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Life-cycle assessment, comparison of biopolymer and traditional diaper systems

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Abstract

Growing space problems accompanying urbanisation and rise in the standard of living have motivated the development of measures to reduce waste production. One such measure is the development of biodegradable materials which can be treated in composts and so recycled. A lot of valuable space is thus saved. The polymer discussed in this study is also made from renewable raw-material, which increases its attraction and makes it particularly interesting from the life cycle point of view. The landfill capacity saved is counterbalanced by land needs and emissions of agricultural production. Thus, an objective judgement on the environmental performance of such a product needs to be based on its whole life cycle. In this study the environmental impacts of a new biopolymer product over its whole life cycle were assessed and compared to those of a conventional plastic product. The study is built on diaper products, because they are assumed to have a significant role in the growth of the future markets of biodegradable materials.

The biodegradable polymer, polylactide, is based on lactic acid produced by fermentation from carbohydrate sources. Consequently, the appropriate system extends to agricultural production. The life cycle of conventional plastic starts from crude oil production and refining. Both product systems include the production of the diaper with its components. The phase of waste management comprises biological treatment, incineration and landfilling as alternatives. Several scenarios were formed to study the effects of variable options in the life cycle of diapers, especially in that based on the new product. The characteristic variables chosen for the scenarios were technology, waste utilisation intensity, location and raw materials. Geographical or agricultural policy aspects were not considered.

An important outcome of the study is that differences between the impacts of the traditional and the biodegradable diaper systems are small. The fluff component (70%) of the diaper turned out to be dominant in most environmental stressors. In most scenarios a polyolefin based diaper is slightly better, but the results are not far from each other. The most important phases in the life cycle of polylactide are agricultural production and fermentation to lactic acid. The biodegradable diaper waste can be converted into compost products, which can be used to enhance soil quality and partly to substitute

mineral fertilisers. Thus, the amount of landfill waste is substantially reduced. Another advantage is that the biopolymer made of annually renewable raw-material. In the production chain of conventional plastic the most important impacts are hydrocarbon emissions to air and water. Because polyolefin products cannot be composted, the only possible way of saving landfill capacity by waste treatment is incineration.

The results vary greatly according to scenario parameters. It should also be taken into account that the whole biopolymer chain is still under development, which obviously adds the uncertainty of the results obtained for the PLA system.

Preface

The target of the project was to compare the cumulative environmental impacts of a renewable and biodegradable plastic to those of a non-renewable and biologically persistent, fossil-based plastic. Since diaper products are a potential application of biodegradable plastic in the future they were selected as a case for comparison. Environmental impacts of both materials were studied in the case selected for the life-cycle approach.

The study was carried out by the LCA Group of VTT Chemical Technology (VTT Energy) in co-operation with Neste Oy. A co-study on the methodology for life-cycle cost analysis was run parallel to the main study. It is reported in a separate paper. Both studies were co-financed by the Neste Group and Tekes Biopolymers Programme.

Thanks are due to all those several company representatives and research scientists who made the study possible by sharing their expertise by supplying data to the project team.

Espoo, December 1997

Authors

Abbreviations

APME	Association of Plastic Manufacturers in Europe
BAT	Best Available Technology
CONS	CONSUMPTION Consumption phase
ELU	Environmental Load Units
EPO	Ecopoint
EPS	Environmental Priority Strategies in product design
DIAP	DIAPER Diaper production and production of components such as fluff pulp, plastic intermediate components, superabsorbent and packaging
FDST	FEEDSTOCK Cultivation and fertiliser production
IDEA	An International Database for Ecoprofile Analysis
LA	LACTIC ACID Lactic acid production chain including production of chemicals, etc.
LACTIDE	Lactide production
LCA	Life-Cycle Assessment
LDPE	Low-Density Polyethylene
LPG	liquefied petroleum gas
NGL	natural gas liquids
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PE	Life Cycle Assessment
PLA	polylactide
POLYMER	Polymerisation
PP&PE	polypropylene and polyethylene (plastics used in the diaper)
PP	polypropylene
SETAC	Society of Environmental Toxicology and Chemistry
SUGAR	Sugar production chain including production of chemicals, etc.
TRP.FU	Transport fuel
WM	WASTE MANAGEMENT Diaper waste treatment processes

Al	Aluminium
As	Arsenic
BOD	Biological oxygen demand
Cd	Cadmium
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
Cr	Chromium
Cu	Copper
GWP	Global Warming Potential
HCl	Hydrogen chloride
HF	Hydrogen fluoride

Hg	Mercury
Mn	Manganese
Mo	Molybdenum
total N	Nitrogen
Ni	Nickel
N_2O	Nitrous oxide
NO_x	Nitrogen oxides
ODP	Ozone Depletion Potential
total P	Phosphorus
Pb	Lead
Se	Selenium
SO_2	Sulphur dioxide
Ti	Titanium
TSP	Total suspended particles
V	Vanadium
VOC / HC	Volatile organic compounds/hydrocarbons)
WMO	World Meteorological Organisation
Zn	Zinc

Contents

APPENDIX A

1. Introduction

The world is in the middle of massive urban transition. Within the next decade, more than half of the world's population, an estimated 3.3 billion, will be living in urban areas (UN 1995). This change, which will have considerable implications both for human well-being and for the environment, is rapidly taking place. In 1975 just over one third of the world's people lived in urban areas. By 2025, the proportion will have risen to almost two thirds. The most rapid change is occurring in the developing world, where urban population is growing at 3.5% per year. Consequently, third world cities are reaching unprecedented sizes, for instance, Sao Paulo, Brazil, 16.4 million and Bombay, India, 15 million. High population concentrations place enormous strains on the institutional and natural resources that support them. In the industrialised countries, in general, population grows slowly and also the urban growth is slower, less than 1% a year. Relatively, however, developed countries are more packed in the cities, for example, the world’s largest city is Tokyo, with 27 million people, and their material consumption is tremendously higher so that they are probably facing burning environmental problems before developing countries.

Although urban environmental problems are difficult to categorise they can be grouped into two broad classes: those associated with poverty and those associated with economic growth or effluence. The worst problems in terms of human suffering occur in the poorest cities of the developing world. At least 220 million urban dwellers lack access to clean drinking water and more than 420 million do not have access to the simplest latrines. Between one and two thirds of the solid waste generated is not collected (WRI 1997). It piles up on streets and in drains, contributing to flooding and the spread of diseases.

Environmental problems are also severe in the cities experiencing rapid economic growth. Cities generate enormous amounts of solid waste that tend to increase with income (Figure 1). In cities of the developing world, an estimated 20 to 50% of the solid waste generated remains uncollected, even though up to one half of local operational expenditures often goes toward waste collection (WRI 1997). In most OECD countries, 100% of the urban population is serviced by municipal waste collection. However, with their higher consumption levels they confront ever-increasing mounds of garbage. Since 1980 the generation of municipal waste per capita has increased in all OECD countries except Germany (UN 1993), where several measures, such as separate collection of recycled materials, have been employed to reduce the waste accumulation and demand for ever more scarce land. On the other hand, Tokyo is unable to handle more than 22 000 metric tons of garbage per day, despite massive recycling and incineration projects. As a result officials are building islands of waste in Tokyo Bay, which threaten both the shipping and fishing industry (Linden 1993).

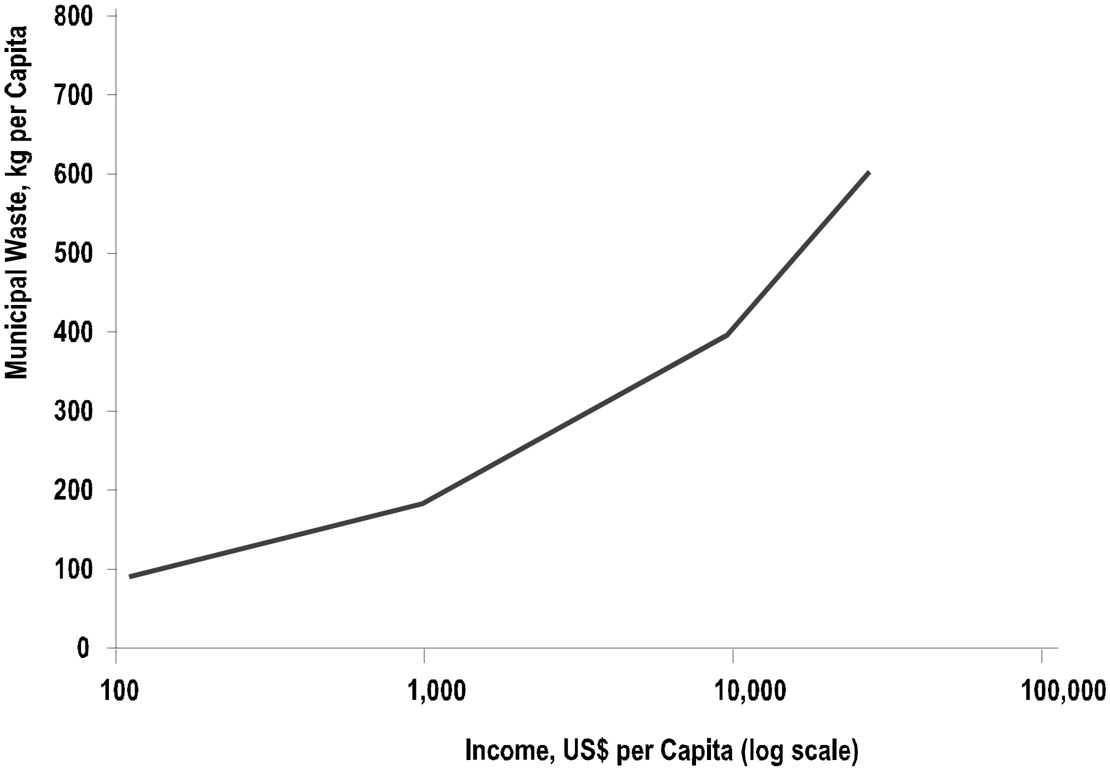


Figure 1. Trend of municipal waste by increasing income (World Bank 1992).

Growing space and hygiene problems accompanying urbanisation and rise of the standard of living have motivated development of measures for reduction of waste production world-wide. Up till today, recycling of materials has been the predominant principle for most plans and actions. In many cases, such as particular paper and steel grades, recycling has worked out quite well, but also such cases exist, where it has more or less failed, because of technical and economical difficulties in the first place. One example is the German packaging ordinance of 1991, whose main motive was to save landfill capacity in the country. The ordinance forced the raise of recovery rates of all packaging materials without providing solutions for their use. As a result, material began to accumulate in unofficial landfills and illegal dumps, and the costs of the recycling system rose steeply (Gronow & Pento 1996).

Because of the practical limitations of material recycling other solutions are needed to complement it in managing the growing waste problems. One such solution are biodegradable materials which can be treated in composts and even recycled. Much valuable space is thus saved. Space is a critical resource from the sustainability point of view, but the bioplastic of this study fulfils also another vital requirement of sustainability, i.e., renewability. This makes such a material very attractive and particularly interesting from the life cycle point of view. Whilst landfill capacity is saved, production of biomass means land use and agricultural emissions.

One reason to develop the biopolymer is also the need to find new applications for agricultural materials to compensate the overproduction in the Western world. Nettherthe-less, various ecological interventions occur at various positions of the life cycles of the biodegradable as well as traditional polymers. Indeed, for an objective judgement on the environmental performance of a product in general, it is necessary to take into account the whole of its life cycle.

Application of the life cycle principle to materials is complicated. To assess the environmental effects of a material would, in fact, mean a study of all relevant product systems where that material is or could be applied. Due to excessive amount of work and costs, this is practically impossible. Therefore, it is necessary to develop substitutive approaches, which would be realistic for their work requirements and yet competent enough to handle the original problem. There are two main principles which could be utilised in simplification. The first is a so-called ”cradle-to-gate” principle, in which the study is limited to the common parts of different product systems, and the second the principle of ”the best representative”, in which a sample product system is selected to represent the whole of the product systems (Figure 2). It is obvious that the cradle-to-gate approach violates the life cycle principle unless the environmental performance of the cut-off parts is independent of the base material, which is not the case when biodegradable and biologically persistent materials are considered. On the other hand, there are several ways of determining ”the best representative” of various parallel product systems depending on the point of view. In the study on hand a new selection is made from the viewpoint of market potential. A planned biodegradable material is compared to a conventional one in a product, which is assumed to have a important role in the growth of the future markets of biodegradable materials.

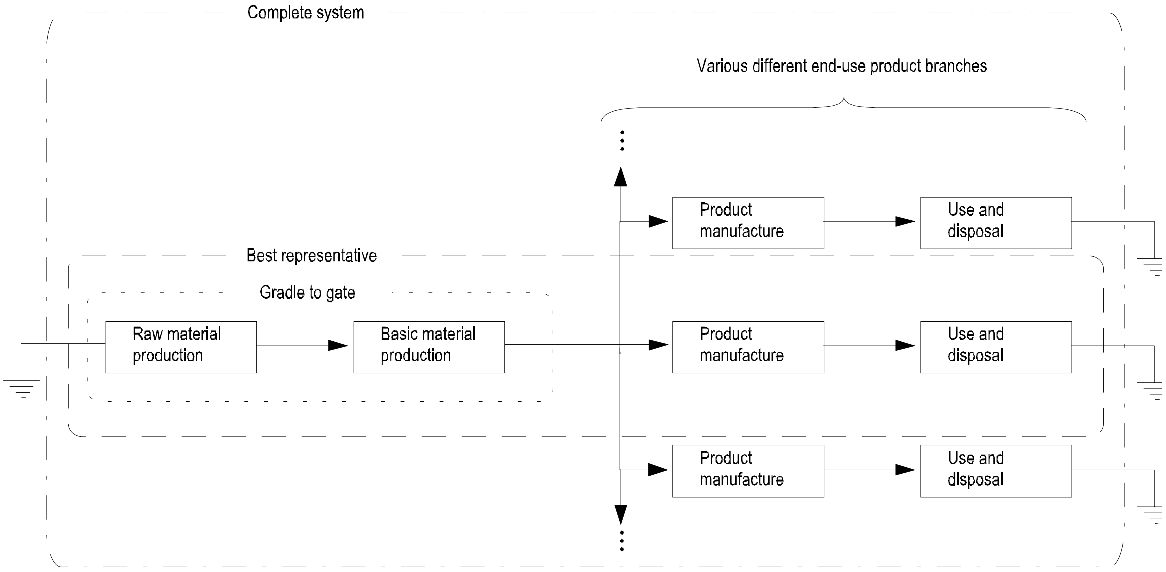


Figure 2. Illustration of the main simplification principles for a material-oriented LCA.

2. Objectives and scope of the study

The goal of the study was a practical method to assess the environmental loads and their costs over the whole life cycle of a product. The aim was to develop an LCA model for comparisons of the environmental quality of renewable and non-renewable products under a range of alternative technological and agri- and silvicultural conditions and to produce a feasible concept for the cost calculations in the LCA context.

The study was built on diaper products which are a potential application of biodegradable plastic in the future. The characteristic variables of scenarios were limited to technologies, waste utilisation intensities, location alternatives and raw materials. Geographical or agricultural policy aspects were not considered.

3. Methodology

The methodology used in the study is life-cycle assessment (LCA). The principle of life cycle analysis implies that products, activities, or even entire economic sectors are analysed from an end-use perspective. The life cycle approach makes it possible to quantify the cumulative impacts that a product generates from the point where materials and energy for this product are extracted from nature, up to the final disposal of the wastes, i.e., when they are returned to nature. The processes that the emissions and wastes undergo in nature should be included, but these processes cannot be studied comprehensively at present because of their complexity and insufficient data.

Life cycle analysis has its roots as far back as the early 1960s. At the World Energy Conference in 1963, Harold Smith published a report on the cumulative energy requirements for the production of chemical intermediates. In the late 1960s and early 1970s, several researchers undertook global modelling studies in which they attempted to predict how changes in population would affect the world's total mineral and energy resources (e.g., Meadows et al. 1972; Mesarovic & Pestel 1974). Around the period of the major world oil crises in the mid and late 1970s, the United States commissioned about a dozen major "fuel cycle" studies to estimate the costs and benefits of alternative energy systems. Later, similar studies were commissioned by both the US and British governments on a wide range of industrial systems. In 1985, the Commission of the European Communities introduced a "Liquid Food Container Directive" (CEC 1985) which charged countries with monitoring the raw material and energy consumption, as well as the amounts of the solid waste they generated. As concern about global air and water pollution problems increased, these emissions were then also routinely added to energy, raw material, and solid waste considerations.

Today, the Society of Environmental Toxicology and Chemistry (SETAC) defines life-cycle assessment in the following way:

> *"Life -cycle assessment is a concept to evaluate the environmental effects associated with any given activity from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth." (SETAC 1993)*

LCA is divided into four constituent parts :

1. *Goal definition and scoping*, where the goal and scope of the study are defined

2. *Inventory analysis*, which comprises the material and energy flow analysis of the studied system within defined system boundaries.

3. *Impact assessment*, which is divided into three phases:

Classification, where emissions are classified into impact categories;

Characterisation, where the contributions to each impact category are calculated;

Valuation, where the impact from each impact category are weighed and the total summarised impact evaluated.

4. *Improvement Assessment*, where the results from the steps above are used to identify potentials for improvements in the system studied.

The first three parts are the actual components of the LCA methodology and the fourth one the major applications of LCA results, however, it is not the only one. Sometimes even a fifth phase is added to an LCA methodology, i.e., a critical review, often called also 'peer review'. This critical review is an essential means of the quality assurance of LCA and it has been carried out for the data quality and methodology of the study.

In this study, the focus is on the *inventory analysis*. The calculations made include mass balances for the subsystems. However, impact assessment, including valuation, has also been included in the study in accordance with the Nordic recommendations for screening and differential LCAs (Nordic Council of Ministers 1995). The status of impact assessment is primarily demonstrative, since the available methods are still much disputed and incomplete. On the other hand, if inventories of different systems come up with different final results, which normally is the case, data for different environmental loads have to be added together into one, or several, still meaningful, numbers in order to answer *policy questions*. This requires a value judgement on the comparability of these various loads and on their relative harm to the environment. From this departure point, the enclosed impact assessment can be helpful by providing new, aggregated and justified views to the comparison problem.

Issues reported on the inventory are given in Table 1. The selection of inventory categories mainly leans on relations to the impact categories and the valuation methods given in the Nordic recommendations. The last two issues, however, are included because they are of specific importance for the systems studied. Some of the inventory categories are aggregates of several individual stressors, e.g., BOD and heavy metals. Thus, the inventory has been wider and more detailed than that given in the table, according to the methodological principles of LCA. Impact assessment and valuation results presented below are based on the complete inventory results.

Impact categories considered in this study are given in Table 2. Basically they follow the Nordic recommendations (Nordic Council of Ministers 1995), where one can also find detailed descriptions of the assessment methods used for different impact categories. Because of missing data on stressors and characteristic impacts, however, some of

Table 1. Reported inventory categories.

Inventory Category
Primary energy usage
SO_2 (sulphur dioxide)
NO_x (nitrogen oxides)
CO_2 (carbon dioxide)
CO (carbon monoxide)
CH_4 (methane)
N_2O (nitrous oxide)
VOC (volatile organic compounds)
TSP (total suspended particles)
Heavy metal emissions to air
Heavy metal emissions to water
BOD (biological oxygen demand)
COD (chemical oxygen demand)
N (nitrogen emission to water)
P (phosphorus emission to water)
Total solid waste
Landfilled diaper waste

the categories suggested in the Nordic recommendations are omitted. They are not, however, deemed crucial for the purpose and goal of the study.

Valuation methods demonstrated in the study are given in Table 3. They are all introduced in a background paper of the Nordic recommendations (Lindfors et al. 1995) as ‘more or less ready to use’. There are other valuation methods that as well deserved to get demonstrated here, but were excluded for practical reasons. Therefore, the demonstration should not be interpreted as a recommendation for the presented methods, but just as application examples of valuation methods available today.

Table 2. Considered Impact assessment categories.

Impact class	Impact category	Assessment method
Resource depletion	Non-renewable energy sources	Maximum effect
	Renewable energy sources	Maximum effect
Ecological impacts	Global warming potential	100 years
	Acidification	Maximum effect
		Minimum effect
	Eutrophication	P-limited
		N-limited
		N-limited + NO_x from air
	Photo-oxidant formation	NO_x; CH_4; CO;VOC
	Ozone depletion	Maximum effect
Human health impacts	Toxicological impacts (excluding impacts in work environment)	Critical body weight, air Units of polluted air Critical air volume Critical body weight, water Units of polluted water Critical water volume
Inflows not followed to the system boundary between the technical system and the nature.		Inventory
Outflows not followed to the system boundary between the technical system and the nature.		Inventory

The omitted impact categories are:

Resource depletion –Water (could be assessed very insufficiently, see chpt. 9.8.5)
Resource depletion - Materials
Resource depletion – Land (could be assessed very insufficiently, see chpt. 9.8.5)
Human health - Non-toxicological impacts
Human health impacts in work environment
Depletion of stratospheric ozone
Eco-toxicological impacts
Habitat alterations and impacts on biological diversity

Table 3. Valuation methods demonstrated.

Effect category (Long Term)	Weighting (EPO) is based on the normalised emission rates and Swedish long-term political goals.
Ecoscarcity (CH)	Weighting (EPO) is based on the ratio between actual flows and the squares of critical flows of emissions. Actual flows are totals and critical flows theoretical maximums (based on legislation) of annual emissions in Switzerland.
Tellus	Weighting (USD) is based on the control costs of CO, NO_x, particles, SO_x, VOC and lead (reference emissions). For other emissions, the prices are obtained by utilising environmental threat potentials relative to the reference emissions.
EPS (Environmental Priority Strategies in product design)	Weighting (environmental load unit, ELU) is based on the estimated contribution to the changes in five safe guard objects (biodiversity, production, human health, resources and aesthetic values) and on the values of the safe guard objects based on the willingness to pay to restore them to their normal status.

4. System boundaries and definitions

The flow-charts of the diaper systems are presented in Figure 3.

The term “biopolastic” or “biopolymer” in this study means biodegradable plastic based on annually renewable raw-materials. Biodegradation is decomposing of polymer caused by bacteria, fungi and other micro-organisms, where in aerobic conditions carbon dioxide and water is produced, in anaerobic conditions additionally methane. (Potts 1984)

The bioplastic under study, polylactide (PLA) is based on lactic acid, produced by fermentation. The common carbohydrate sources presently used for the fermentation substrate are maize, wheat and sugar beet. Alternative sources are included in the study. The yield from different raw materials varies.

The product studied, a diaper, is composed of 70% fluff pulp and 20% plastic. The plastics in the conventional diaper are polypropylene and polyethylene. Production and consumption of diapers are assumed to take place in Western Europe. The phase of waste management is of special interest, and thus all relevant waste treatment alternatives, composting, incineration and landfilling, are included.

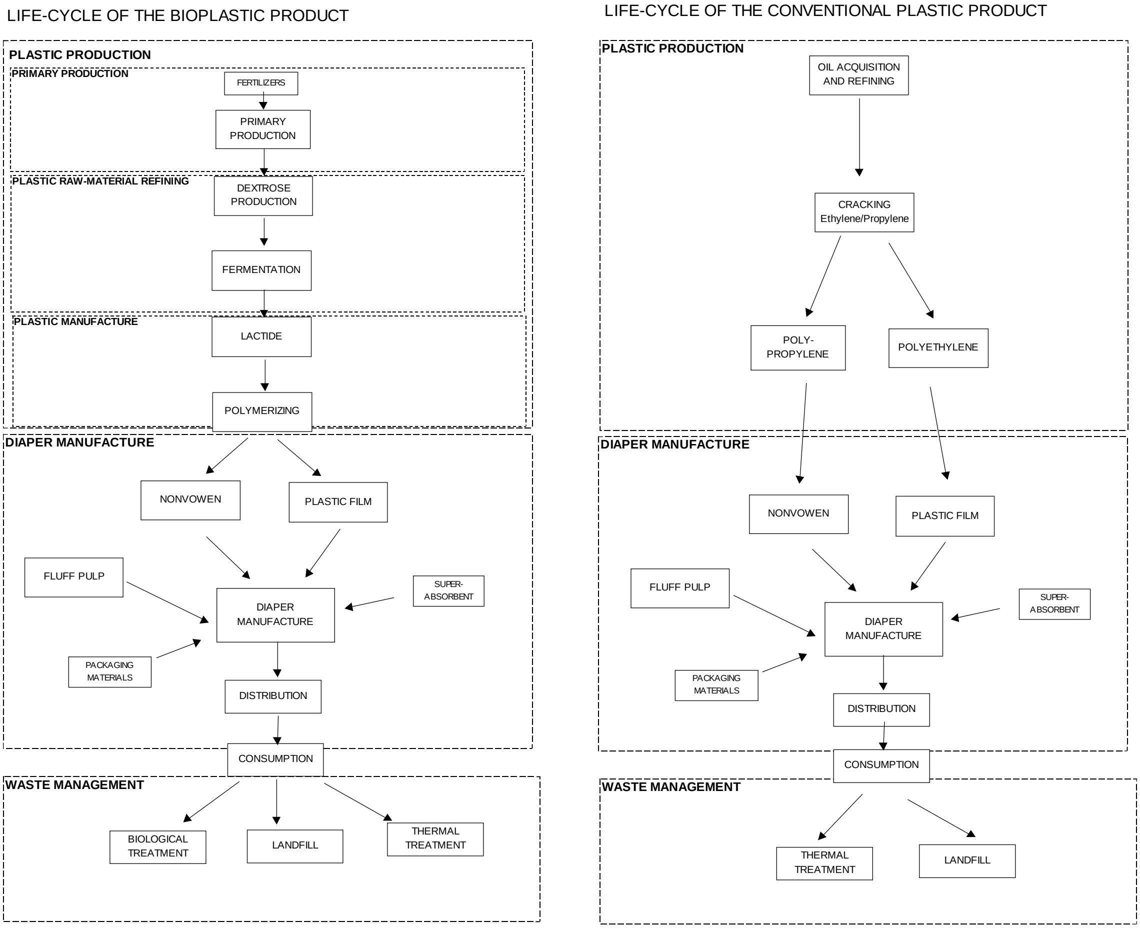


Figure 3 Flow-charts of the diaper systems.

