos Pilot System is a 10-fold parallelized version of the Cytos Lab System [18] with identical fluidic behavior. Thus, nine Cytos microreactors were used for production with a cumulative product mass flow of 0.6 kg h^{-1}, while alternately one reactor was treated with tetrahydrofuran in a rinsing cycle at a mass flow rate of 0.4 kg h^{-1} to avoid clogging of the microchannels. The continuously running Cytos Pilot System was cooled by an electrically tempered cooling system.

All other reaction parameters, such as the concentration of reagents and reaction temperature, were the same as on the laboratory scale.

On the laboratory scale, the transfer of the model reaction from macroscale batch mode (60% yield) to a continuous microscale set-up (88% yield) resulted in an increase in yield of 28%. This effect influences the results of the LCA considerably (see above). However, under industrial-scale reaction conditions the same high yield of 88% would be expected in the batch mode if the reaction temperature of the batch process is kept constantly below 193 K.

14.4.5
Inventory Analysis on the Industrial Scale

For the inventory analysis of the industrial-scale production of *m*-anisaldehyde, two simplifications were made. First, the work-up procedure was disregarded because it is the same for both alternatives. Second, the results obtained for the laboratory-scale synthesis had demonstrated that the contribution of the supply of the peripheral equipment is irrelevant for the environmental impact of the overall systems. For this reason, only the fabrication of the reaction devices was included in the balance on the industrial scale and lifetimes of 10 years for the batch vessel and of 1 year for the microstructured devices were assumed. Thus, the system boundary spans from the production of the starting materials and solvents over the supply of energy and inert gas, the fabrication of the reaction devices, the realization of the model reaction including rinsing and transports, to the disposal of waste.

14.4.6
Selected Results of the Life Cycle Impact Assessment on the Industrial Scale

Although no yield increase could be expected from the transfer of a conventional industrial production of *m*-anisaldehyde into a microscale process, the results of this study clearly indicate again a significant ecological advantage resulting from continuous synthesis in the microreactor set-up. This outcome can be related to the feasibility of conducting the reaction at a higher temperature (temperature difference: 80 K) and thus the avoidance of using a cryogenic system. Compared with this saving potential, the additional energy and material demands during the fabrication step of the microstructured devices play only a minor role. Against this background, in the case of the continuous microscale set-up, lower environmental impact potentials for all impact categories considered have been found. Figures 14.5 and 14.6 show the variation within four selected impact categories as a consequence of the change from the macroscale batch to microreaction mode on the industrial scale. They allow for a detailed look into the processes and into the influence of single modules on the overall environmental impact. All results are related to a functional unit of 1000 kg of *m*-anisaldehyde.

Again, the supply of the starting materials and solvents used for the synthesis have a significant environmental impact, as does the electrical current demand. However,

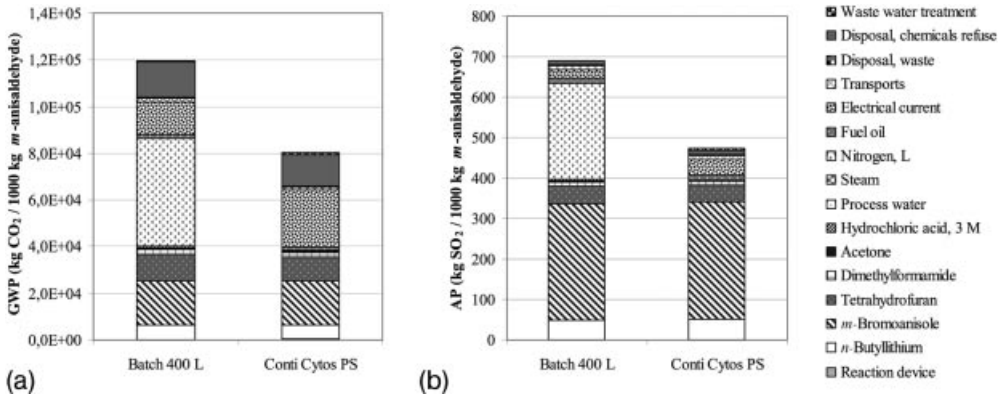


Figure 14.5 Industrial scale ($Y_{batch,\ conti} = 88\%$, FU = 1000 kg *m*-anisaldehyde) – comparison of the impact categories GWP (a) and AP (b).

the batch process is dominated in most impact categories by another module: the supply of liquid nitrogen for cooling processes.

As an example, the GWP for this module is much higher than that for the demand of electrical current in the case of the microreaction mode (Figure 14.5a). In the case of the conventional industrial batch production, the supply of liquid nitrogen for the cryogenic system amounts to 39% of the resulting greenhouse gases. The supply of the starting materials and solvents contributes 33% and the demand of electrical current during the reaction process comes to 12% of the over-all GWP. The GWP resulting from the synthesis of *m*-anisaldehyde in the Cytos Pilot System, on the other hand, is dominated by the supply of the chemicals (47%) and the demand for electric

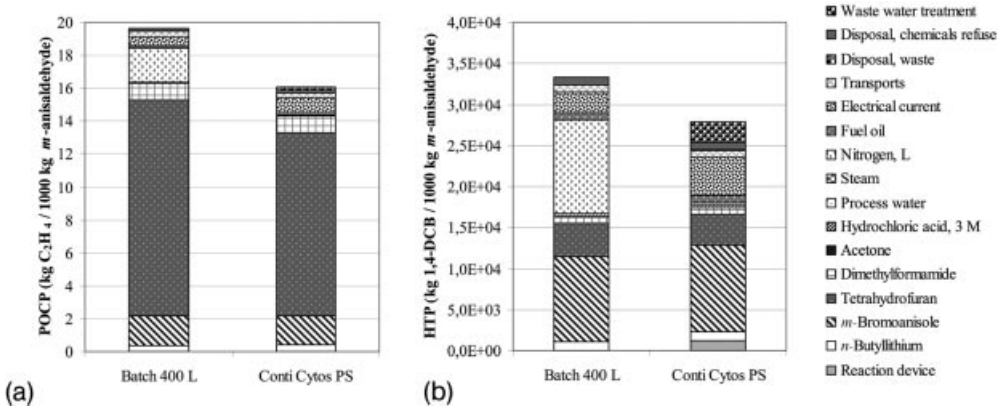


Figure 14.6 Industrial scale ($Y_{batch,\ conti} = 88\%$, FU = 1000 kg *m*-anisaldehyde) – comparison of the impact categories POCP (a) and HTP (b).