In the case of the biopolymer product system, the *cradle* extends until the agricultural production including plant biomass formation and activities related to field cultivation and harvesting. Accordingly, the inputs to the primary production are, e.g., CO_2 up-taken, fuel consumed, nutrients and pesticides used. The outputs are, e.g., emissions from the nutrients and pesticides, respectively. Production of fertilisers is included comprising also the extraction of mineral raw materials. The boundary of the oil-based product system is extended until oil pumping from natural reservoirs.

Both product systems include the production of the diaper components, such as non-woven or film materials, and that of fluff pulp, which starts from the formation of wood biomass. Principally, the production chains of common basic chemicals consumed in the main chain of plastic and in the pulp production are included (e.g., the production of NaOH until salt rock mining).

The energy consumed in the system (electric power, heat and fuels) are studied starting from the primary energy extraction from nature in all subsystems.

On the *grave* side, in the waste management stage, the study extends until the emissions to air or to water. The decomposition of solid wastes in landfills occurs over an extended period of time. Estimations of air emissions have to be based on assumptions about the degree and rate of decomposition and on the composition of air emissions.

The temporal limit of the study is defined by the cycle of the biological product, from carbon dioxide to carbon dioxide. The longest phase is landfilling.

The production chains of the additives used in various processes, e.g. additive chemicals, are excluded from the system because of their negligible relative quantities and lacking data. In some cases, e.g., triacetin plasticiser for PLA film, the additives have been studied cursorily to identify potential hot spots.

The product flows into or out of the diaper systems not followed further in the calculations (Table 4) consist of products of minor mass flows or have been assumed to be of minor importance for some other reasons.

Additive chemicals include, e.g., HCl (hydrogen chloride) and S_2 (sulphur) used in other chemicals production for use in the biopolymer raw material chain or for diaper components such as fluff pulp and superabsorbent. Detergent chemicals nor chemicals used for waste water treatment are neither studied further.

Concerning the list above it must be noticed, that the data concerning the PLA production chain may include more accurate information on the by-products and additives, that could be listed here. The data concerning PP and PE is average European data for “average products”. The production chains of all minor auxiliaries have not been included but there was no data available so that those cut-offs could have been reported.

Table 4. The product flows not followed further in the calculations.

PRODUCT INPUTS (kg/1000 diapers)			REMARKS
	Diaper with PLA	Diaper with PP&PE	
Additives for lactide production and polymerisation	0.58	-	Of total amount 50% xylene as solvent, rest is H_2SO_4 and other
Additives for sugar products	1.33	-	Amylase and other auxiliary materials
Plasticiser for PLA plastic film	0.66	-	Triacetin
Other chemicals	0.00	0.00	
Chemicals for fluff pulp	5.95	5.95	
Other additive chemicals	4.60	0.83	Largest shares S_2, HCl (for acid production used in fermentation and for NaOH production used mainly in the diaper sector)
Wood-based auxiliary products	1.18	1.18	Recycled paper, packaging materials
Plastic-based auxiliary products	0.01	-	Fertiliser packagings
Oil-based auxiliary products	0.01	0.01	Lubricating oils for fluff pulp proc.
Iron based auxiliary products	0.11	0.11	Nails for pallets
Explosive	0.00	0.00	
Washing detergents	0.77	-	Fermentation process
Fertiliser	0.03	0.03	Wood production
Ink	0.02	0.02	Packaging films
Nutrition for fermentation	1.02	-	
Tree plants (pcs)	1.21	1.21	

PRODUCT OUTPUTS (kg/1000 diapers)			REMARKS
	Diaper with PLA	Diaper with PP&PE	
By-products from starch refining	18.00	-	
Cl_2 by product	2.98	2.75	From NaOH production used mainly in the diaper sector
H_2SO_4 by product	0.24	0.22	
By-product from lactide production	1.63	-	
By- products from fluff pulp production	1.04	1.04	Tall oil, etc.
Other by-products	0.07	0.00	

5. Allocations

Allocation principles applied to by-products at different phases of the product systems in the case of the allocation scenarios are presented in Table 5**.**

Table 5. Allocation principles applied to by-products at different phases of the product systems.

System phase	By-products for		Basis of allocation
	Bioplastic product (PLA system)	Plastic product (PP & PE system)	
PLASTIC PRODUCTION			
Petrochemical production		By-products of oil refining	Mass
Plastic raw-material refining	Fodder, raw-mat. for food industry		Mass, dry mass, economic value
DIAPER PRODUCTION	--	--	
WASTE MANAGEMENT			
Biological treatment	Compost product	--	Replaces the demand in the system
Incineration	Energy	Energy	Replaces the demand in the system

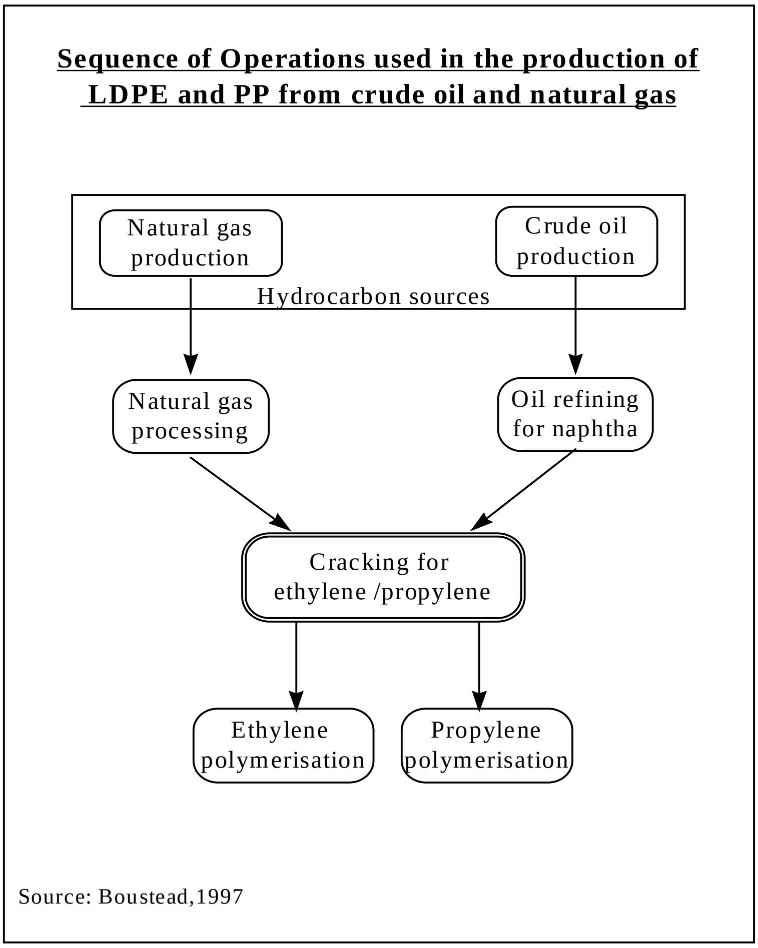
For oil refining the allocation of material and energy inputs as well as released emissions to different useful product outputs is done on the mass basis by the data supplier (see also chapter.6.1.2). For the by-products from the refining of bioplastic raw material (fodder etc.) economic values are also used as an alternative to masses in specific scenarios. Soil (compost) and energy recovered by waste management are credited by respective reductions in the demands of the systems.

6. Data quality

6.1 Raw material chains of polyolefins

6.1.1 Production chain

Polyolefins, in this study low-density polyethylene (LDPE) and polypropylene (PP), are used for diaper components. Polyolefins are produced through polymerisation of cracker products. Feedstocks for the crackers are naphtha from oil refining or natural gas from oil or gas reservoirs (Figure 4).



Source: Boustead,1997

Figure 4. LDPE and PP production, sequence of operations.

6.1.2 Data quality

Data on polyolefins are based on eco-profile reports of the Association of Plastic Manufacturers in Europe (APME 1993, 1997). To create the data APME organised in 1990 a special task force consisting of representatives from several member companies. The first report set was compiled by four leading LCA consultants, Dr. Ian Boustead, UK, as leader, Prof. Fink, Switzerland, Dr. Langowski, Germany, and Gustav Sundström, Sweden. The second updated issue was edited by Dr. Ian Boustead. Data from each plant of the member companies were collected with the same very comprehensive questionnaire form. Dr. Boustead calculated the eco-profiles for each company separately, but only the weighted European average values were published. The basic work was carried out over the years 1990 to 1993. The later issue includes new data for crackers, marked with double lines in Figure 4. The updated eco-profiles for ethylene and propylene are used to calculate the LDPE and PP data for this case study.

APME has used gross calorific heat values throughout the LCA inventory work. In the case of the polyolefin production chain (Figure 4) allocations are made using simple mass parameters. When performance characteristics of several plants are needed, the average values are calculated using both vertical and horizontal allocation procedures. All averages are weighted by mass.

6.1.3 Data characteristics

In the plastic production chain from crude oil to polymer, cracking is the most energy consuming process step corresponding to roughly 20 - 25% of the total energy. For polyolefins, PE and PP, feedstock energy comprises more than 53% of the total energy demand, refining 5 - 7%, and polymerisation about 15%.

The values for North sea gas and oil in the APME data base are based on the statistics of the British Government. The total gross energy needed to produce 1 kg North sea crude oil is 47.96 MJ. The feedstock energy share is 45 MJ/kg, and the residue 2.96 MJ/kg is used for production and transport. In a Norwegian study (Bakkane 1994), the total gross energy is reported as 45.6 MJ/kg, of which the production and transport cover 0.56 MJ/kg.

The refining data are based on the APME eco-profile reports from 1993 (APME 1993). The cracker data were updated in 1996 in connection with the polystyrene updating work. The data now cover 25 crackers producing 8.5 million tonnes of ethylene. There are eight new crackers included and two old one excluded from the data set. The updated data were used in this study.

Crackers producing the monomers ethylene (C_2) and propylene (C_3) for polyethylene (PE) and polypropylene (PP) production use different feedstocks. The product composition as well as the energy consumption in cracking vary depending on the type of feedstock (Table 6).

Table 6. Product composition for different feedstock types.

Product	Ethane	LPG	Naphtha	Gas oil
Methane	6.3	25.0	17.2	11.2
Ethylene	77.8	41.0	33.6	26.0
Propylene	2.8	17.0	15.6	16.1
Butenes	2.6	7.4	8.7	9.3
Others	10.5	9.6	24.9	37.4
Total	100.0	100.0	100.00	100.0

Ethane is a gas. LPG, *liquefied petroleum gas,* is a mixture of gases from ethane (C_2) to butenes (C_4), also called *natural gas liquids* (NGL), or *condensate*. The refinery products naphtha and gas oil (atmospheric) are gasoline with a specified boiling point (30 - 175 ^{o}C), and light gas oil with boiling point around 200 - 300 ^{o}C, respectively.

To enable a comparison with the biopolymer, data on electricity, steam and fuel consumed in the polymer production are needed. APME reports the gross energy required to produce PE/PP partitioned into electricity and oil fuel and other type fuels. Steam data on polymers were calculated by VTT using a typical portion of steam and fuel consumption from refining to polymer granules.

6.2 Raw material chains of bioplastic

The data concerning the agricultural production are based on several studies and consultation of experts. (Audsley et al. 1996, Brouwer et al. 1995, Rekolainen & Pitkänen 1995, Palonen & Oksanen 1993, etc.).

The agricultural production practices, conditions (such as soil type and weather conditions) and the environmental effects vary greatly between geographical regions. For example, estimating the emissions from fertiliser use for a specific product is difficult. The data should be based on nutrient balances, but several factors have to be taken into account (the amounts added, absorption from the atmosphere, contents in the field, amounts taken by the specific crop, crop rotation, the impact of soil and weather conditions on the leachate, etc.) Data on emissions and environmental effects caused by pesticides has not been included, because of it´s complexity. These data should include information about degradation rates and fate models.

Data on dextrose production and fermentation have been collected from several producers and vary rather much between the plants, depending on differences in technologies, capacities and product mixes, etc. The rate and method of energy production in these processes affect the results of the whole system. The yields of sugar and lactic acid per hectare differ between alternative raw material chains. Energy consumption also differs to some extent. Detected ranges of variation are given in Table 7.

Table 7. Ranges of property and yield variations for different raw materials of bioplastic.

	Corn	Wheat	Sugarbeet
Yield t/ha	8	7 - 8	55
Total solids content %	85 - 88	85 - 88	25
Demand t/t lactic acid (100%)	1.6 - 2.0	1.8 - 2.2	8.4 - 9.9
Energy of prod. chain MJ/kg LA	10 - 30 (20)	10 - 35 (25)	15 - 45 (30)
Area ha/t LA	0.2 - 0.25	0.23 - 0.28	0.15 - 0.18
Area for cultivation ha/ 1000 diapers	0.0052 - 0.0065	0.006 - 0.007	0.0042 - 0.0047

6.3 PLA production

The data on PLA production including lactide production and polymerisation are still under development, and hence the data are based on engineering calculations. Because the product is new, the quantities produced are still minor, at least compared with the conventional plastic. Neither have the processes been developed to full efficiency, etc. Energy efficiency is crucial for the final results.

6.4 Diaper components and manufacture

The data on diaper components are based on a previous study, a comparison of disposable diaper and cloth diaper (Nylander & Parming 1993). The diaper manufacturing process and the production chains of the main components, fluff pulp, fibre web and plastic film have been checked and updated with data from present manufacturers.

6.5 Waste management

The data on waste treatment processes are based on data available from the operating plants and from the literature. (OWS 1995, Reimann & Hämmerli 1995, Muesken & Bidlingmeier 1994, Sundqvist et al. 1993, Verschut & Brethouwer 1993, Koch et al. 1991, etc. The data on waste treatment processes vary to some extent according to the various data sources, because of variations in technologics etc.

Assessing data on waste management processes for a certain product is problematic. Waste management processes are normally run for mixed waste (multiple input process). Some emissions generated are process-dependent, some are material-dependent. Certain emissions, e.g., heavy metals, can in principle be rather easily allocated for different waste fractions according to the heavy metals contents of the materials. Detailed emissions from landfills are, however, very difficult to estimate because of the long time frame during which they occur. Furthermore, the treatment processes are constantly affected by environmental regulations in each country and thus rapidly changing in their environmental performance.

7. Scenarios

In the life-cycle of the diapers consumed in Western Europe and in particular in the case of a new product under development, the “life cycle” includes many possible options, from which several scenarios were formed.

7.1 Characteristic variables

The scenarios studied are characterised by the factors presented in Table 8.

The main properties reflected by the chosen factors are the level of technology and the intensity of waste utilisation. Scenario properties comprise the composition of the lactic acid raw material, where the technology ranges from BAT to low, the energy supply in the biopolymer production chain, including energy production efficiency such as the shares of combined heat and power or fuels and the geographical concentration of the production (location). Factors that contribute to the technology levels of the systems are marked with (T) and those contributing to the intensity of waste utilisation with (W). The latter is minimum when neither the energy nor material of the waste are being utilised, grows through recovery of the inherent energy in the waste, to the best situation where both the energy and material by-products, e.g., compost product, are utilised and the utilisation is credited in the system. In Table 8 the level growth is from right to left, i.e., the options resulting in the lowest technology or waste utilisation level are given in the rightmost cell of each factor.

7.2 Descriptions

7.2.1 Base scenario

The basic scenario studied is described in Table 9 (base scenario). The following assumptions are made for all scenarios:

1. Raw materials for bioplastic, sugar and lactic acid are produced in Central Europe.
2. Corn is transported partly from Central Europe, partly (20%) from the United States, the transport distance of sugar beet to the sugar factory is short, on average 50 km.
3. The production of diaper components (except for fluff pulp) and diapers are within the area of Central Europe. The fluff pulp comes from Scandinavia. The diapers are consumed within the area of Central Europe. The transportation distance of wastes is on average 50 km.

Table 8. Characteristic scenario factors (T = technology factor, W = waste utilisation factor).

SUGAR PRODUCTION		
Technology level described by the data (T)		
High = best values reported	“Today’s average”	Low = worst values reported
Energy supply (T)		
Profile of power supply		
Maximal combined heat and power production	Zero combined heat and power production	
Fuels for on-site production		
Natural gas	Oil	
LACTIC ACID PRODUCTION		
Base raw materials		
Corn	Sugar beet	
Technology level described by the data		
High = best values reported	“Today’s average”	Low = worst values reported
RESIN PRODUCTION (FROM SUGAR TO PLA)		
Location		
Lactic acid, lactide and PLA production all in one location = Belgium	Lactic acid and lactide production in Belgium, polymerisation in Finland	
Energy supply (T)		
Profile of energy supply		
Maximal combined heat and power production	Zero combined heat and power production	
Fuels for on-site production		
Natural gas	Oil	
WASTE MANAGEMENT		
Shares of waste treatment methods (W)		
Biological %/Thermal %/Landfilling %		
For diaper with PLA		
75%/20%/5%	0%/35%/65%	
For diaper with PP & PE		
0%/80%/20%	0%/35%/65%	
Technology level described by the data (T, W)		
High <u>Biological treatment</u> = anaerobic treatment and energy recovery from gas <u>Thermal treatment</u> = BAT = wet method for flue gas <u>Landfilling</u> = BAT = landfill gas collected and utilized for energy	Low <u>Biological treatment</u> = composting with no energy recovery <u>Thermal treatment</u> = worst values reported <u>Landfilling</u> = worst values reported	

Table 8 continues…

ALLOCATIONS	
By-products in diaper system with PLA (W)	
Sugar production	
A share of loadings allocated to by-products	No allocation
Waste management	
Surplus energy replaces demand in the system	No allocation
Compost product replaces demand for fertilisers in the system	No credit for compost product
By-products in diaper system with PP & PE (W)	
Oil refining	
A share of loads allocated to by-products	No allocation
Waste management	
Surplus energy replaces demand in the system	No allocation

Table 9. Base scenario description.

Scenario	Characteristic factor	Value or description
”Basic” for diaper with PLA	Raw material shares of corn and sugar beet	50/50%
	Technology level in PLA production chain (from sugar to PLA)	High
	Energy supply in PLA production chain	“Feasible share” of electricity is produced with combined heat and power production (CHP; specific energy production), the rest of the energy is from average European network. Fuel in on site energy production is natural gas (100%).
	Location of resin production	From lactic acid to PLA in one location (Belgium).
”Basic” for diaper with PLA and diaper with PP&PE	Waste treatment mix	Biological (composting) 0%, incineration 35%, landfilling 65%
	Technology level for waste treatment	High
	Allocations made	No allocations made, by-products produced are inventored as outputs from the systems.

7.2.2 Alternative scenarios

In alternative scenarios the factors in the PLA production chain vary according to alternative raw materials and production technology levels, from BAT to low values. The energy supply in the PLA chain varies according to the share of combined heat and power production from the maximum share to zero and according to the fuel, natural gas 100% to oil 100%.

In the high waste utilisation scenarios the shares for the biopolymer product are 75% to biological treatment, 20% to thermal treatment and 5% to landfilling (this corresponds to the studies made on separate collection of diaper waste for biological treatment) and, respectively, for the conventional product 80% to thermal treatment and 20% to landfilling. The technology level in the waste treatment processes also ranges from low to high.

A combination of the scenario factors named above would have produced numerous alternatives, from which the most realistic ones were chosen. The need to find the ultimate range of environmental performance of the product studied was also used as a criterion.

In Figure 5 the locations of the basic scenarios, which the following comparisons are primarily based on, are shown on the “scenario map”.

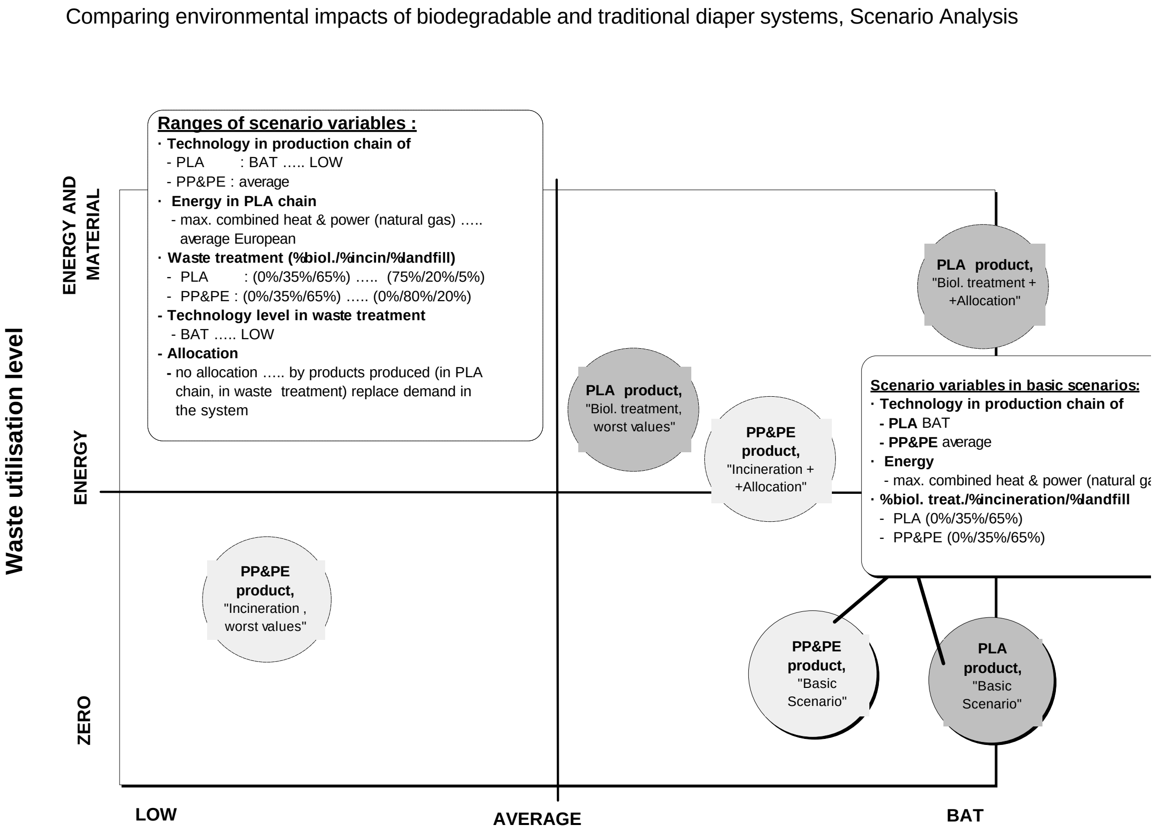


Figure 5. Scenario map.

8. Inventory results

8.1 Life-cycle sectors

In order to analyse the distribution of the environmental loads inside the systems in detail and to apply the obtained results to potential future assessments, the systems have been divided into sectors.

SECTORS: (see Figure 6)

Each sector comprises the production, transportation and energy conversion processes up to the extraction of primary raw materials from the nature and to emissions to nature.

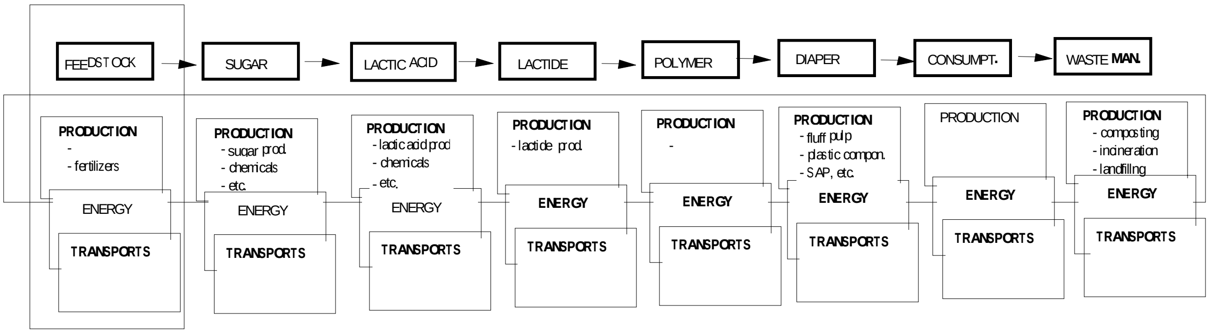


Figure 6. Diaper sectors and subsectors (Diaper with PLA).

<u>Diaper with PLA:</u>

POLYMER
Subsectors:

FEEDSTOCK
Cultivation and fertiliser production.

SUGAR
Sugar production chain including production of chemicals, etc.

LACTIC ACID
Lactic acid production chain including production of chemicals, etc.

LACTIDE
Lactide production

POLYMER
Polymerisation

DIAPER
Production of diapers and components such as fluff pulp, plastic intermediate components, superabsorbent and packaging.

CONSUMPTION
Consumption phase.

WASTE MANAGEMENT
Diaper waste treatment processes.

TRANSPORT FUEL
Transport fuel production for the total life-cycle system (separated for technical reasons).

Diaper with PP & PE:

POLYMER
Plastic production chain from crude oil to granule.

DIAPER
Diaper production and production of components such as fluff pulp, plastic intermediate components, superabsorbent and packaging.

CONSUMPTION
Consumption phase.

WASTE MANAGEMENT
Diaper waste treatment processes.

TRANSPORT FUEL
Transport fuel production for the total life-cycle system, (separated, because of technical causes).

8.2 Product flows of the diaper systems

The basic product flows of diaper systems calculated for 1 000 diapers are listed in Table 10. The smaller amount of the PLA plastic compared to the conventional plastic PP & PE for 1 000 diapers follows from the relatively greater need of filler material in the PLA plastic.

Table 10. The basic product flows of the diaper systems.

BASIC PRODUCT FLOWS PER 1 000 DIAPERS					
Plastic production for diapers					
Diaper with PLA					
PLA	kg	13			
Diaper with PP & PE					
PP	kg	10			
PE_LD	kg	4			
TOTAL		14			
Diaper production					
				Materials:	Materials:
Diaper				Diaper with PLA	Diaper with PP&PE
Components					
Fluff pulp	kg	44	69%		
Plastic film	kg	4	7%	PLA 85%, plastisiser + filler 15%	PE-LD
Non-vowen	kg	4	7%	PLA	PP
Diaper products	kg	5	8%	PLA	PP
Superabsorbent	kg	6	9%		
Components total	kg	64			
Losses in production		3			
Diaper	kg	61			
Packaging materials					
Corrugated board	kg	5			
Pack. Film	kg	1		PE-LD	PE-LD
Diaper consumption					
Urine	kg	150			
Faeces	kg	8			
Diaper	kg	61			
Waste	**kg**	**219**			

8.3 Total energy utilities consumption in diaper systems

Figure 7.1:

Electricity consumption in the biopolymer diaper system is from 40% to 60% higher compared to the conventional diaper system. In the “allocation” scenarios the total electricity consumption of the biopolymer diaper system decreases by around 15%, and that of the conventional diaper system by 10%.

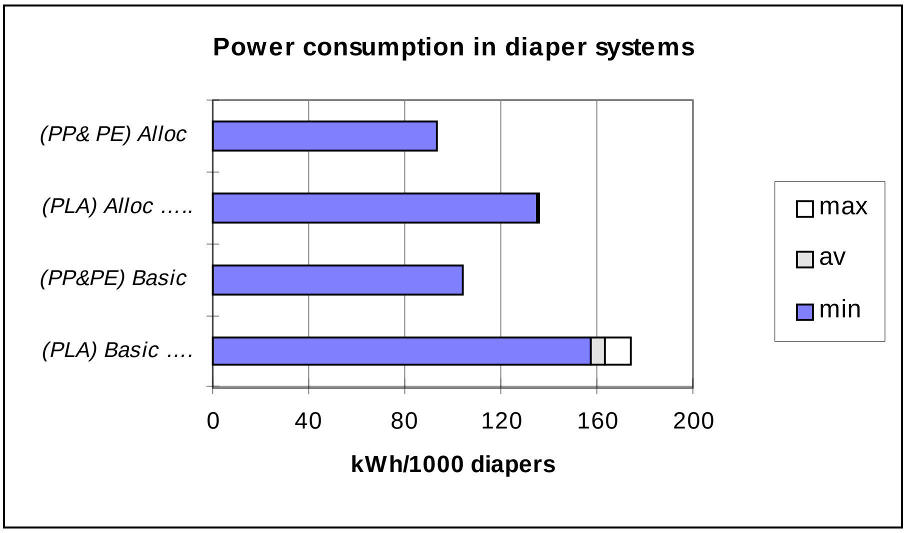


Figure 7.1. Power consumption in diaper systems.

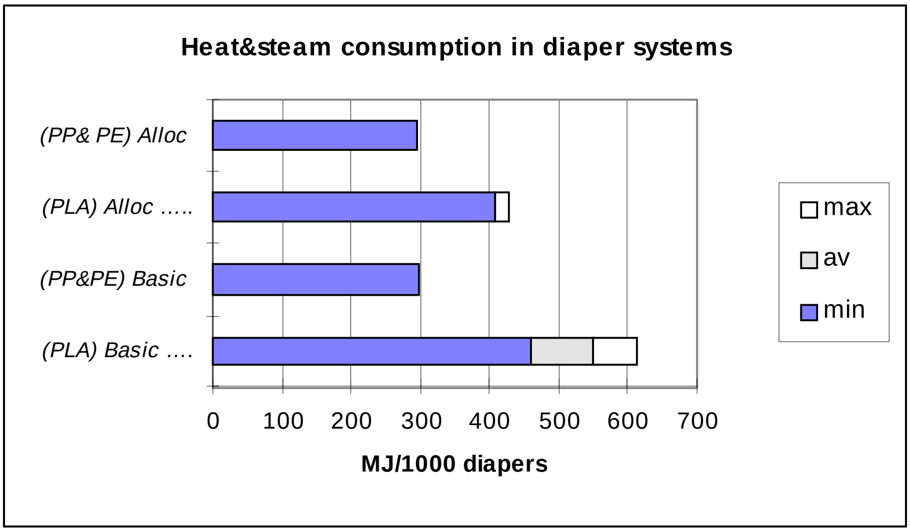


Figure 7.2. Heat & steam consumption in diaper systems.

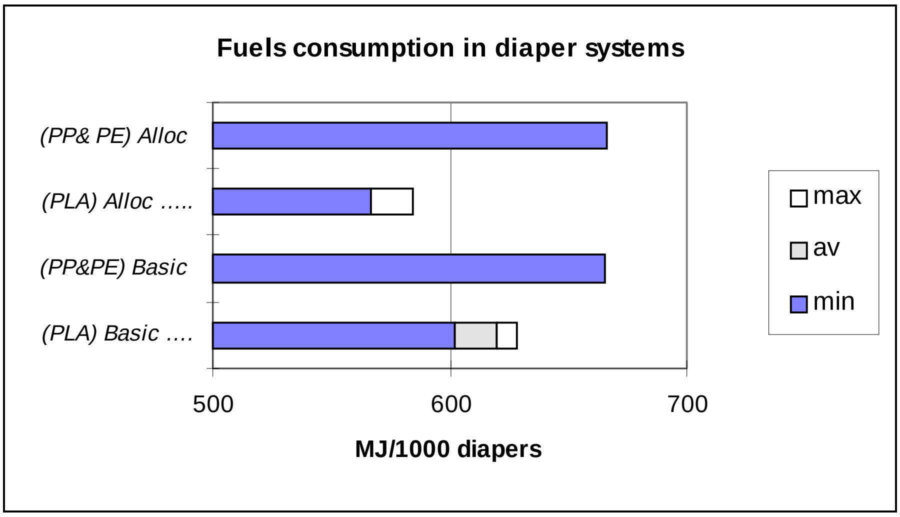


Figure 7.3. Fuels consumption in diaper systems.

Figure 7.2:

The total heat and steam energy consumption of the biopolymer diaper system is 50% (maximum values up to 100%) higher compared to the conventional diaper system. In the “allocation” scenarios the total heat and steam consumption of the biopolymer diaper system decreases by a few per cents, while in the conventional diaper system no heat energy is compensated.

Figure 7.3:

The total fuel consumption of the biopolymer diaper system is 10% lower compared to that of the conventional diaper system. In the “allocation” scenarios the total fuel consumption of the biopolymer diaper system decreases by a few per cents. In the conventional diaper systems no fuels are compensated.

8.4 Primary energy

Primary energy consumption comprises the energy sources extracted from the nature for energy production for the system.

The diaper systems with sectors are illustrated in Figures 8 and 9.

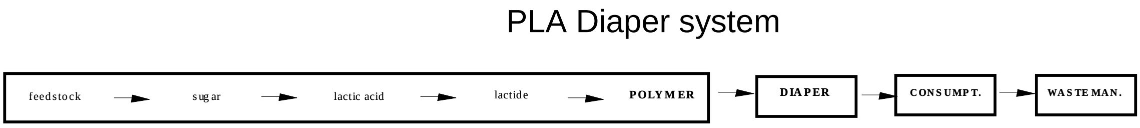


Figure 8. PLA diaper system, sectors (for descript. of sectors see chapter 8.1).

Figure 9. PP & PE diaper system, sectors (for descrpit. of sectors see chapter 8.1).

Figure 10 presents the total results of primary energy consumption for the basic scenarios of PLA and PP & PE diaper systems, separated for life-cycle subsystems (sectors).

Additionally, the estimated result variation between the scenarios calculated for technology levels in the PLA production chain (comprising technologies in raw materials refining and energy production efficiency) and for waste utilisation level (shares and technology level of waste treatment) are illustrated. For more detailed descriptions of the scenarios see chapter 7.

In the basic scenario of the PLA diaper system the share of the ”diaper” sector in the total energy consumption is just under 60%. The share of the plastic sector is 30% of the total. In the plastic sector the share of the raw material chain, from agricultural production up to lactic acid (FDST - LA) is about 80%, and that of the lactide production and polymerisation (PLA) is 20%. The clearly larger share of the raw material chain is a trend in the case of most environmental loadings in the biopolymer plastic chain.

The primary energy consumption of the PLA diaper system varies slightly according to the technology and waste utilisation levels. The greatest variation is between the low and high technology levels. If no site-specific, combined heat and power production is used, the primary energy consumption is slightly increased. The effect of using energy from the national grid, instead of site-specific combined heat and power production, is higher emissions. Assumption of the allocations reduces the energy consumption by nearly 10% from the basic case.

In the basic scenario of the PP & PE diaper system, the share of the ”diaper” sector in the primary energy consumption is good 60% of the total and the share of the total plastic sector is just under 25%. Performing the allocations reduces the energy consumption nearly 10% from the basic case.

Comparison of diaper systems

For the basic scenarios, the difference in the total primary energy consumption between the biopolymer and traditional diaper systems is less than 10%. The comparison of the diaper systems is shown in Figure 10.

Considering all the scenarios, the difference varies from less than 5% up to around 30%, depending on the technology level in the PLA production chain and on the allocations made.

The shares of primary energy sources

A large share of the emissions caused by the systems relate to the quality of the energy used. The share of coal in the energy mix of the PLA diaper system is, because of a good share of average European energy, larger compared to the PP & PE diaper system. In the PP & PE system a good share of the primary energy sources is used as raw material, not for energy conversion and that in turn means less energy-related emission in comparison to the PLA system. (Figure 11)

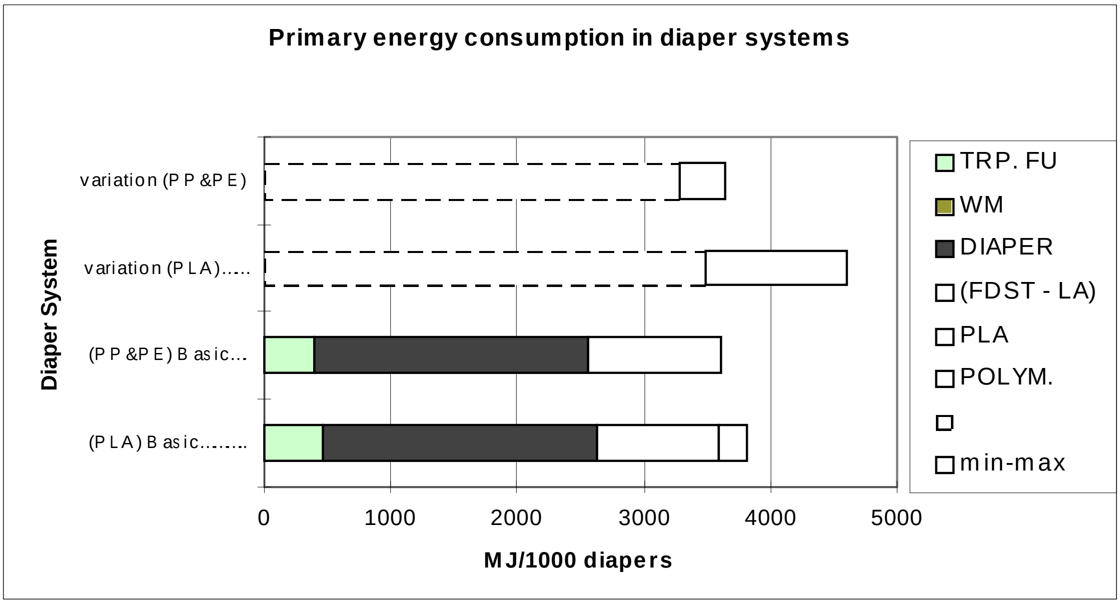


Figure 10. Primary energy consumption in diaper systems. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (conventional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP&PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2). Note: All the sectors listed in the figure (left side) are not visible in the columns, if the share in the column is negligible.

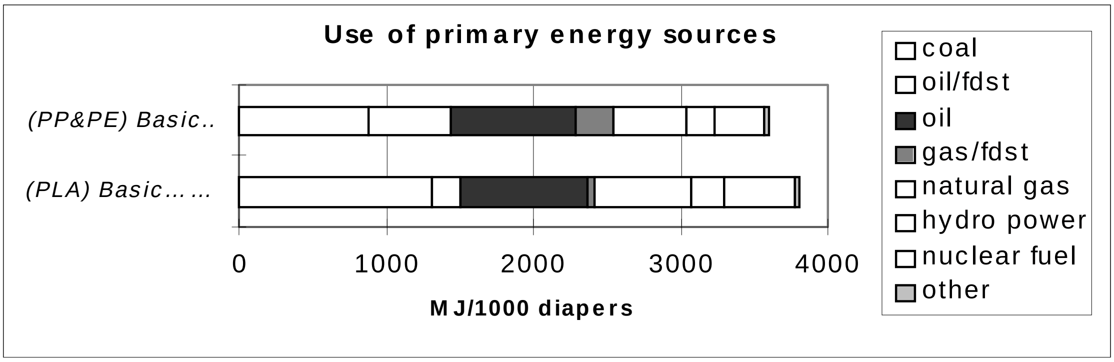


Figure 11. Shares of primary energy sources for energy production in diaper systems.

8.5 Air emissions

Various emissions to air from PLA and PP & PE diaper systems, total result for basic scenarios, separated for life-cycle subsystems are presented in Figures 12 - 20. Additionally, the estimated result variation between the scenarios calculated for technology levels in PLA production chain (comprising technologies in raw-materials refining and energy production efficiency) and for waste utilisation level (shares and technology level of waste treatment) are illustrated. For more detailed descriptions of the scenarios see chapter 7.2).

8.5.1 CO_2

CO_2 is consumed in biological growing processes. The CO_2 emission is produced in energy conversion and in the transport sector and in biological degradation processes. About 30% of the CO_2 bound in the agricultural sector remains bound in sugar by-products. A minor share remains bound in landfills. Emissions of CO_2 into air are shown in Figure 12.

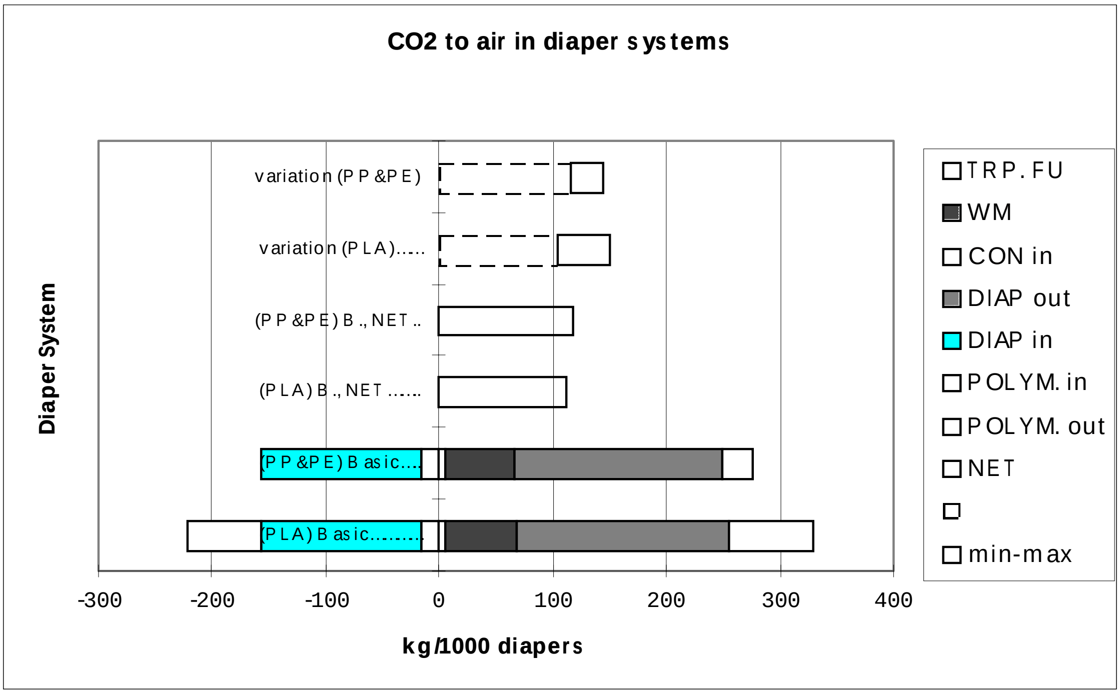


Figure 12. Air emission of CO_2. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (conventional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

PLA diaper system

In the basic scenario of the PLA diaper system the share of the ”diaper” sector in the gross CO_2 emission is good 55%. The share of the total plastic chain is of the order of good 20%. In the plastic chain the share of the lactic acid subsector is about 45% and the share of the feedstock subsector is around 10%. The share of the sugar subsector is good 20%, the share of lactide is nearly 20% and the share of polymerisation is about

5%. 20% of the total CO_2 emission occur in the ”waste management” sector, generated in the degradation processes of diapers.

In the PLA system the gross CO_2 input is good 65% of the total CO_2 output. The input in the feedstock subsector is 30% of the gross CO_2 input, for growth of plant biomass for sugar beet and corn. The share of CO_2 input in the ”diaper” sector is 65% of the total CO_2 input, for growth of wood biomass for fluff pulp. In the ”consumption” sector the CO_2 input corresponding the output in waste management is taken into account.

The CO_2 emission varies due to variations in technology levels and, accordingly, in energy consumption. The emission rate also depends on the waste utilisation level. When landfilled, the PLA diaper degrades more efficiently producing CO_2 compared to the conventional diapers.

PP & PE diaper system

In the basic scenario of the PP & PE diaper system, the share of the ”diaper” sector is 70% of the total CO_2 output and the share of the total plastic sector is 10%. The share of the CO_2 emission in the waste management is good 20% of the total output.

The emission rises in the higher waste utilisation, because a larger share of the wastes is degraded to CO_2 in incineration, and a smaller non-degrading share remains in landfills. The slightly higher CO_2 emission is caused by the PP & PE diaper incineration compared to the degradation of the PLA diaper, due to a somewhat higher carbon content of PP and PE plastic.

Comparison of the systems

In the basic scenarios the net CO_2 emission from the conventional diaper system is somewhat larger compared to that from the biopolymer system. The variation in the emission of the biopolymer diaper system is larger compared to that of the conventional diaper system, and for the maximum emission (low-technology values) of the biopolymer diaper the difference is in favour of the conventional diaper.

8.5.2 SO_2

The SO_2 emissions are generated in the energy production processes, especially in the combustion of coal and oil and in the combustion of waste as well. Emissions of SO_2 into air are shown in Figure 13.

PLA diaper system

In the basic scenario of the PLA diaper system the share of the ”diaper” sector in the total SO_2 emission is short 60%. The share of the total plastic chain is of the order of 35% of total. In the plastic chain, the share of the lactic acid-subsector is good 70%. The share of the feedstock subsector is of the order of short 10%. The share of the sugar subsector is of the order of short 10 %, the share of lactide is about 5% and that of polymerisation is slightly below 10%. The larger share of SO_2 by polymerisation in comparison to lactide production is due to more (Western-European) power consumption in polymerisation. The share of SO_2 caused in the transport fuel chain is short 5% of the total.

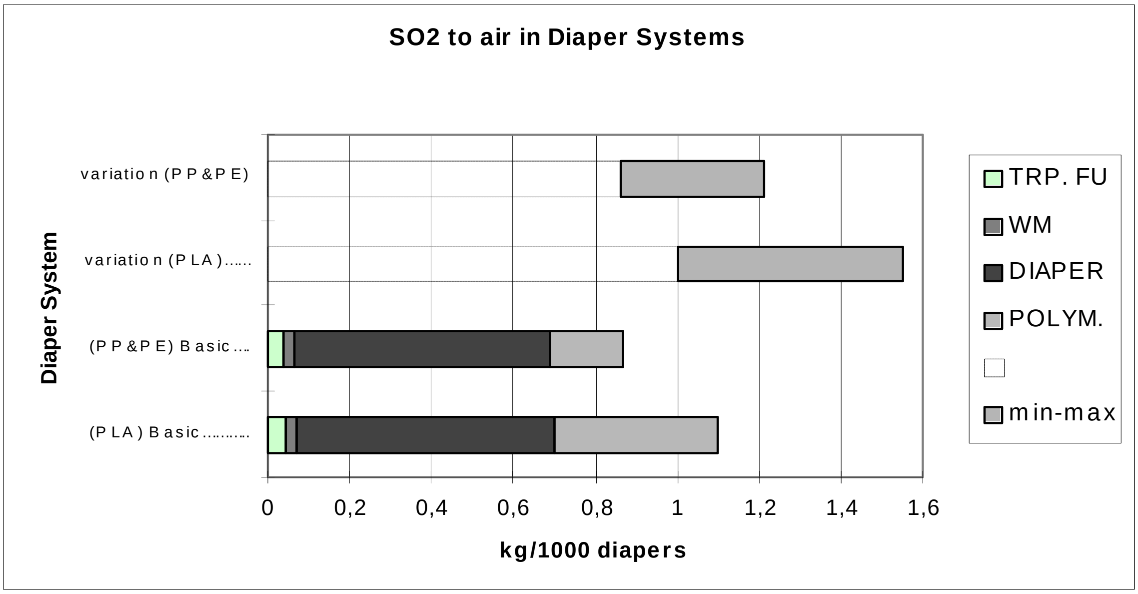


Figure 13. Air emission of SO_2. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

The SO_2 emissions of the PLA diaper system vary in alternative technology scenarios. In the sugar beet chain, one significant source of SO_2 emission is H_2SO_4 production. If the energy source in site specific production is fuel oil instead of natural gas, the SO_2 emission increases considerably. In the average European energy scenario the SO_2 emission increases by slightly less than 10%.

PP & PE diaper system

In the basic scenario of the PP & PE diaper system the share of the ”diaper” sector is 75% of the total and that of the total plastic sector is short 20%.

The SO_2 emission data for an average waste incineration process varies to great extent. At the highest the contribution of waste incineration is 30% of the total. The reduction of energy consumption in the allocation scenarios reduces the SO_2 emission as well.

Systems comparison

The difference in the SO_2 emission between the biopolymer and the conventional diaper systems in the basic scenarios is of the order of 30%, the result of the biopolymer system being higher. With the low-level technology values in the PLA chain the difference could grow up to good 50%. The difference between the biopolymer and the conventional systems in the SO_2 emission is greater compared to that in primary energy use. The result of the biopolymer system indicates more unfavourable, i.e., the fuels used in energy production contain more sulphur.

8.5.3 NO_x

The NO_x emission is caused in transports and in fuels combustion processes. Emissions of NO_x to air are shown in Figure 14.