current (30%), 80% of which can be attributed to the thermostat necessary for cooling of the continuously running system to 273 K. In summary, Figure 14.5a illustrates that the transfer of the model reaction to the microreaction mode results in a reduction in the GWP by 34%.

The impact category AP (Figure 14.5b) includes the environmental impact of acidifying pollutants. This may be, for example, fish mortality, forest decline or crumbling of building materials [16]. Nearly the same reduction in the AP (32%) was determined if the synthesis of *m*-anisaldehyde was conducted in the continuous microreactor mode rather than the batch mode. Here, on the one hand the supply of *m*-bromoanisole [42% (batch) and 62% (microreactor)] and on the other hand the supply of liquid nitrogen [34% (batch)] play the major roles. In contrast, the electric current demand (3% and 8%, respectively) and the other chemicals (except *m*-bromoanisole) have no outstanding effect.

The impact category POCP comprises the formation of reactive chemical compounds by the action of sunlight on certain primary air pollutants [16]. The POCP is dominated by the supply of the solvent tetrahydrofuran (66 and 69%, respectively) (Figure 14.6a). The additional consumption of tetrahydrofuran for cleaning of the batch reactor and also the supply of liquid nitrogen leads to a slightly higher POCP. Finally, Figure 14.6b shows the breakdown of the impact category HTP. Again, the increasing demand for electric current in the case of the continuous microreaction process does not have the same impact as the supply of liquid nitrogen. In addition, an effect of the supply of the reaction devices is detectable in this impact category, albeit small [4% (microreactor)].

Figure 14.7 shows a summary of all variations within the impact categories resulting from the change from the macroscale batch (0%) to the microreaction system on the industrial scale.

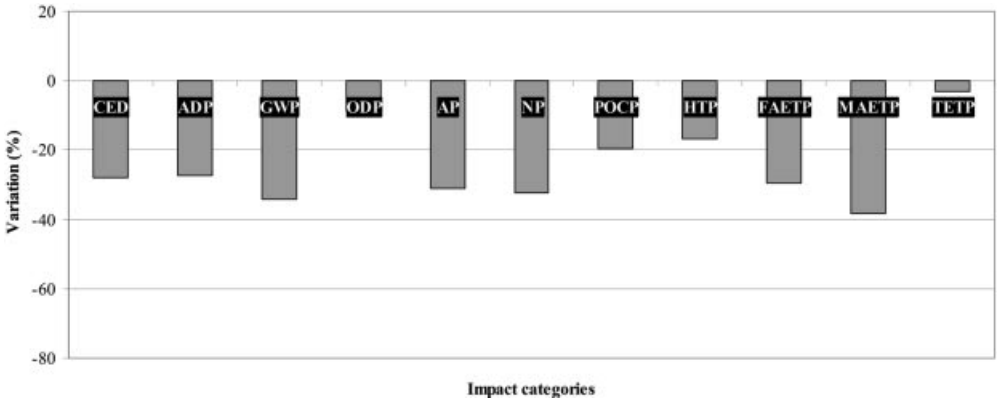


Figure 14.7 Industrial scale ($Y_{batch} = 88\%$, $Y_{conti} = 88\%$, FU = 1000 kg *m*-anisaldehyde) – variation of environmental impact potentials as a consequence of the change from macroscale batch (0%) to microreaction mode [14].

14.5 Conclusions

The results of this LCA clearly indicate that significant ecological advantages can be gained from the transfer of the macroscale batch synthesis of *m*-anisaldehyde to microreaction technology. This was found to be true on both the laboratory and industrial scales.

On the laboratory scale, the advantages consisted of savings in energy consumption, the reduction in solvent use and the increase in the reaction yield achieved in the microscale set-up.

On the industrial scale, the avoidance of a cryogenic system due to the possibility of conducting the reaction at a higher temperature was the most important feature. Compared with these saving potentials, the fabrication of the reactors and the peripheral equipment plays only a minor role. Toxicity potentials resulting from stainless-steel production become increasingly important only if a frequent exchange of the microreactors is required. In certain cases, these toxicity potentials may exceed those of the alternative batch process. For both environmental and economic reasons, special attention should therefore be paid to the lifetime of microstructured devices made of stainless steel. If this is the case, the results indicate that microreaction technology can be a very promising way to an increased ecological sustainability of production processes.

Abbreviations

ADP	abiotic resource depletion potential
AP	acidification potential
CED	cumulative energy demand
Conti Sc 1	scenario 3-month lifetime of the microreactor
Conti Sc 2	scenario 3-year lifetime of the microreactor
Conti Sc 3	scenario 10-year lifetime of the microreactor
Conti Sc wc	scenario 1-week lifetime of the microreactor
FAETP	fresh aquatic eco-toxicity potential
FU	functional unit
GWP	global warming potential
HTP	human toxicity potential
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
MAETP	marine aquatic eco-toxicity potential
NP	nutrification potential
ODP	ozone depletion potential
POCP	photochemical ozone creation potential
TETP	terrestrial eco-toxicity potential

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