PLA diaper system

In the basic scenario of the diaper PLA system the share of the ”diaper” sector of the total NO_x emission is nearly 70%. The share of the total plastic chain is good 20%. In the plastic chain, the share of the lactic acid subsector is nearly 40%. The share of the feedstock subsector is nearly 30%, the half of which is caused by farming machinery. (The share of the farming machinery is probably too high). The share of the sugar sector is of the order of 25%, the share of lactide is good 5% and the share of polymerisation is slightly lower. The share of NO_x caused by the production chain of transport fuels

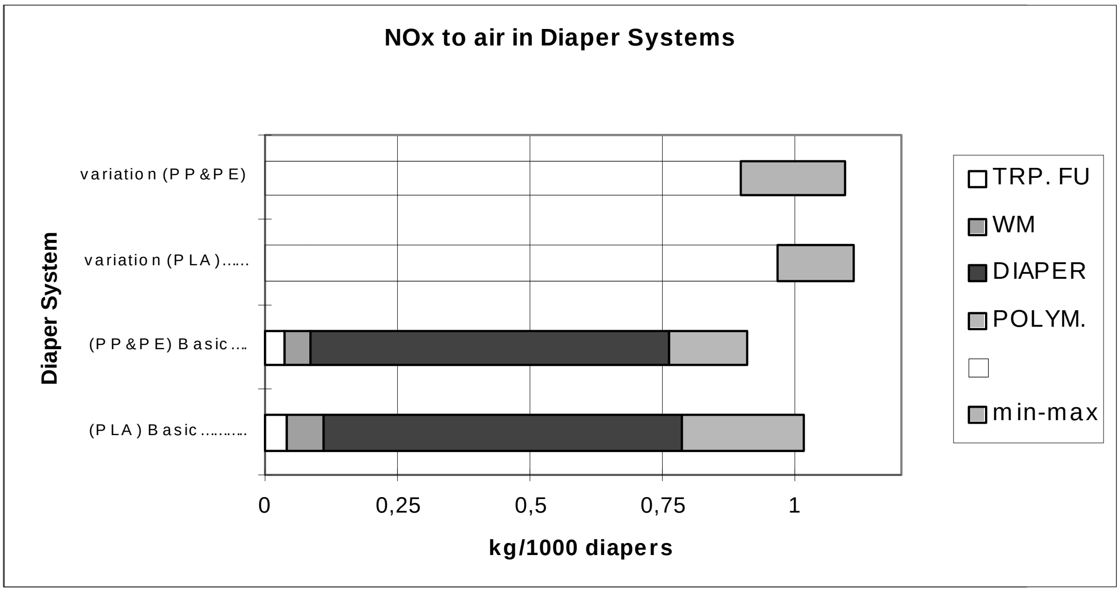


Figure 14. Air emissions of NO$_x$. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

is short 5% of the total. The share of the transportation sector in the total NO$_x$ is about 45%.

The NO$_x$ emissions of the PLA diaper system vary to some extent in alternative raw-material scenarios; the difference is caused by different transports and energy demands in the plastic chain.

PP & PE diaper system

In the basic scenario of the PP & PE system the share of the ”diaper” sector of the total NO$_x$ emission is 75% of total and the share of the total plastic sector is short 20%.

The NO$_x$ emission data for an average waste incineration process varies much. In the case of the PP & PE system by the maximum incineration scenario the contribution of waste incineration is good 15% of the total. In the allocation scenarios the NO$_x$ emission is slightly reduced according to reduction in energy consumption.

In the basic scenarios the difference in the NO_x emission between the biopolymer and the conventional diaper systems is of the order of good 10%, the result of the biopolymer system being higher. With the low level values in the PLA plastic chain the difference could grow up to 20%. On the other hand, due to the variation in the result of the conventional system the result of both systems could also be on the same level.

8.5.4 CH_4

The CH_4 emission is caused mainly by anaerobic degradation processes in landfills. Other sources with a minor contribution to the total system are the fuel chains. Emissions of CH_4 to air are shown in Figure 15.

In the basic scenarios, where 35% of the waste is landfilled, more CH_4 emissions are caused in the biopolymer system than in the conventional diaper system, as biodegradable diapers decompose to larger extent in landfills. In the maximum composting and incineration scenarios the CH_4 emissions are significantly reduced and the results of the both systems are on the same level.

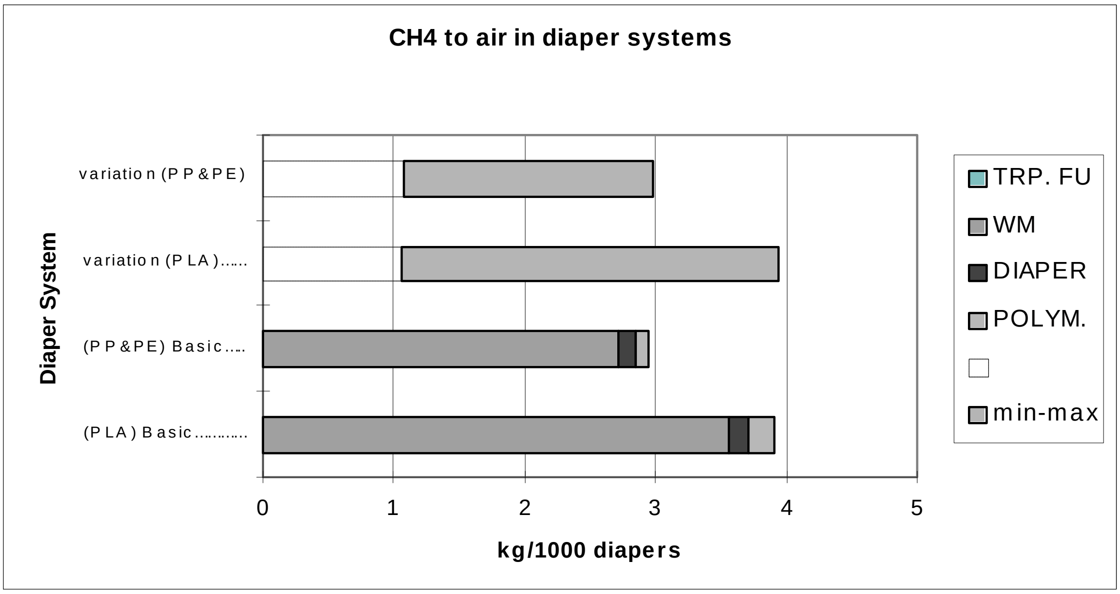


Figure 15. Air emissions CH_4. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

8.5.5 VOC/HC

The VOC emissions are caused by the oil fuel production chain, in transportation and to some extent by energy conversion (Figure 16).

PLA diaper system

In the PLA diaper system the share of the feedstock production is short 10% of the total VOC emission. The emission is mainly caused by farming machinery. The share of the lactic acid subsector is short 5% of the total, where the emission is mainly caused by energy conversion. The largest share of the ”diaper” sector is caused by the energy production and transportation chains and by plastic product chains.

In the ”oil” energy scenario more VOC emissions compared to the basic scenario are caused by the oil production chain. 15% of the total emission is from the transport fuel chains.

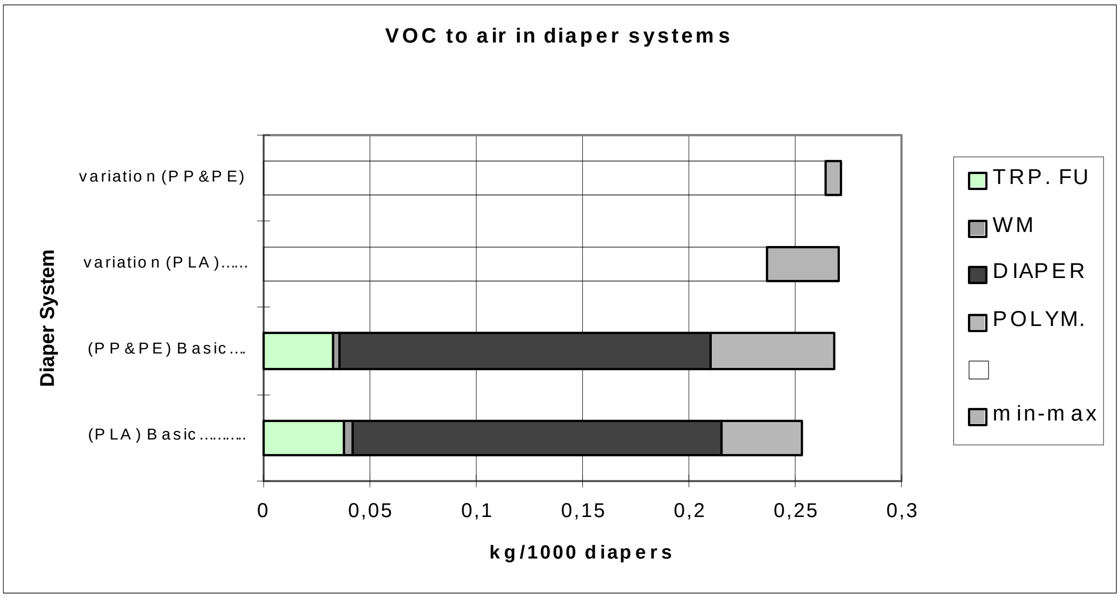


Figure 16. Air emissions of VOC. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

PP & PE diaper system

In the PP & PE diaper system good 20% of the total VOCs are generated in the plastic production sector. 65% is generated in the ”diaper” sector. The rest of the emission is caused by the transport fuel chains.

Systems comparison

The total VOC emission of the traditional system is 5 - 10% higher than that of the PLA system.

8.5.6 N_2O

The N_2O emission is caused by fossil fuels in energy conversion, in fertiliser production and from fertilisers in the fields. Scenarios of N_2O emission are shown in Figure 17.

In the PLA diaper system 90% of the total N_2O emission is caused in the feedstock subsector and the rest is from the ”diaper” sector. The result of the biopolymer diaper system is clearly bigger compared to the conventional diaper system.

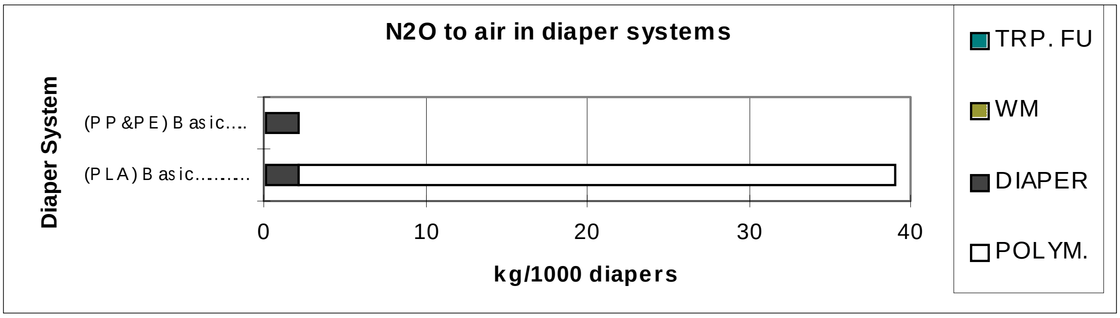


Figure 17. Air emissions of N_2O. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP&PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

8.5.7 CO

CO emission is generated in combustion processes, in energy conversion, in transports and in waste management (Figure 18).

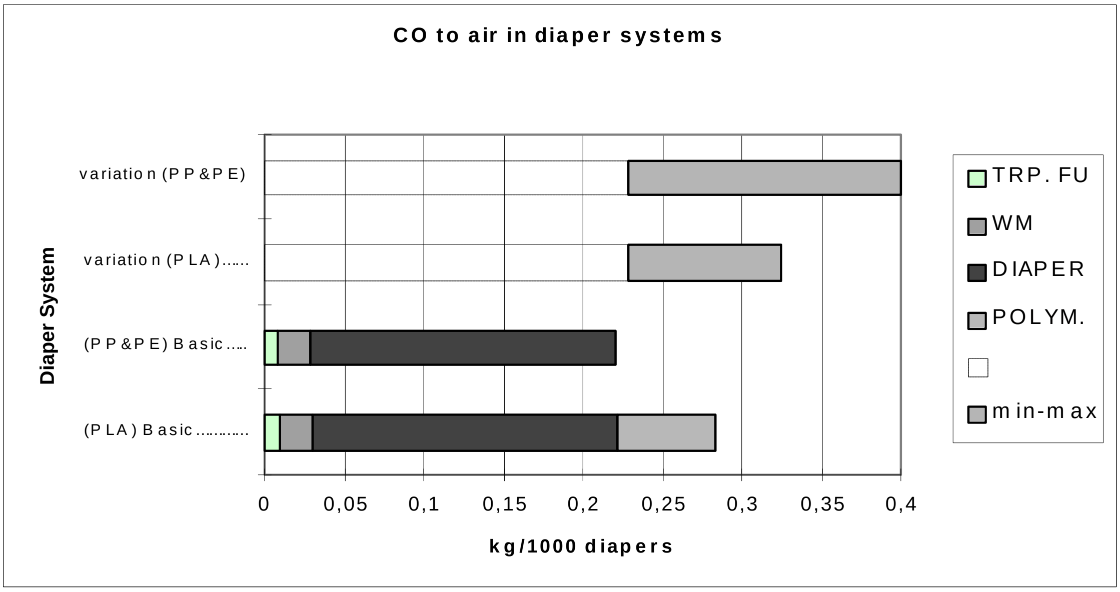


Figure 18. Air emissions of CO. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper).(PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description. of sectors POLYM., DIAPER, etc. see chapter 8.1, for scenarios, see chapter 7.2).

PLA diaper system

In the PLA diaper system good 20% of the total CO emission is formed in the plastic production chain. The share of the feedstock subsector is 50% in the plastic chain. The share of lactic acid is nearly 25% and that of sugar 20%. The share of the ”diaper” sector is nearly 70% of the total. The share of waste management ranges from 5 to 10%. The variation in the results is caused by differences in energy consumption and in the waste utilisation scenarios.

PP & PE diaper system

In the PP & PE diaper system the share of the plastic sector is of the order of 5% and that of waste management is 10%.

The CO emission data for an average waste incineration process varies to great extent. In the case of the PP & PE system by the maximum incineration scenario and with the low technology level values, the contribution of waste incineration is good 40 % of the total CO emission, and with the high level values the share is 10%.

Systems comparison

The difference in the CO emission between the basic scenarios of the biopolymer and conventional diaper systems is of the order of good 20%, the result of the biopolymer system being higher. When the ”maximum incineration” and ”biological treatment” scenarios are compared, the result of the conventional system is higher.

8.5.8 TSP (total suspended particles)

The TSP emission is caused in the limestone mining and to some extent in energy conversion processes from oil and coal (Figure 19).

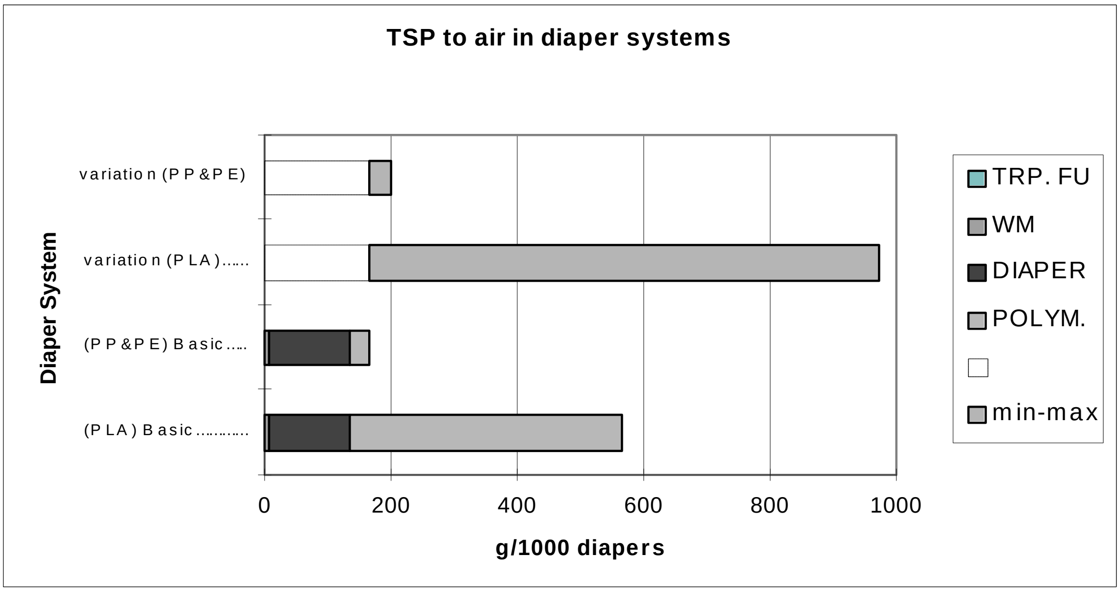


Figure 19. Total emissions of suspended particles into air. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc. see chapter 8.1, for scenarios, see chapter 7.2).

In the PLA system 80% of the total TSP emission is formed in the sugar and the lactic acid subsectors. Lime is used in the plastic chain based on sugar beet. The share of the

”diaper” sector is 20% of the total TSP and it is caused by energy conversion and, e.g., by lime production for the fluff pulp chain.

The TSP emission of the biopolymer diaper system can be very much larger than that of the conventional system or on the same level.

8.5.9 Heavy metals into air

Heavy metal emissions to air (Al, As, Cd, Cr, Hg, Ni, Pb, V, Zn) are caused by the energy conversion processes from fossil fuels, oil and coal and by incineration of average waste. The emission scenarios of heavy metals are shown in Figure 20.

The largest share of the emission is caused in the ”diaper” sector, where also a remarkable share of energy used is average European energy, including a lot of coal and oil. The main share in the total heavy metals is Pb from power production from oil and coal.

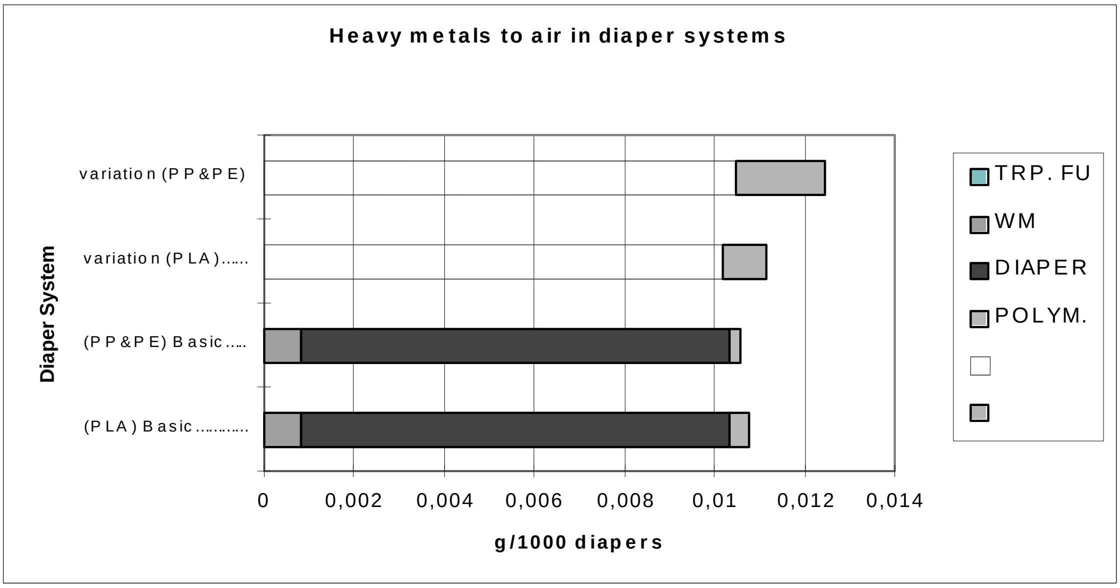


Figure 20. Air emission of heavy metals. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc. see chapter 8.1, for scenarios, see chapter 7.2).

In the PLA diaper system the variation of the heavy metals emission is according to energy consumption in the PLA chain. In the PP & PE system, the result varies according to the waste treatment scenario.The main contribution in the ”waste management” sector is Zn. Diapers contain Zn from baby cremes. The exact contribution of diapers to heavy metals from waste incineration is not available, but it could be estimated to be lower compared to average waste. The heavy metals emission from the waste incineration can be considerable. The variation of the PP & PE system results are in the estimated range of emissions from waste incineration.

The heavy metals emission to air from the biopolymer and conventional diaper systems could be of the same level. The variation according to separate scenarios can move the comparison in favour of either system.

8.6 Water emissions

8.6.1 Heavy metals to water

Emissions of heavy metals to water (Al, As, Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, V, Zn) are caused in the fuel chains, e.g., in coal mining, and from fertilisers in cultivation. In the “waste management” sector the main contributors are landfills and in biological treatment processes where water is involved. Emission scenarios of heavy metals to water are shown in Figure 21.

PLA diaper system

In the PLA diaper system the share of the “diaper” sector is 65% of the heavy metal emissions to water and that of the plastic chain is 30%. The contribution of the feedstock subsector in the plastic chain is less than 10% and the shares of the sugar and lactic acid subsystems follow the pattern of energy consumption. The share of the “waste management” sector is negligible compared to the total and could be a few percents with the maximum values.

The results vary according to the technology level and the energy consumption as well as the fuels used in the PLA chain.

PP & PE diaper system

In the PP & PE diaper system the share of the polymer sector of the heavy metal emission to water is about 10% of the total. In the ”allocation” scenarios the emission is slightly smaller according to the lower total energy consumption.

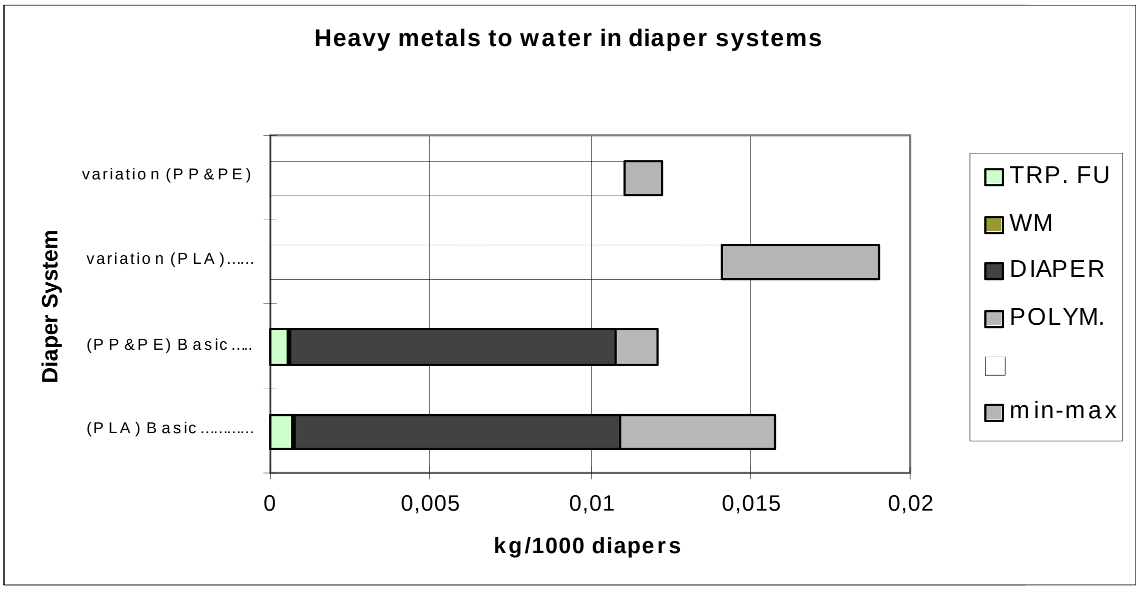


Figure 21. Emission of heavy metals to water. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA) : result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

Systems comparison

The heavy metals emission to water from the biopolymer diaper system is larger compared to that from the conventional diaper system.

8.6.2 BOD

The emission of organic substances leading to BOD in the ”diaper” sector is caused by fluff pulp production and corrugated board production but also by waste treatment processes of organic matter where water is involved (Figure 22). Some BOD is caused by emissions from fermentation. The shares caused by sugar and lactide production are negligible. The data values for the biological waste treatment processes differ to great extent.

In the case of the basic scenarios the ”diaper” sector dominates in the total emission, and the results of the biopolymer and conventional diaper systems do not differ much.

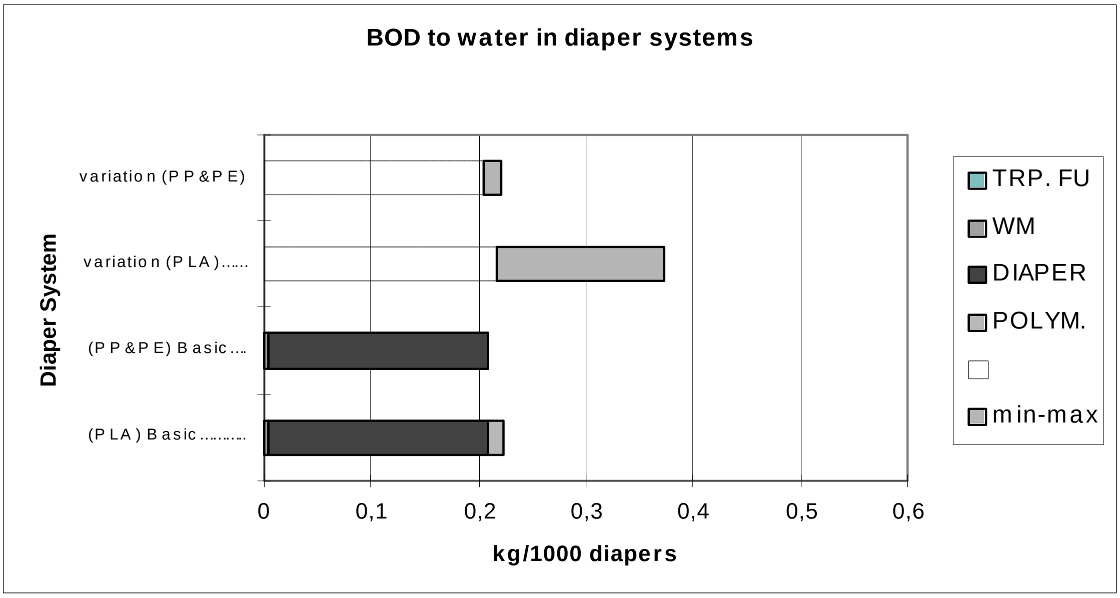


Figure 22. BOD emissions to water. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

When the maximum waste utilisation scenario is applied the result of the biopolymer diaper system varies considerably according to the technology level in waste treatment and could be clearly higher compared to the conventional diaper system.

The results of the COD emission follow the same pattern as the BOD emission. The share of the “diaper” sector is even larger than in the BOD emission.

8.6.3 Total N (nitrogen)

The nitrogen emissions are caused by fertilisers in the cultivation processes and in the biological waste treatment processes. In the ”diaper” sector the emission is caused by the fluff pulp process and by the corrugated board production.

The scenario variation of the nitrogen emission in the PLA diaper system is mainly caused by varying raw-material with varying yields and emission from the cultivation (Figure 23). The nitrogen emission from the biopolymer diaper system is clearly larger compared to that of the conventional system because of the agricultural production in the plastic production chain.

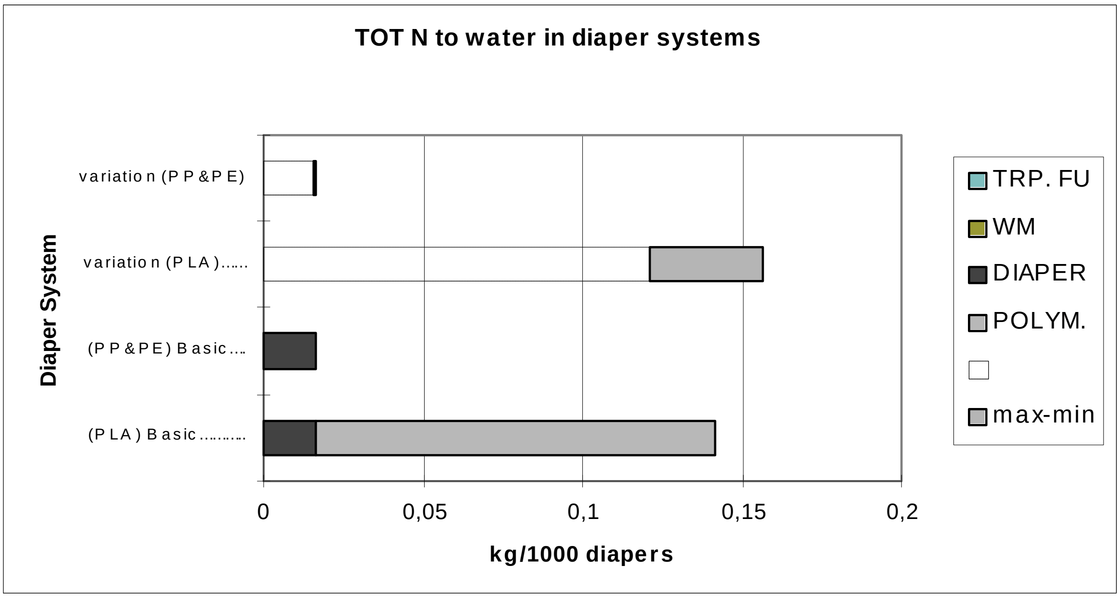


Figure 23. Emissions of total N to water. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

8.6.4 Total P (phosphorus)

The phosphorus emission is caused in the "diaper" sector by the fluff pulp process and by corrugated board production (Figure 24). In the PLA diaper system the emission is formed in the PLA chain from nutrients in cultivation and in the biological waste treatment processes. The result of the biopolymer system is clearly larger compared to that of the conventional system due to agricultural production.

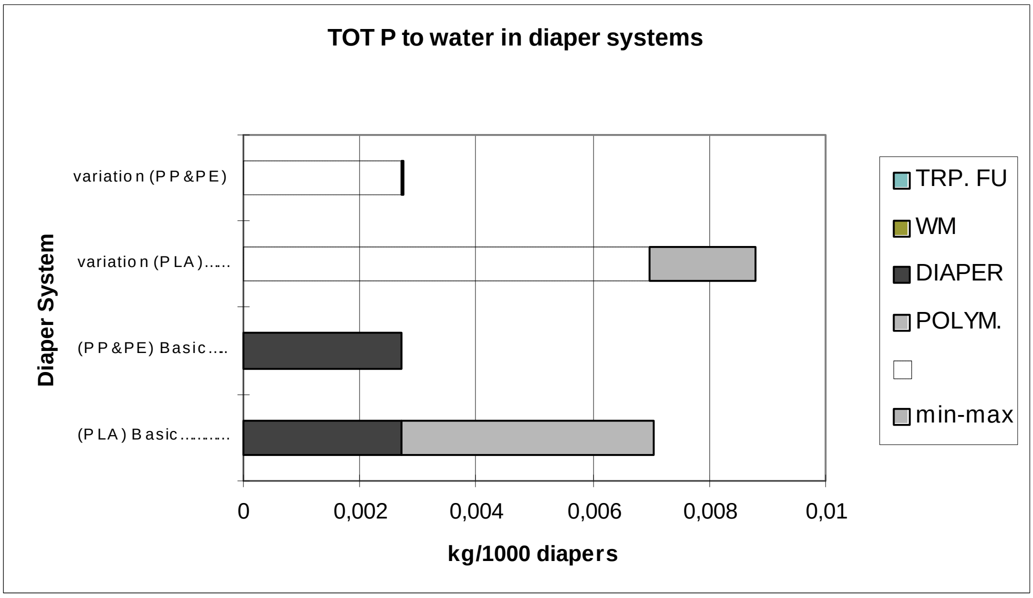


Figure 24. Emissions of total P to water. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP&PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

8.6.5 Oils

The oil releases are from the production chain of oil fuels. The emission is larger in the biopolymer diaper system due to more transports and to oil-based energy production. This emission may have been overestimated in the data used for the biopolymer system, as efforts have been put to eliminate these emissions in the recent years (Figure 25).

8.6.6 Total waste water

The total waste water emissions are formed in the "diaper" sector, in the fluff pulp process, in the energy conversion sector, and in the production of plastic products and various chemicals. In the biopolymer diaper system significant amounts of waste water are produced in sugar and lactic acid processes of the PLA chain, and the total amount of waste water is larger compared to that of the conventional system (Figure 26).

A water amount equivalent to that disposed as waste water is needed in the system. Water consumption is a difficult inventory variable. It should be taken into account, e.g., if surface or ground water is consumed.

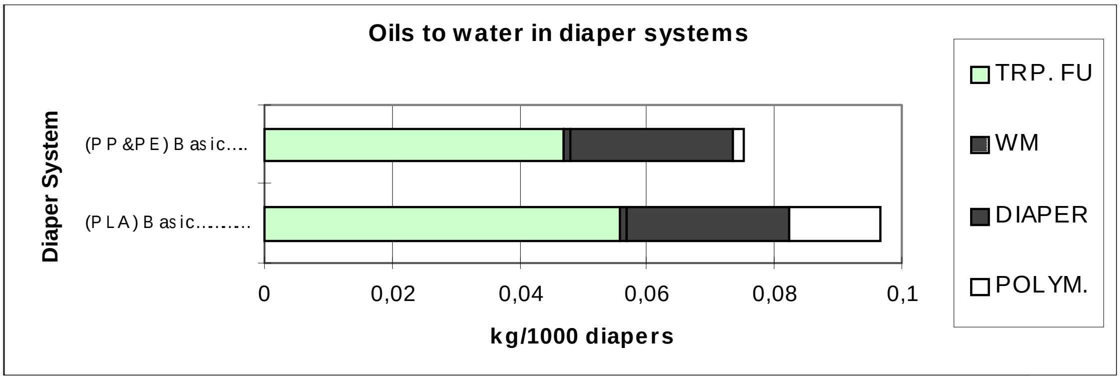


Figure 25. Emission of oils to water. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

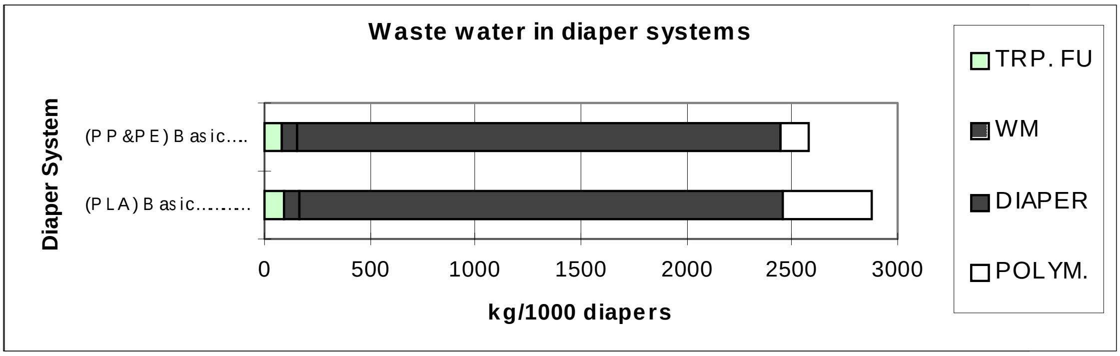


Figure 26. Waste water. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

8.7 Wastes

In the PLA system, the largest waste amount generated in the sugar subsector consists of vegetable waste and soil matter from crops brought for sugar production. The lime recovered from the process is assumed to be returned to agricultural production. In lactic acid production the wastes comprise gypsum waste, which can be used in cement industry, and biomass waste from the process, which is landfilled or burned (Figure 27).

The wastes in the lactide and polymerisation sectors are mainly from energy conversion, the amount compared to the result of the total system is negligible. The rest waste from the PLA production chain is, e.g., from fertiliser production processes and energy conversion processes. All biological wastes are expressed in wet weight, including the water content, the solid content ranging from 30 to 80%.

In the ”diaper” sector the largest share of wastes is generated in energy conversion processes. The diaper transport packages (corrugated board) and spill from the diaper production also makes a significant share. In both biopolymer and conventional diaper systems the largest waste amount is formed by diaper waste from consumption. When the share of the utilisation fraction is subtracted from the total waste amount the total waste produced in the biopolymer system is 15% larger compared to that of the conventional diaper system.

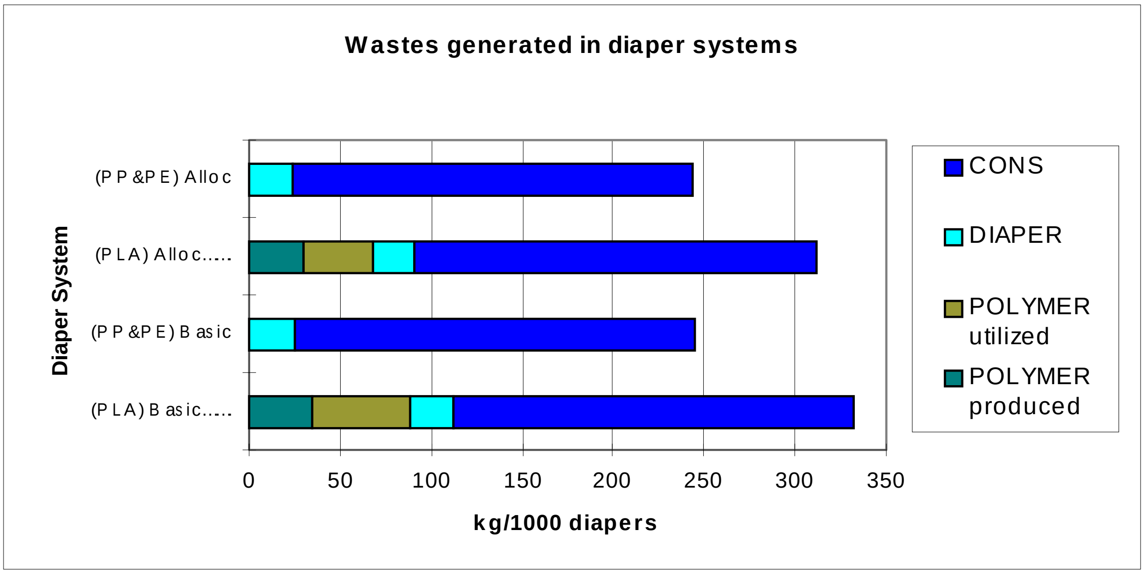


Figure 27. Wastes. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

The municipal waste landfilled in different scenarios of waste management includes diaper waste directly landfilled and a minor share left over from diaper incineration (Figure 28).

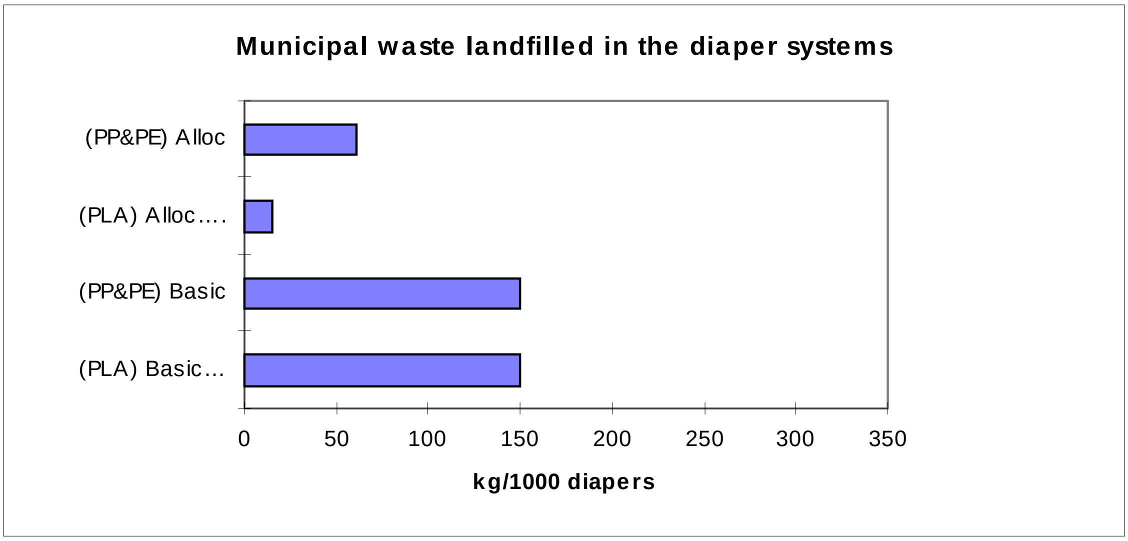


Figure 28. Municipal wastes landfilled in diaper systems.

In the basic scenarios the level of waste utilisation and the amount landfilled are same for the both diaper systems. Biological treatment of diaper waste in the high waste utilisation scenarios reduces essentially the amount landfilled.

Special wastes, demanding special treatment, from the "diaper" sector are generated mainly in energy conversion, in flue gas cleaning. In the PLA chain the largest share of special waste is caused by the solvent purge of the lactide process. Due to the toxic chemicals used in conventional plastic production, the amount of special wastes generated in the conventional plastic diaper system is larger compared to that of the biopolymer system (Figure 29).

Figure 29. Special wastes (for subsystem DIAPER and POLYMER (descript. p. 16). (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP & PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for of scenarios, see chapter 7.2).

8.8 Transports

In the PLA plastic system a significant share of the transports is caused in the sugar subsector, by crop transport from agriculture to sugar production. The transports sector in the ”corn” scenario is significantly larger compared to that of the ”sugar beet” scenario. The transport of lactic acid subsector is 20% of the result of the PLA production chain, assuming that sugar is transported from the distance of 500 km (Figure 30).

In the ”diaper” sector the share of diaper distribution is good 40% of the total transports. The next significant share is the transport of fluff pulp and after that the diaper components to diaper manufacture.

In the data concerning the PP & PE system, the share of transports in the plastic production chains have not been reported separately, but the loadings caused by transports are included in the other inventory results. (The share has been estimated in the figure 30.)

In the basic scenario of the biopolymer diaper system the share of transports is about 15% larger than that of the conventional system.

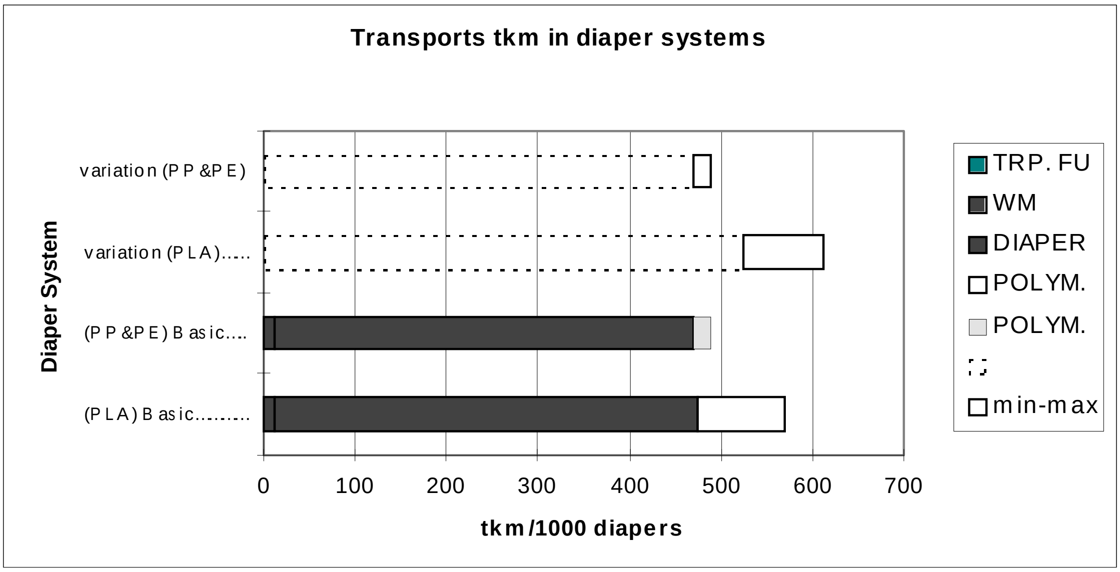


Figure 30. Transport tkm. (PLA) Basic: basic scenario of the diaper system with PLA (biopolymer diaper). (PP & PE) Basic: basic scenario of the diaper system with PP & PE (traditional diaper). Variation (PLA): result variation (min-max) of the diaper system with PLA in alternative scenarios. Variation (PP & PE): result variation (min-max) of the diaper system with PP&PE in alternative scenarios. (For description of sectors POLYM., DIAPER, etc., see chapter 8.1, for scenarios, see chapter 7.2).

9. Demonstration of impact assessment

9.1 General

In the following chapters, impact assessment is demonstrated for the impact categories presented in Table 2 previously. Selection of categories is based on the Nordic recommendations for screening and differential LCAs (Nordic Coucil of Ministers 1995). More detailed overviews of the methods can be found in LCA-Nordic Technical Report No 10 (Nordic Council of Ministers 1995).

The eventual aim of the impact assessment is to analyse and assess the environmental impacts of the environmental interventions identified and quantified in the inventory analysis. Its ideological goal is to bring up the relative and objective environmental benefits and disadvantages of different systems in comparison with each other and, consequently, to support judgements on environmental preferences of the compared systems.

The nature of the impact assessment here is, however, mainly demonstrative for two main reasons. The first reason is that, as a whole, the methods are not yet very well developed. There is no consensus about them in many of the impact categories. There are even important categories, e.g., eco-toxicological effects, where either available methods are too primitive or inventory data too incomplete and often too aggregated for a meaningful assessment. Secondly, the aggregated nature of some inventory data and, on the other hand, missing characterisation data, may cause significant errors in the presented results for some categories. From the viewpoint of methodological maturity and also of inventory data quality, the best results can be anticipated for global warming potential, acidification, eutrophication and depletion of energy resources.

9.2 Depletion of resources

Renewable and non-renewable primary energy resources

The primary energy consumption of the diaper systems is shown in Figure 31. In both diaper systems the share of fossil energy is over 90% of primary energy. Renewable energy comprises mainly hydropower. In the PP & PE diaper system a significant share of fossil resources is used as material constituting the feedstock energy.

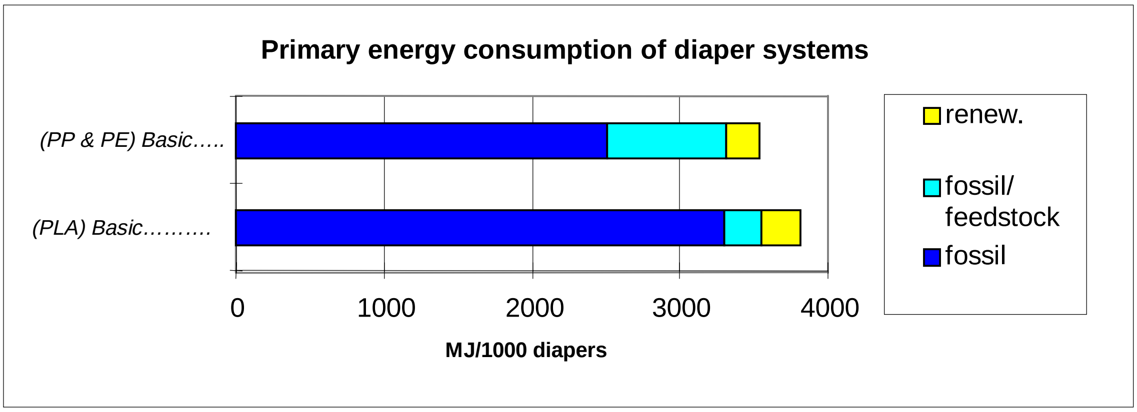


Figure 31. Primary energy resources.

9.3 Global warming potential (GWP)

In the impact class ”global warming” the emissions are reduced to CO_2 equivalents using coefficients for GWP. In the basic scenarios of both systems, the share of net contribution to global warming by CO_2 is good half, the share of CH_4 is short half. In the PLA system the share of N_2O is good 5% (Figure 32).

Negative results in the sub-system columns, both in the ”polymer” and in the ”diaper” sector are caused by biological CO_2 fixation in growing processes.

In the global warming impact the difference between the biopolymer and traditional systems basic scenarios, the net result is less than 10%, the result of the PLA system being higher. Depending on the scenario, the results of the comparable systems can be on the same level (Figure 33).

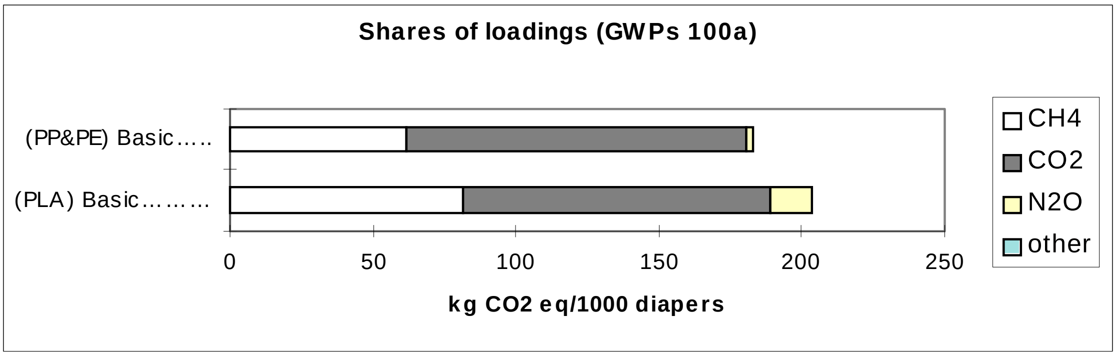


Figure 32. The shares of loadings in the global warming potentials. Note: All the sectors listed in the figure (left side) are not visible in the columns, if the share in the column is negligible.

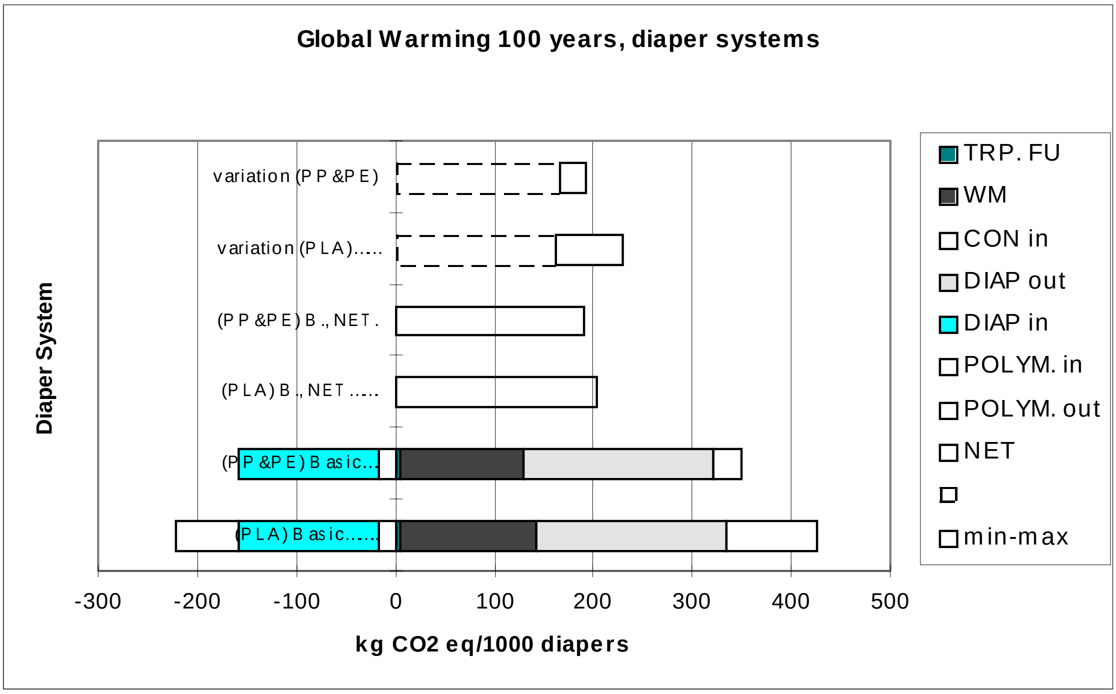


Figure 33. Global warming potentials, 100 a.

In the case of the basic scenario the some higher result for the PLA system is due to a higher energy demand and more complete biological degradation in the waste treatment phase. The variation in the PLA system results is caused by the technology level and energy consumption in the PLA chain. The variation in both systems is affected by the waste utilisation scenario. Methane production is lowered by biological treatment. The amount of methane is also highly dependent on the landfill technology applied. Incineration of the conventional plastic produces more CO_2.

9.4 Ozone depletion potential (ODP)

Various fluorinated, chlorinated and brominated emissions cause ozone depletion. In the systems studied such emissions should not occur to a significant extent, but data concerning these emissions can be incomplete to some extent as well. Generally, the data available on the ozone depletion potentials of the specific emissions is insufficient.

9.5 Acidification

The emissions causing acidification according to *the maximum effect method* are NO_x, SO_2, NH_3 (ammonium) and HF (hydrogen fluoride) to air and HCl, H+ (acids as hydrogen ions) to water. The emissions are reduced to H+ equivalents (according to the proton transfering potentials of the emissions). In *the minimum effect method*, determined for different environmental conditions, NH_3 and NO_x are not taken into account.

Acidification, maximum effect

For both comparable systems, the primary maximum acidification effect originates from SO_2 (nearly 60%) and NO_x (40%) (Figures 34 and 35). In the PLA system the contribution of NH_3 is of the order of 5%. In the feedstock subsector, NH_3 originates from ammonia production for fertilisers, from fertilisers in the field and from the production of some chemicals.

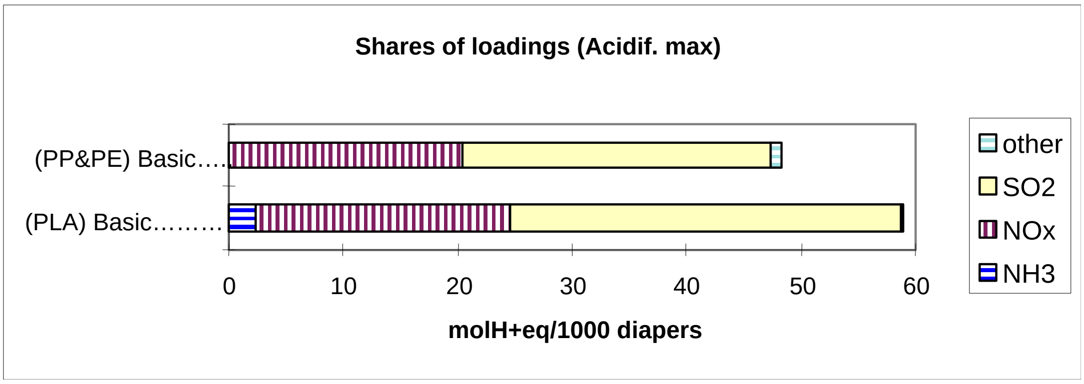


Figure 34. Acidification maximum effect, shares of loadings.

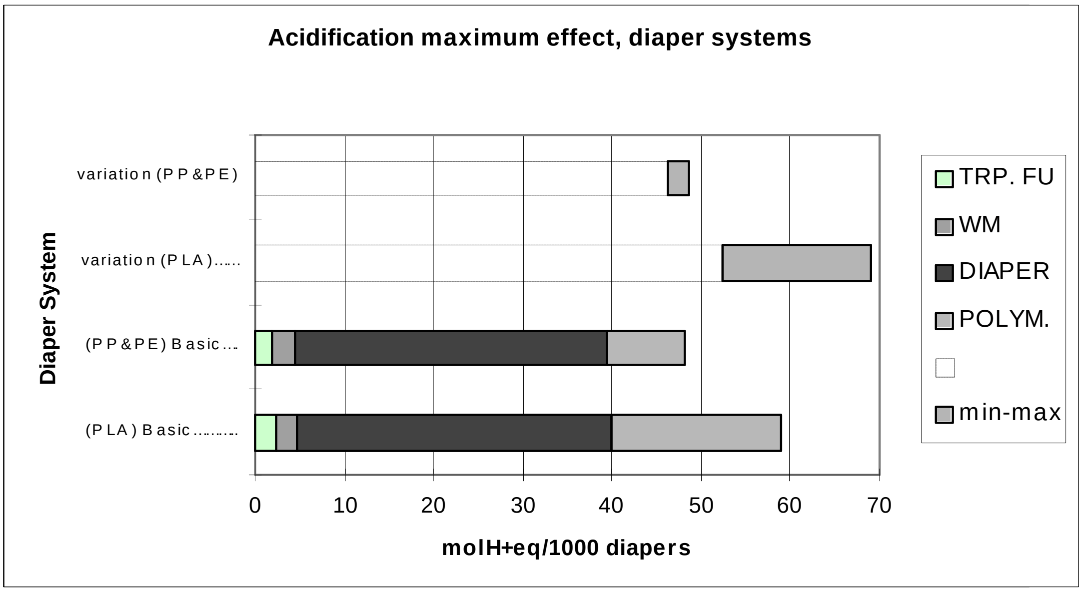


Figure 35. Acidification, maximum effect.

In the basic scenarios the result of the biopolymer diaper system is 25% higher than that of the traditional diaper system. The difference is primarily due to lactic acid production, which is energy-intensive. The agricultural sector is also of significance.

The variation in the PLA system results is caused by the technology level and energy consumption in the PLA chain. In the high-level waste utilisation scenarios the result of the PP & PE system could increase slightly due to emissions from waste incineration. In the range of variation the difference between the systems could increase to 40%.

Acidification, minimum effect

In both systems the contribution of SO_2 to the minimum acidification effect is nearly 100%. The pattern of the scenario results is very similar to that of the SO_2 inventory results (see chapter 8.5.2).

9.6 Eutrophication

The contribution to eutrophication is measured as oxygen consumption equivalents. Oxygen consumption is caused by biomass, resulted from the increase of nutrients. Separate methods have been determined, because eutrophication is limited by different nutrients in different local conditions.

Eutrophication, N-limited + NO_x emissions to air

In the N-limited method total N to water, BOD and COD emissions and NO_x emissions are taken into account (Figures 36 and 37).

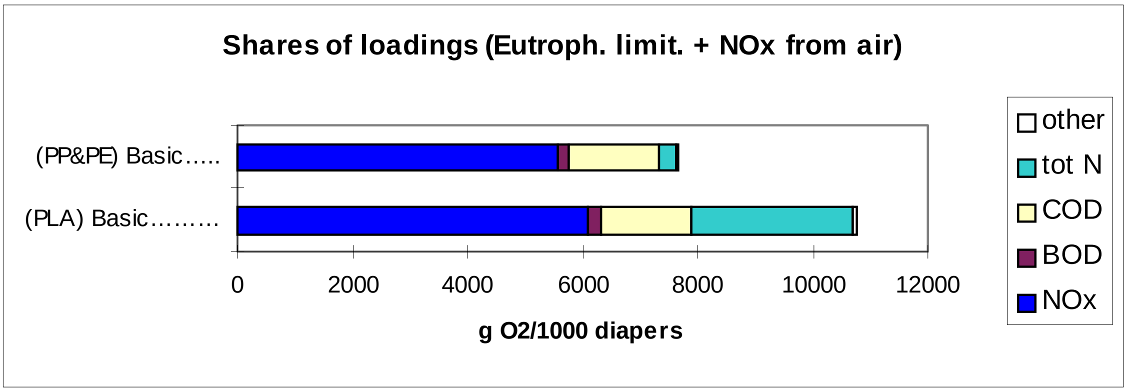


Figure 36. Eutrophication, N-limited + NO_x, shares of loadings.

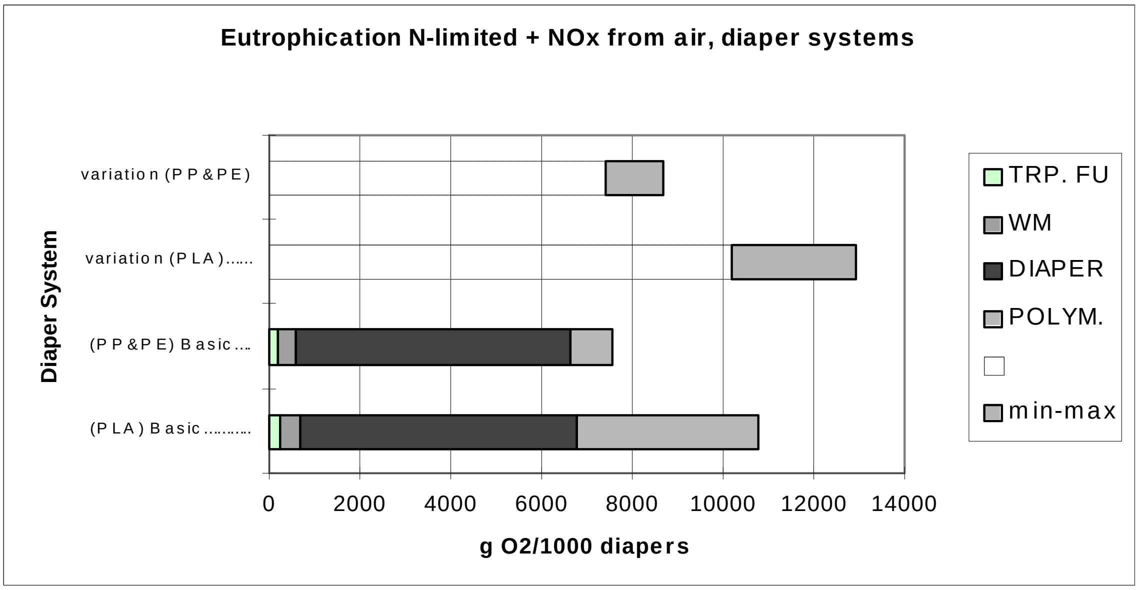


Figure 37. Eutrophication, N-limited + NO_x.

In the PLA system, the share of NO_x in the eutrophication effect is nearly 60%, COD 15%, BOD a few per cents and total N to water good 25%. In the PP & PE system the share of NO_x is good 70%, COD 20%, BOD and total N to water a few per cents each.

The shares of the ”diaper” sector in both systems, and those of agricultural production in the PLA system are the most important ones. In the high waste utilisation scenarios the ”waste management” sector is also of significance because of eutrophicative water emissions from biological treatment and NO_x emissions from waste incineration.

The difference between the biopolymer and the conventional diaper systems is from 20% to 50%, the PLA system having the higher result.

The variation in the PLA system is caused by the variation in the technology level, by energy-related emissions in varying yields and by emissions from cultivation and from transports in the PLA raw material chain. The variation in the result of the PP & PE system is caused by variations in the waste utilisation level and the technology of waste incineration.

Eutrophication, N-limited

Compared with the N-limited method discussed above, the NO_x emissions to air are not considered. Due to the N emission from cultivation the result of the PLA system is more than twice that of the PP & PE system. Eutrophicative emissions have a relatively large share in the impact in the maximum biological treatment scenario.

Eutrophication, P-limited

The P-limited method takes into account the BOD, COD and total P emissions. Differently from the N-limited methods, in the P-limited method the BOD and COD emission are more emphasised than the nutrient emission from cultivation. Thus the difference between the biopolymer and conventional diaper systems is smaller. In the high waste utilisation scenarios the difference is greater again. The result of the biopolymer system is higher due to emissions from cultivation and from biological waste treatment.

9.7 Photo-oxidant formation

The NO_x, CH_4, CO and VOC emissions contribute to photo-oxidant formation. The impacts are calculated for each emission separately. The comparison between the diaper systems studied for each emission is presented in the inventory results.

9.8 Toxicological impacts

The methods applied in this study to toxicological impact assessment are described in detail in the Nordic recommendations (Nordic Council of Ministers 1995). The *Critical Body Weight methods* are based on the acceptable or tolerable daily intake of the substances in relation to the body weight. The weighting factors for the various substances are based on the data of RIVM (the National Institute of Public Health and Environmental Protection in the Netherlands) and WMO. *The Critical Air Volume* method uses the MIK values (Maximal Immissions Konzentration). *The Critical Water Volume* method uses Swiss directives for emissions into surface water as the inverted weighting factor. Having the same approach as the critical volume methods, *Units Polluted Air* method uses Dutch MAC values (Maximum Accepted Concentration, for example occupational exposure limits). The *Units Polluted Water* method uses EU directives for drinking water standards, respectively.

9.8.1 CBWA (Critical Body Weight Air)

In the basic scenario of the PLA system, the shares of loadings for CBWA impact are Cr 30%, NO_x 20%, SO_2 good 30%, TSP 15%, V, Pb, As of the order of a few per cents. In the PP & PE system the shares of contributions are Cr 25%, SO_2 nearly 40%, NO_x nearly 30 %, TSP 5%, As, Ni, Pb, V of the order of 1 - 2% (Figures 38 and 39).

In both systems the energy and transport related emissions from the ”diaper” sector are contributing mostly to this impact. The heavy metal chromium is emitted in energy conversion from coal. TSP emissions is caused by chemicals production in the biopolymer chain. The higher result of the biopolymer system is formed in the ”sugar” and ”lactic acid” subsectors because of high energy consumption.

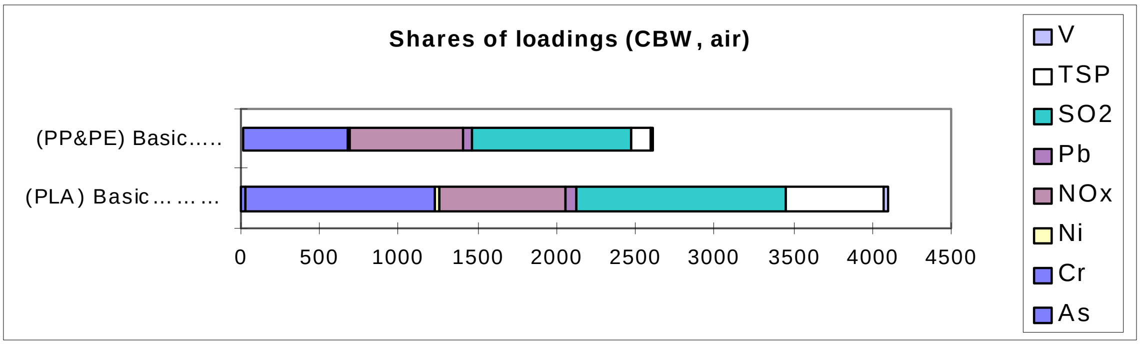


Figure 38. Critical Body Weight Air, shares of loadings.

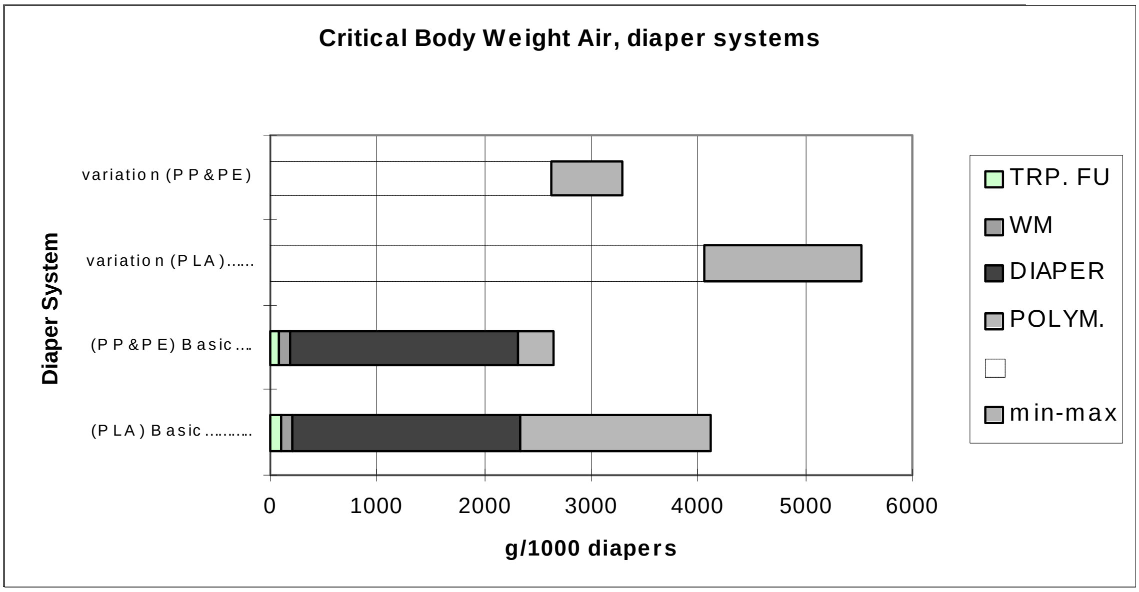


Figure 39. Critical Body Weight Air.

The variation in the PLA system results is caused by the variation in the technology level and accordingly in the energy-related emissions. In the PP & PE system results the variation is according to the waste utilisation scenario and the emissions from waste incineration.

Units Polluted Air, Critical Air Volume

The primary contributions to the results of the Units Polluted Air and Critical Air Volume methods for both diaper systems are SO_2 and NO_x, about half each. In addition, in the PLA system the contribution of TSP is nearly 10%.

9.8.2 CBWW (Critical Body Weight, Water)

In the PLA system, nitrate emissions from cultivation are the most important ones in the CBWW impact, around 50%, then heavy metals Hg 20%, Cd, Mo, about 10%, As and Fe slightly less, cyanides a few per cents. In the PP & PE systems, the shares of heavy metals As is 10%, Cd 20%, Mo good 30%, Fe good 10%, total N 15%, cyanides 5% (Figures 40 and 41).

The significantly higher result for the biopolymer diaper system compared to that for the conventional system is mainly due to nitrate emissions from plant cultivation. The variation in the results for the PLA system is caused by varying raw materials and by varying yields and emissions from cultivation.

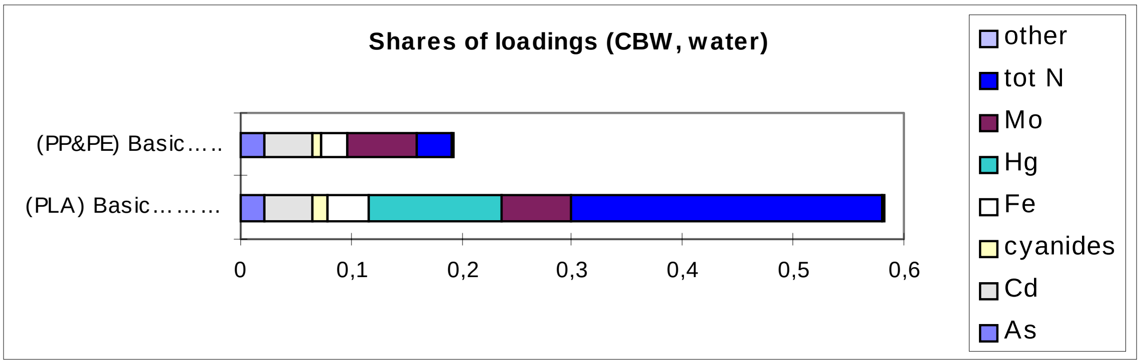


Figure 40. Critical Body Weight Water, shares of loadings.

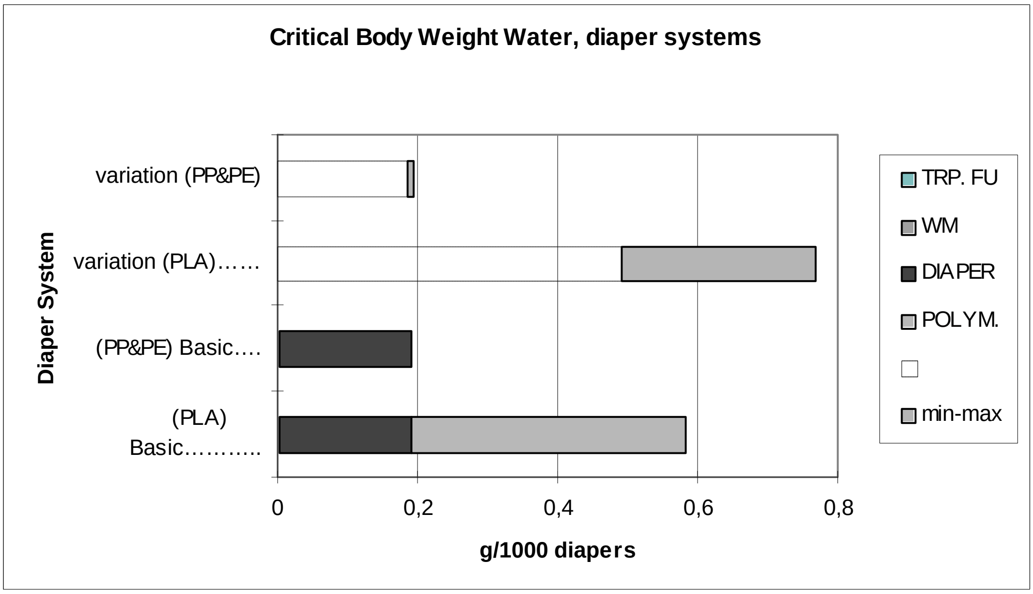


Figure 41. Critical Body Weight, Water.

9.8.3 UPW (Units Polluted Water)

In the PLA system the share of oils and greases is nearly 60%, total N to water is nearly 20%, Hg 10%, Fe a few per cents, and P a few percents in the UPW impact. The oils and greases are formed in the oil fuel chain and in oil distribution, the nitrate emissions are from cultivation (Figures 42 and 43).

Oil consumption is higher in the PP & PE system than in the PLA system but the emissions of oils and greases are considerably lower. An explanation is that there are differences in the oil raw material chains for different purposes (for plastic raw material or for transport fuel). Situation in the oil distribution chain has probably been changed in the recent years and it could be that the emissions in the PLA system are too high because of some outdated data. The difference between the systems is presumably smaller than the result presented here.

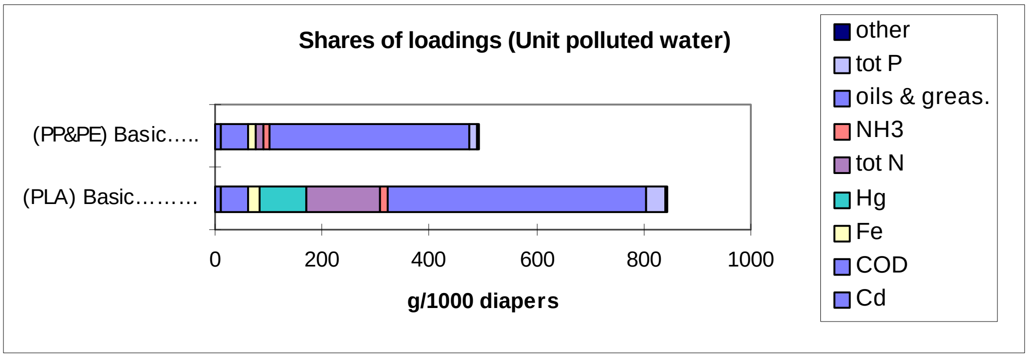


Figure 42. Units Polluted Water, shares of loadings.

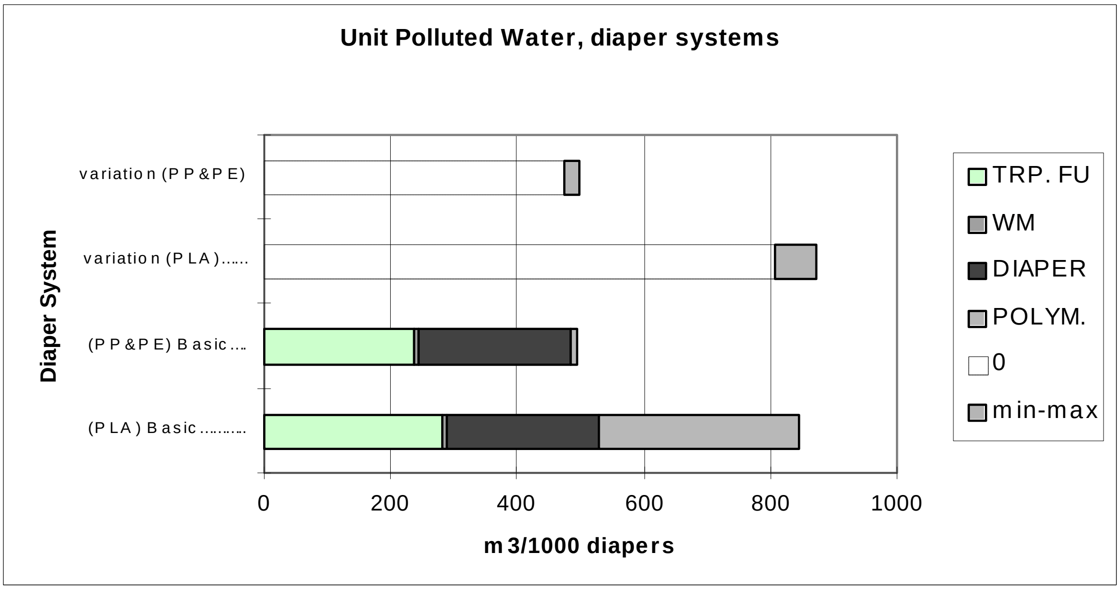


Figure 43. Units Polluted Water.

9.8.4 Critical Water Volume

In the results calculated with the Critical Water Volume method the main contribution is from COD, total N and from BOD emission. The results of the PLA system is bigger because of the nitrogen emissions from plant cultivation.

9.8.5 Other impacts

Some impacts, not yet evaluable with the available impact assessment methods for the results of the diaper systems to be easily comparable, are briefly discussed in the following.

Land use

In the diaper systems remarkable areas of land could be assumed to be occupied by cultivation, forestry, oil production and waste management.

Calculation of land use in relation to functional unit is not very simple. For example, how to take into account the time frame of the use and to estimate the total output flow per specific area of land. Comparing the area of land used for different purposes would also cause problems. The environmental impacts differ strongly in different uses. It should also be considered, how long it takes until the area occupied is returned to the original, natural condition. In this study the calculations made as an example for the basic scenarios of the diaper systems are presented in Table 11.

Table 11. Land use in diaper systems.

Process	Diaper with PLA (ha*a/1 000 diapers)	Diaper with PP & PE (ha*a/ 1 000 diapers)	Remarks
Cultivation (for PLA plastic)	0.022	-	Yields vary according to region and year
Oil production (for PP&PE plastic)	-	0.0001	Comprises different uses: time of use 5 - 50 a, quality and impacts of use vary (Bakkane 1994, Frischknect et al. 1994).
Forestry (for fluff pulp, packaging)	0.0380	0.0380	Based on new wood material production per ha per a. (Nylander & Parming Vass1993, Sandgren 1993) *
Incineration	0.0002	0.0002	Based on yearly waste throughput and estimated time of use, 50 a
Biological treatment	0	0	No biological treatment in basic scenario.
Landfilling	0.0002	0.0002	Based on yearly incoming waste

* *Could also be based on the area needed for harvesting.*

Water use

Water use can lead to an important impact in certain regions. Especially in agricultural production large water volumes are used, and ground water may be used for irrigation. In some regions ground water is also used for household water and in industry.

Biodiversity

Methods for biodiversity assessment are not yet available. Such methods would require, e.g., ecological risk assessment, incorporation of time functions, etc.

Other toxicological impacts

The emissions, e.g., from pesticide residues, waste incineration and chemical industry (PCBs, PAHs, dioxins…) are not yet sufficiently known to be used for impact assessment.

10. Demonstration of valuation methods

In the valuation the relative importance of different environmental impacts are weighted against each other. In the following, valuation is demonstrated using seven different valuation methods. There is a brief overview enclosed to each method. It should be emphasised that the valuation methods are still under development. It is also important to bear in mind the fact that the valuation methods are based on subjective judgements and, hence, the choice of the valuation method always affects the results.

10.1 EPS

In the EPS (Environmental Priority Strategies in product design) system five safeguard objects are valued. The objects are biodiversity, production, human health, resources and aesthetic values. The valuation of the objects is based on the willingness to pay for restoring them to their normal status. Emissions, use of resources and other human activities are then valued according to their estimated contribution to the changes in the safeguard objects. The environmental indexes are expressed as ELU (Environmental Load Units) per kg. One ELU is equal to approximately one ECU (Figures 44 and 45).

In the basic scenarios of both systems, the greatest contribution to the EPS valuation result is caused by crude oil consumption. The next ones are the use of land for cultivation and forestry and the CO_2 emission. The consumption of coal and natural gas and the CH_4 emissions also cause significant contributions.

The more than 10% higher result of the PLA system in the basic scenario is caused by a higher energy consumption and related fossil fuel consumption and land use in the plastic chain. The difference in the systems decreases in higher waste utilisation scenarios, and in the allocation scenarios the difference is less than 10%.

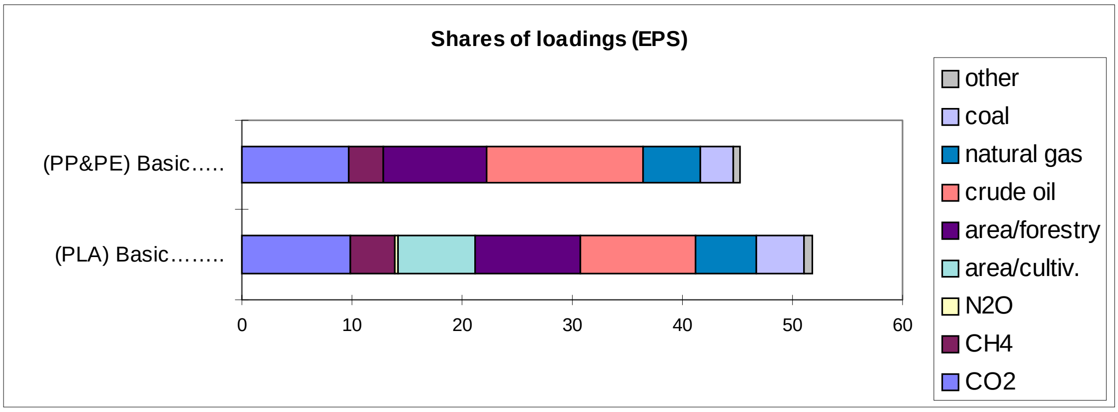


Figure 44. Shares of loading (EPS). Note: All the sectors listed in the figure (left side) are not visible in the columns, if the share in the column is negligible.

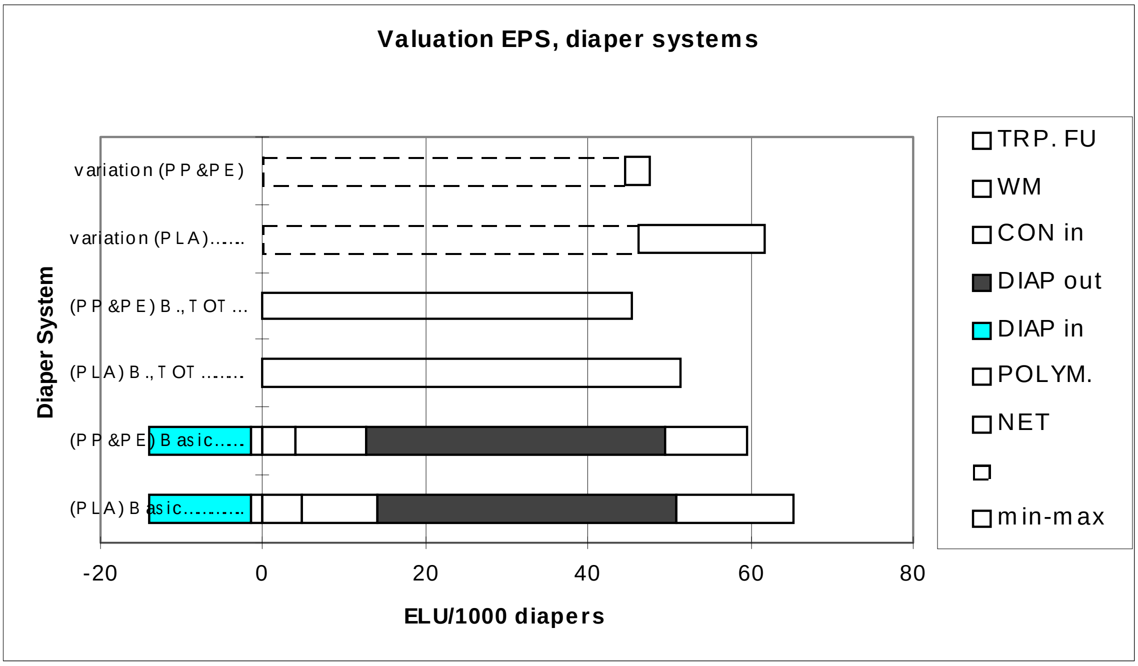


Figure 45. EPS valuation, diaper systems.

10.2 Ecoscarcity

Ecoscarcity in Swiss conditions

In the Ecoscarcity method the different emissions are weighted against each other directly using ecofactors (Figures 46 and 47). Ecofactors for each emission are calculated by dividing the actual flow of emission by the critical flow. The critical flow is evaluated from the annual load limits for a certain area, which are set by Swiss national environmental protection laws and regulations. The actual flow is the total annual amount of emissions in the area. The unit of environmental index is ecopoint (EPO).

The main contribution to the valuation result in the basic scenarios of both comparable systems comes from NO_x emissions and landfill waste, about 30% from each, the next one being SO_2 emission.

In the case of basic scenarios the result of the PLA system is 10% higher. The difference is due to higher energy consumption and transports in the plastic production chain. In the high waste utilisation scenario the difference is decreased, because less landfill waste remains in the PLA system. In this scenario the position of the PP & PE system depends on emissions from waste incineration. In the allocation scenarios the results of the compared systems are on the same level.

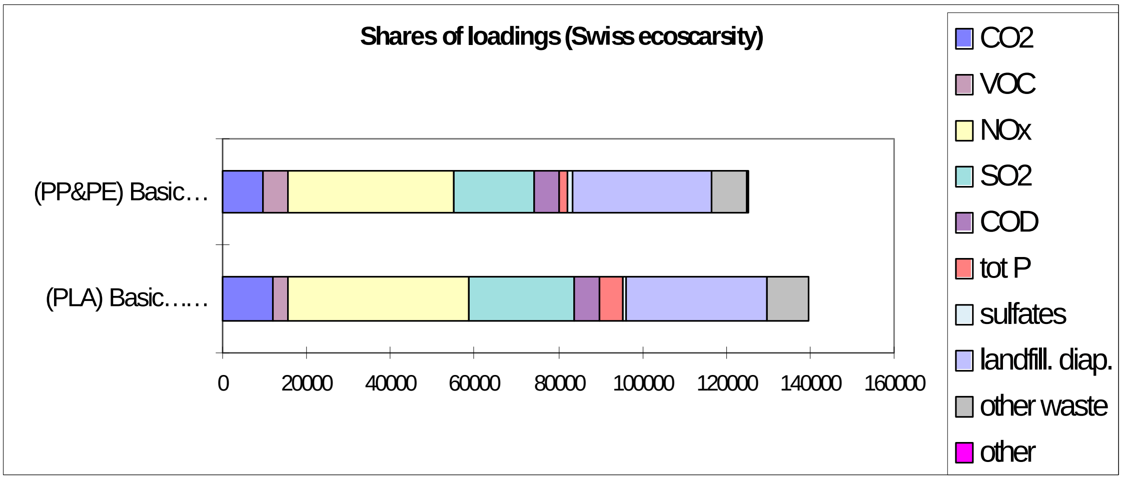


Figure 46. Swiss ecoscarcity valuation, shares of loadings.

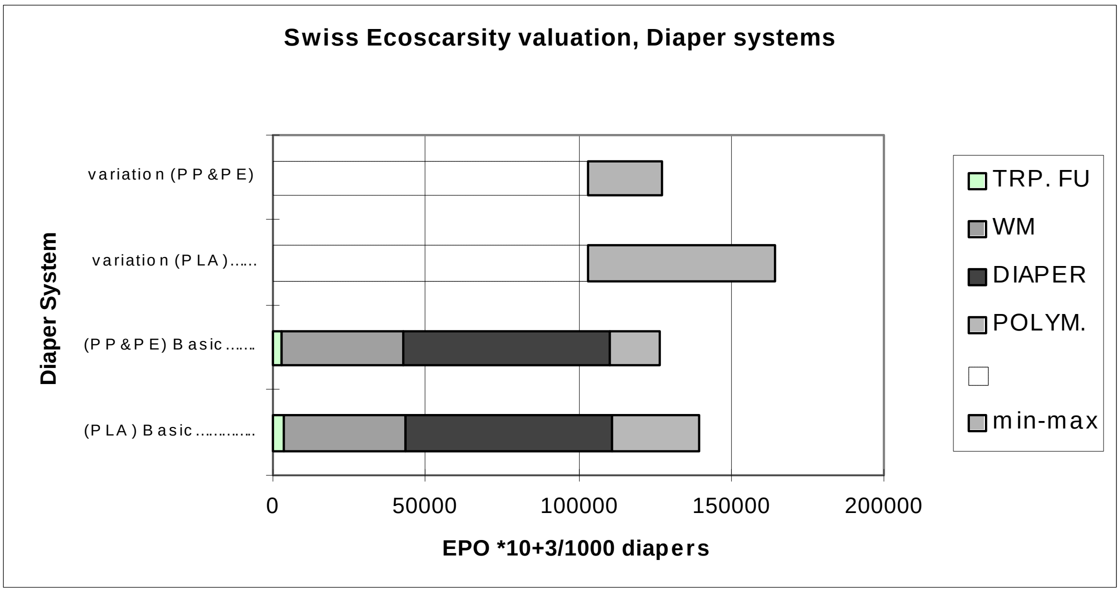


Figure 47. Swiss Ecoscarcity valuation, diaper systems.

10.3 Effect category

In the characterisation step of Effect Category method the environmental loads are grouped into effect categories, i.e., selected environmental themes (Figures 48 and 49). The result per theme is normalised by dividing with the corresponding total pollution of the same theme within the geographical area relevant to the study. The impact fractions of several themes may be summarised after applying weighting factors for environmental themes. This weighting is based on Swedish short and long term political goals.

Effect category, long term

The main contribution for the valuation result in both systems comes from oil emissions caused in the oil fuel production chain. The next ones are CO_2, CH_4, NO_x and SO_2. VOC emission also have significant shares, especially in the PP & PE system.

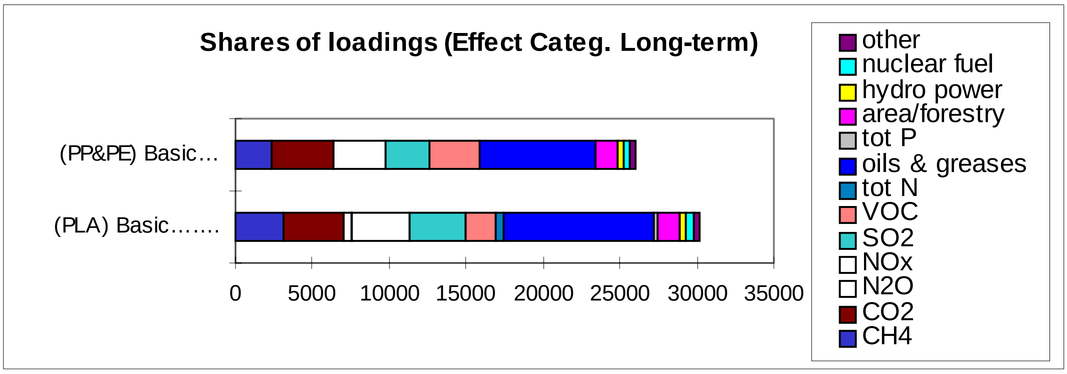


Figure 48. Effect Category, long-term, shares of loadings.

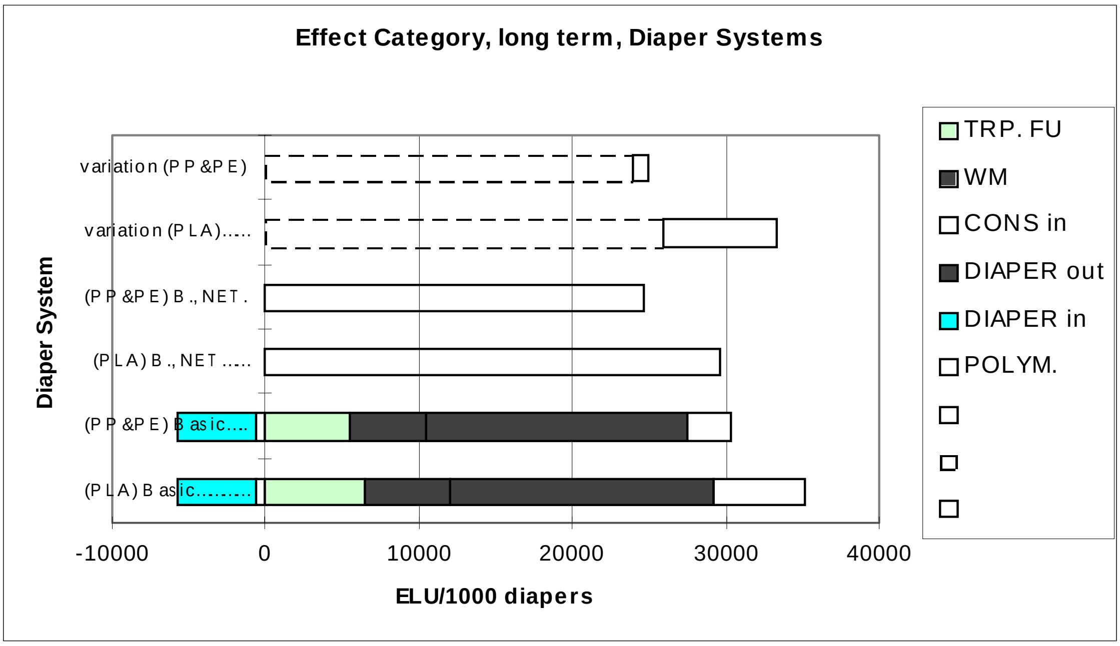


Figure 49. Effect Category, long-term, diaper systems.

The higher result for the biopolymer diaper system compared to that of the conventional system is caused by the higher energy consumption (based on oil-based fuels) and higher transportation demand. The difference between the systems decrease in the high waste utilisation and allocation scenarios, when the methane production is lowered and also conventional diapers are degraded to CO_2.

10.4 Tellus

The valuation system is based on the control costs of a number of air pollutants, such as CO, NO_x, particles, SO_x and VOC (Figures 50 and 51). The valuation of greenhouse gases is based on the costs of afforestation for a carbon "sink". For the valuation the hazardous substances are ranked on the base of health risk factors (US Council for Environmental Quality). The units of environmental indices are in USD. The valuation result is mainly affected by CO_2 emissions. SO_2 and NO_x also have significant shares as well as TSP emission in the PLA system.

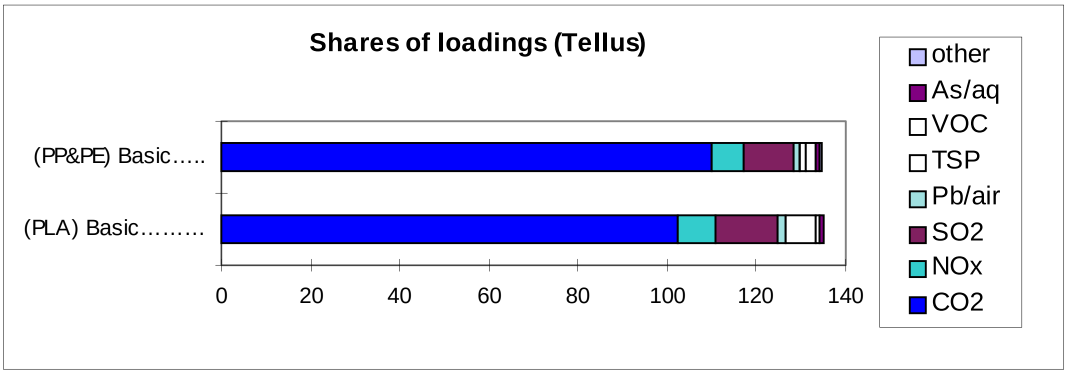


Figure 50. Shares of loadings (Tellus).

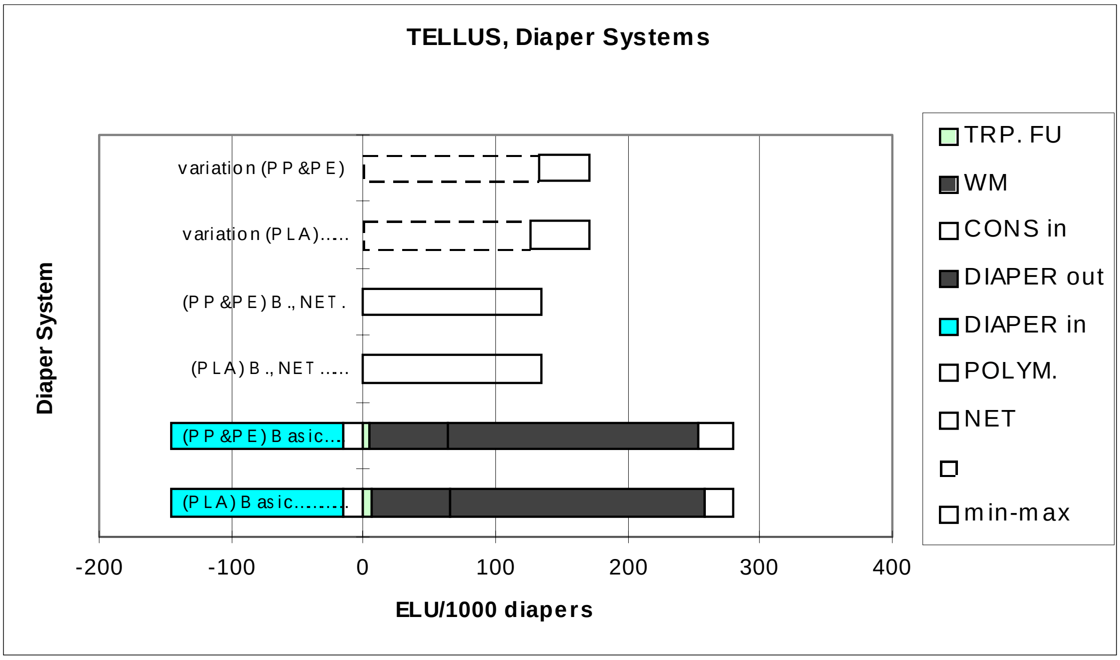


Figure 51. Tellus, diaper systems.

The results of the biopolymer and traditional diaper systems are on the same level.

11. Uncertainty considerations

When drawing conclusions of the environmental impacts of biopolymer and traditional plastic on the basis of this study, the following issues regarding the uncertainty of the results need to be taken into account:

1. The general quality of the data used (discussed in chapter 6).

2. For the uncertainty of the data and the methodology applied for the inventory analysis of the conventional plastics polypropylene and polyethylene APME's latest report on polystyrene (APME 1997) is referred to. The data for PP and PE is discussed in chapter 6.1.

3. In the PLA production chain, from crops to polymer, the technologies and the process data vary relatively much.

4. In agricultural production the yields, energy consumption, use of nutrients, and especially nitrogen emissions released from the fields differ by region and year. Furthermore, the impacts on the environment differ depending on environmental conditions.

5. In the raw material chain of the bioplastic up to lactide the technologies vary by plants, affecting especially the total energy consumption. Fermentation of lactic acid is still a process under development. In sugar production, e.g., relatively complex systems of starch refining, comprising several products, make it difficult to collect and calculate data for a specific product.

6. In the systems compared there are some inconsistencies in calculating hydrocarbon emissions to air and water in the fossil raw material chain. In APME's data, used for conventional plastic, no emissions have been calculated for the oil transportation phase. In the PLA system, also due to some out-dated data on the oil fuel chain, these emissions caused in the transportation phase are probably too high.

7. The share of used diapers ending up in each waste treatment process depends on the pattern of waste management in the region.

8. The data on waste treatment processes are for average household, or municipal organic waste. Data could be matched in particular for diaper products only in case of carbon-related emissions (CO_2 and CH_4). A diaper could, e.g., be assumed to contain very little heavy metals compared to mixed waste.

9. How much energy can be recovered in waste treatment processes depends on the applied technology. Utilisation of the produced energy is limited by the local demand. Compensating the electricity demand of the system with the energy recov-

ered in waste treatment affects the results to some extent as can be seen in the allocation scenarios.

10. Everything could not be included in the calculations. For example, data on some chemicals used in the biopolymer chain were not available. Qualitative information was collected about the fillers used in biopolymers. The rates of product flows not followed until the environment are presented in chapter 4.

11. There are also impacts other than those demonstrated here, such as impacts of water consumption, impacts on biodiversity and toxicological impacts caused, by pesticides that could not be evaluated at a satisfactory level or at all due to the complexity of the problem and the lack of data.

12. For example, the land use for different purposes, for cultivation, forestry, oil production, land filling, etc., is difficult to assess in such a way that the different uses would be comparable. I.a., the time span of use, the condition of the land after use as well as the value of land use should be considered. Calculating the area used per functional unit is not simple. Anyhow, according to some examination the land use of oil production seems to be fairly negligible compared to that used for cultivation (in the biopolymer system) and forestry (in both systems).

13. For the reasons presented above the uncertainties related to the PLA system are obviously greater than those of the conventional plastic. Many open questions still remain.

12. Discussion and conclusions

12.1 Comparison of products made of bioplastic and conventional plastic

A scenario analysis was used in comparing the diaper systems (Figure 52). The utilised technologies were

- sugar, lactic acid and polymer production,
- oil production and traditional plastic production
- biological, thermal, or landfill treatment of waste,

and served as parameters for the different scenarios. Also the levels of these technologies, which vary from poor to the best available technology (BAT) were used as parameters. The general technology level is affected by the means of energy production, such as the fuel used, the share of combined heat and power production as well as by the ratios of heat and power.

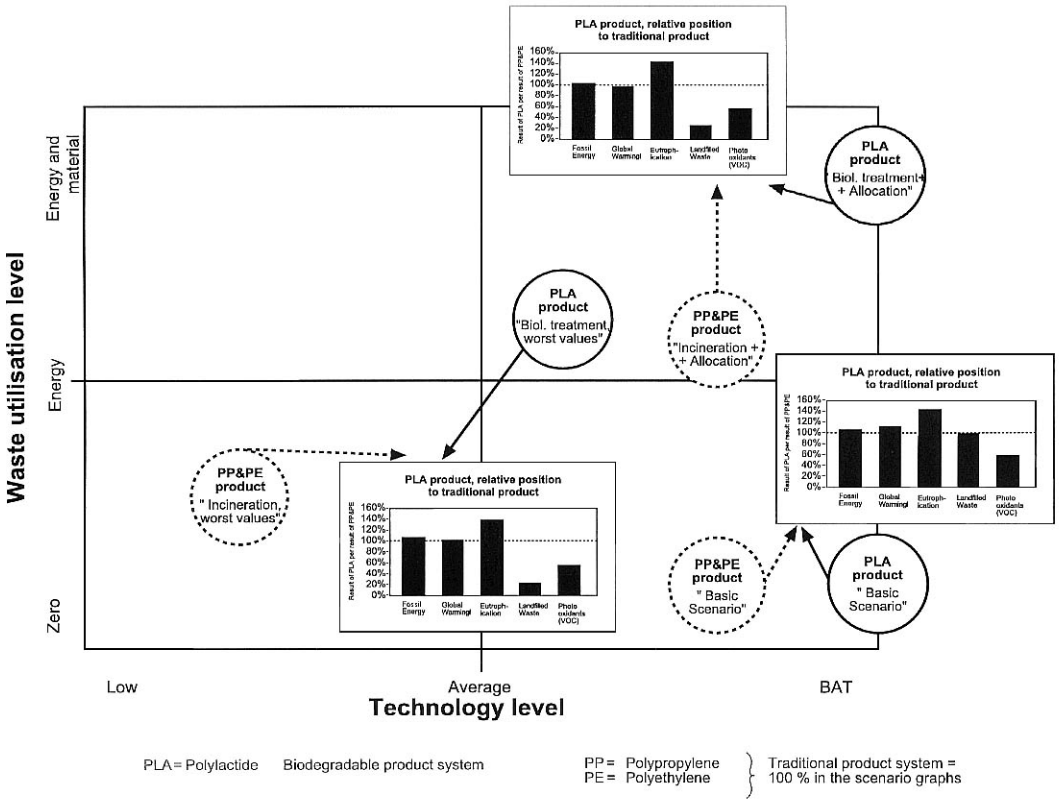


Figure 52. Comparing environmental impacts of biodegradable and traditional diaper systems, a scenario analysis.

The levels of waste utilisation were scenario parameters too. In the scenario with the highest utilisation level, the products from waste treatment replace some demands for inputs to the system. The share of loadings was allocated to the by-products from the plastic production chain.

The Figure 52 “Comparing the Environmental Impacts of Biodegradable and Traditional Diaper Systems, A Scenario Analysis” illustrates the relative environmental loadings in some scenarios.

In the environmental impacts of the bioplastic over the life cycle, the most important phases are the agricultural production of raw materials and the fermentation of lactic acid (eutrophicative emissions and energy consumption). Appropriate waste treatment produces compost products and decreases the amount of waste to landfill.

The use of fossil sources as raw materials for conventional plastic results in hydrocarbon emissions to air and water. For these plastic incineration or landfilling are the only possible waste treatment methods.

The advantages of a biodegradable product appear in the potential use of annually renewable resources and in the waste management phase, where landfill area can be saved.

12.2 Key findings

The most important outcome of the study is the small differences between the impacts of the conventional and the biodegradable diaper systems. For most environmental loading agents, the fluff part (70%) of the diaper product turned out to be dominant. In most scenarios the polyolefin-based diaper is slightly better, but the results are not far from each other.

In the environmental impacts of the polylactide-based plastic over the life cycle important phases are the agricultural production of the raw materials and the fermentation of lactic acid (eutrophicative emissions and energy consumption). The impacts of cultivation are largely dependent on geographical factors (soil quality, cultivation practices, background concentrations), etc. Furthermore, political aspects related to agricultural production also play an important role.

The fermentation process, although conventional, is still under development. At the moment, the process is not well appropriate for bulk products. The fermentation of lactic acid on commercial scale is still a batch process. A lot of energy is consumed in keeping the temperature and in pumping dilute liquids and solids. Research on continuous fermentation processes is going on in several countries. The development of more efficient bacterial strains will enable a higher concentration and yield, which will decrease the consumption of energy and water.

Appropriate waste treatments for biodegradable products are controlled aerobic or anaerobic processes, which have lately been under active development. A well-implemented process can produce compost products for use as fertilisers, thus reducing the amount of waste to landfill. In anaerobic processes the generated methane gas can be utilised for energy production. Biological treatment produces eutrophicative water emissions, which have to be treated.

When conventional plastics made from fossil raw materials are compared to biopolymers, the most important impacts are the hydrocarbon emissions to air and water. Most of these emissions originate in the polymerisation processes. These emissions are slowly decreasing, as more sophisticated collection systems of hydrocarbon emissions are implemented.

Two waste treatments possible for polyolefin products are incineration and landfilling. Landfilling requires space but incineration may result in harmful emissions, especially if hazardous materials end up in the waste fractions, which according to the recent reports seems to be the case. On the other hand, decisions concerning waste treatment are also political.

The advantages of a biodegradable product lie in the potential use of annually renewable resources and in the waste management phase, when landfill space can be saved. Land area is required for the primary production, however.

The results vary greatly among the scenarios. Obviously, the uncertainties related to the PLA system are essential. Many options and questions still remain open.

These two systems cannot be compared without emphasising the differences in technology levels: Conventional plastic manufacturing, from oil production to polymerisation, is a mature business, in which all the processes are smooth and refined. The production of biodegradable polymers is still young with several stages in a pre-commercial phase. Large-scale cultivation and fermentation may change, and the monomer and polymer production processes for biopolymers will be further developed. Even minor changes in the technology level may strongly affect the environmental impact of the system.

When using an LCA method to study the environmental impacts of a complex product with several components and several options, there will be no simple answers. However, LCA helps to start and feed a thinking process in considering, which issues are important.

12.3 Remarks from the viewpoint of product development

When this project was started the aim was to evaluate a product developed by Neste, polylactide, but another target was also to develop a tool for use by other projects inside Neste Oy and Tekes Programme. The bar was raised high, the persons involved at Neste had to learn to understand life cycle thinking to be able to deliver the right figures for the inventory. But, as it has been said by several people of different companies, to start an LCA project when you are a novice in the field is to start a learning process, and without this process you will never reach your goal. Now some goals have been reached, but not all.

One of the targets was to create a tool suited for R & D and product and process development. For process development a simplified LCA, or a gate-to-gate LCA for internal use, could give enough information. However, it soon became clear that for a particular product much more had to be done. The biopolymer introduces raw materials totally new and different for the company, and thus it was seen essential to clarify the production chain preceding the company's own processes. As the most important property of the polymer, biodegradability, can be utilised only in highly developed waste treatment systems, this part needed to be investigated, too.

The choice of product was much discussed. A product was wanted in which the benefit of biodegradability would be clear, but also a product in which the higher price of the biopolymer would not affect the total product price too much. The comparison to polyolefins seemed natural as polylactide can be processed on the same lines as polyethylene and polypropylene. A baby diaper seemed a good choice, as all components of the conventional diaper are well studied and inventory data are available. The only fear was that the fluff part (70 %) would be too dominant, resulting in very small differences. This fear showed to be real, the difference between the two diaper systems seems very small, which perhaps will lead to discussions.

The inventory part comprises the most reliable data available, but it should always be borne in mind that several stages include processes still in their research or pilot phase, and the inventory data on these are based mostly on calculations. The company's own part, the polymerisation process, is very small with relatively low energy consumption and few emissions, even if they are studied separately in a mere plastic material chain. The inventory data on the polymerisation part is reported as a whole. It was not possible to to separate the parts of the line as a use for process development demands would have required. The process development has, however, gained a lot of the questions arisen while collecting the inventory data.

The resulting LCA study is a base for further development and pre-marketing of the biopolymer. It can also be used to study the effects of different raw materials or geographical areas used for agricultural production. It is not ready to be used as a tool, but a lot of knowledge has been gathered about renewable raw materials and biochemical processes that can be utilised by other projects.

References

APME 1993. Eco-profiles of the European Plastic Industry, Report 3: Polyethylene and Polypropylene, May 1993, Dr. I. Boustead.

APME 1997. Eco-profiles of the European Plastic Industry, Report 4: Polystyrene. 2nd Ed., April. Dr. I. Boustead.

Audsley, X.X. ...et al. 1996. Harmonisation of environmental life-cycle assessment for agriculture. Report of Concerted Action AIR3-CT94-2028. Brussels: European Commission DG VI Agriculture.

Bakkane, K. K. 1994. Life cycle data for Norwegian oil and gas.: TAPIR Publishers.

Bockman, O., Kaarstad, O., Lie, O. and Richards, I. 1990. Agriculture and fertilizers. Agricultural Group, Norsk Hydro a.s. Oslo, Norway. Drammen, Norway : Tangen Grafiske Senter.

Brouwer, F. M., Godeschalk, F. E., Hellegers, P. J. G. J. and Kelholt, H. J. 1995. Mineral balances at farm level in the European Union. The Hague : Agricultural Economics Research Institute (LEI-DLO). 141 p.

CEC 1985. The Commission of the European Community: Liquid Food Container Directive.

Frischknecht, R., Hofstetter, P., Knoepfel, I., Dones, R. and Zollinger, E. 1994. Ökoinventare für Energiesysteme. Zürich: ETH Eidgenössische Technische Hochschule.

Gronow and Pento, T. 1996. Life cycle inventories and joined material projections in national environmental planning. Jyväskylä. University of Jyväskylä, Dept. of Economics and Management.

Koch, T. C., Seeberger, J., and Petrik, H. 1991. Ökologische Müllververtung. Bad Dürkheim: Stiftung Ökologie und Landbau. 414 p.

Lindfors, L-G., Christiansen, K., Virtanen, Y., Junttila, V., Hanssen, O-J., Ronning, A., Ekvall, T., and Finnveden, G., 1995. Nordic Guidelines on Life-Cycle Assessment, Nordic Council of Ministers, Copenhagen 1995. Nord 1995:20. 222 p.

Linden, E. 1993. Megacities. Time, no. 2.

Meadows, D. H., Meadows, D. L., Randers, J. and Behrens, W. W. 1972. The limits to growth. New York: Universe Books. A Potomac Associate Book.

Mesarovic, M. D. and Pestel, E. 1974. Mankind at the turning point. New York: Dutton.

Muesken, J. and Bidlingmeier, W. 1994. Vergärung und Kompostierung von Bioabfällen - Methodenvergleich. Karlsruhe: LFU. 142 p.

Nylander, G. and Parming Vass, A. M. 1993. Disposable diapers - cloth diapers a comparison. Stockholm : STFI. 75 p.

OWS. 1995. The Salzburg plant: A case study for the biomethanisation of biowaste. Biological Waste. In First International Symposium, Biological Waste Management " A Wasted Chance", April 1995. University of Essen.

Palonen, J. and Oksanen, E. 1993. Labour, machinery and energy data bases in plant production. Helsinki: Työtehoseura. 106 p. (Työtehoseuran julkaisuja 330.)

Potts, J.E. 1984. Plastics, environmental degrable. Kirk-Othmer Encyclopedia of Chemical Tehcnology, Supplement volume, 3rd edition, John Wiley & Sons. Pp. 626 - 668.

Reimann, D. O. and Hämmerli, H. 1995. Verbrennungstechnik für Abfall. Bamberg: Schriftenreihe Umweltschutz). 247 p.

Rekolainen, S. and Pitkänen, H. 1995. Nitrogen and phosphorus fluxes from Finnish agricultural areas to the Baltic Sea. Helsinki : Water and Environment Research Institute. In Nordic Hydrology, 26, 1995, p. 55 - 72.

Sandgren, J. 1993. Screening life cycle assessment for comparison of cloth and disposable diapers used in Norway. Oslo: Det Norske Veritas Industri Norge AS. (Report No. 93-3329.) 68 p.

SETAC 1993. Guidelines for Life-Cycle Assessment: A "Code of Practise". Society of Environmental Toxicology and Chemistry.

Sundqvist, J.-O., Albertsson, A-C, Berendson, J., Eriksson, E., Finnveden, G., Höglund, L. O. and Karlsson, S. 1993. Life Cycle assessment and Solid Waste. Research report. Stockholm: IVL. 107 p.

United Nations. 1993. Environment Program. Environmental Data Report 1993 - 1994. Oxford: Blackwell.

United Nations. 1995. Population Division. World urbanization prospects: The 1994 revisions. New York: United Nations.

Verschut, C. and Brethouwer, T.D. 1993. Composting of a mixture of VGF waste and used diapers. TNO- Report, ref. 94-130. Apeldoorn, The Netherlands : TNO Institute of Environmental and Energy Technology. 40 p.

World Bank. 1992. World development report. Washington: The World Bank.

World Resource Institute. 1997. World Resources 1996 - 97. WRI.

Additional literature on the subject

Aguiló. 1990. Acetic acid. Ullmann's Encyclopedia of Industrial Chemistry. Vol. A 1. Weinheim: Ullmann. Pp. 45 - 56.

Buchholz, E. 1990. Polyacrylamides and poly(acrylic) acids. Ullmann's Encyclopedia of Industrial Chemistry. Vol. A 21. Weinheim: Ullmann. Pp. 143 - 154.

Chahal, S. P. 1990. Lactic acid. Ullmann's Encyclopedia of Industrial Chemistry. Vol. A 15. Weinheim: Ullmann. Pp. 97 - 105.

Dahlbo, H. 1994. Kiinteän yhdyskuntajätteen metallivirrat (Metal flows of solid municipal waste). Helsinki: Board of Waters and the Environment. 93 p. (Publications - Series A.) (In Finnish)

Dekker, M. 1988. Lactic Acid. In: Encyclopedia of Chemical Processing and Design. Vol. 28.

EDANA 1996. Diapers Health Benefits and Environmental Aspects. Brussels : European Disposables and Nonwovens Association. 16 p.

Eggels, P. and Ven, B. van 1995. Allocation model for landfill. In: Proc. International Workshop on LCA and Treatment of Solid Waste. AFR-report 98, November 1996. Stockholm : Swedish Environmental Protection Agency.

FAO 1994. Yearbook. Vol 47. Production. Rome FAO

Fiedler, E., Grossmann, G., Kersebohm, B., Weiss, G. and Witte, C. 1990. Methanol. Ullmann's Encyclopedia of Industrial Chemistry. Vol. A 16, Weinheim: Ullmann, pp. 465 - 484.

Franke, M. 1991. Environmental Aspects of Baby Diapers - Research Projects and Future Considerations. Procter & Gamble GmbH. In ”2. Kasseler Abfallforum” April, 1991. Conference on Biowaste Composting, University Kassel.

Haug, R. 1993. The practical handbook of compost engineering. Boca Raton (FL), Lewis.

Heinonen, R . 1992. Maa, viljely ja ympäristö. Porvoo: WSOY.

IEA 1995. Combustion. A Vital Bioenergy Technology for the 21st Century. July 1995. Harwell, United Kingdom: ETSU.

ISO. 1996. Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis. Paris: ISO. (ISO/CD 14 041.4. AFNOR.)

Juuti M. 1995. Sokerijuurikas ja sen perustuotteiden ekotase. Helsinki: Cultor. 86 p.

Järvenpää, M. 1994. Bioenergiantuotanto elintarviketuotannosta vapautuvalla peltoalalla. Helsinki: Työtehoseura. 109 p.

Lenz, R. W. 1993. Biodegradable Polymers. In: Advances in Polymer Science, Vol. 107.

Lindfors, L-G., Christiansen, K., Virtanen, Y., Junttila, V., Hanssen, O-J., Ronning, A., Ekvall, T. and Finnveden, G. 1995. Nordic guidelines on life-cycle assessment. Copenhagen: Nordic Council of Ministers. Nord 1995:20. 222 p.

Maatalousalan tiedotuskeskus. 1994. Euro-Vakka. Numerotietoa läntisen Euroopan maataloudesta. Helsinki: Maatalousalan tiedotuskeskus.

Mälkki, H., Hakala, S., Virtanen, Y. and Leppänen, A. 1995. Life cycle assessment of environmental impacts of Finnish beverage packaging systems. 60 p. Helsinki: Pakkausteknologiaryhmä r.y. (Report no. 43.)

Manahan, S. E. 1994. Environmental chemistry. 6th edition. Boca Raton, Florida : CRC Press. 811 p.

Manninen, H., Peltola, K., Järvi-Kääriäinen, T. and Leppänen, A. 1994. Pakkausten energiahyötykäyttö. Helsinki: Pakkausteknologiaryhmä r.y. 24 p. (Report no. 39.)

Müll und Abfall. 1995. No. 8/95, p. 577, 3/95, pp. 149 -, 4/95, pp. 217 -.

Myllymäki, O., Ahvenainen, R., Sipiläinen-Malm, T. and Poutanen, K. 1993. Tärkkelys biohajoavien elintarvikepakkausmateriaalien raaka-aineena. Kirjallisuuskatsaus. (Starch as raw material of biodegradable foodstuff packaging materials. Literature review). VTT: Espoo. 61 p. (VTT Research Notes 1466.)

Mölnlycke. 1993. Vaippakoulu. Helsinki : Martinpaino Oy.

Obermeier, T., Jager, J. Franke, M., Jager, E. and Rueden H. (1991) Co-composting of Diapers and Biowaste Using the Box-Composting and Rotating Drum Process. Procter & Gamble GmbH. In ”2. Kasseler Abfallforum” April, 1991. Conference on Biowaste Composting, University of Kassel.

Ohara, T., Sato, T., Shimizu, N., Prescher, G., Schwind, H., Weiberg, O. and Marten K. 1990. Acrylic acid and derivatives. In: Ullmann's Encyclopedia of Industrial Chemistry. Vol. A 1. Weinheim: Ullmann. Pp. 161 - 174.

Patyk, A. 1996. Balance of energy consumption and emissions of fertilizer production and supply. International Conference on Application of Life Cycle Assessment in Agriculture, Food and Non-Food Agro-Industry and Forestry : Achievements and Prospects. Brussels : VITO Vlaamse Instelling voor Technologisch Onderzoek. Pp 47 - 68.

Penzel, E. 1990. Polyacrylates. Ullmann's Encyclopedia of Industrial Chemistry. Vol. A 21. Weinheim: Ullmann. Pp. 157 - 175.

Rekolainen, S., Ekholm, P. Ulén, B. and Gustafson, A 1995. Phosphorus losses from agriculture in northern Europe. Helsinki. Finnish Environment Agency.

Pipatti, R., Hänninen, K., Vesterinen, R., Wihersaari, M. and Savolainen, I. 1996. Jätteiden käsittelyvaihtoehtojen vaikutus kasvihuonepäästöihin. (Effect of waste handling altrnatives on greenhouse emissions.). Espoo: VTT. (VTT Publications 811). (In Finnish).

Poutanen, H. 1992. Metallien virrat yhdyskuntajätehuollossa. (Metal flows in municipal waste management.). 3rd Research Seminar on Waste Management. Espoo: Helsinki University of Technology. (In Finnish)

Reini, J. 1992. Biodegradable plastic. Options for the future. Helsinki: Tekes. (Reports of Scientific Councellors).

Rogalski, W. and Charlton, J. 1995. Status and trends for biological treatment of organic waste in Europe. Vienna : ISWA Austria.

Ronkainen, M. 1995. Poly-L-laktidikalvojen valmistus ja ominaisuudet. (Production and properties of poly-L lactide films). Diploma work. Tampere: Tampere University of Technology. (In Finnish). Materiaalitekniikan osasto/Muovitekniikka. 104 p.

Scherer, ? 1995. Aktuelle Marktübersicht zur Vergärungsanlagen für feste Abfälle - Vorteile gegenüber Kompostierungsanalgen. In Müll und Abfall 12/95. Pp. 845 - 856.

Schroeter, J. 1995. Establishing material cycles for biodegradable plastic. Annual Seminar on Biodegradable Polymers, Raisio 21 Sept. 1995. 5 p.

Seeberg, A., Schneider, U., Kuehn, B., Rohmer, G., Chilian, U., Ruedel, A., Hense, H., Bartsch, U., Basanes, Y., Dehoust, G., Both, G., Jenseit, W., Petitjean, T., Rausch, L., Gebhardt, P. and Jager, J. 1994. Systemvergleich Restabfallbehandlung. Dieburg/Darmstadt: ITU GmbH und Öko-Institut. 129 p.

Senior, E. 1990. Microbiology of landfill sites. Boca Raton, Florida : CRC Press, Inc.

Sleeswijk, A. 1996. LCA of Agricultural Products. International Conference on Application of Life Cycle Assessment in Agriculture, Food and Non-Food Agro-Industry and Forestry : Achievements and Prospects. Brussels : VITO Vlaamse Instelling voor Technologisch Onderzoek. Pp. 15 - 28.

Sleeswijk, A. 1993. Life cycle assessment of wheat fertilization: Methodological aspects and results. Proceedings of the 1st European Invitational Expert Seminar on Life Cycle Assessment of Food Products. November 1993, Leiden. Lyngby, Denmark : Technical University of Denmark. Pp. 43 - 51.

Sprinckx, C. and Ceuterick, C. 1996. Comparative life-cycle assessment of diesel and biodiesel. International Conference on Application of Life Cycle Assessment in Agriculture, Food and Non-Food Agro-Industry and Forestry : Achievements and Prospects. Brussels : VITO Vlaamse Instelling voor Technologisch Onderzoek. Pp. 213 - 238.

SRI International, PEP Yearbook 1989, Acrylacid acid-starch graft copolymer, superabsorbent. California: SRI International. Pp. 2.21.

SRI International, PEP Yearbook 1989, Acrylic acid, ester grade. California: SRI International. Pp. 2.19.

Teulon, H. 1993. LCA in the food industry: The French experience. Ecobilan. Proceedings of the 1st Expert Seminar on Life Cycle Assessment of Food Products. November 1993, Leiden. Lyngby, Denmark : Technical University of Denmark. Pp. 68 - 80.

Thomas, A. 1990. Fats and fatty oils. Ullmann's Encyclopedia of Industrial Chemistry, Vol. A 10, Weinheim: Ullmann. P. 173 - 232.

Whistler, R. L., BeMiller, J. N. and Paschall, E. F. 1984. Starch chemistry and tehcnology. 2nd edition. San Diego, CA: Academic Press. 718 p. ISBN 0-12-746270-8. :

Weidema, B. P. and Mortensen, B. 1996. Livscyklusvurdering af levnedsmidler - Hvordan kommer vi i gang?. Lyngby: ATV. 45 p.

Weidema, B. P. 1993. Life cycle assessment of food products. Proceedings of the 1st European Invitational Expert Seminar on Life Cycle Assessment of Food Products. November 1993, Leiden. Lyngby, Denmark : Technical University of Denmark. Pp. 91 - 94.

Zeijts, H. van and Reus, J. A. W. A. 1996. Toepassing van LCA voor agrarische produkten. The Hague : Landbouw-Economisch Instituut (LEI-DLO).

Zeijts, H. van.1996. Fitting fertilization in LCA - allocation to crops in a cropping plan. International Conference on Application of Life Cycle Assessment in Agriculture, Food and Non-Food Agro-Industry and Forestry : Achievements and Prospects. Brussels : VITO Vlaamse Instelling voor Technologisch Onderzoek. Pp 69 - 76.

APPENDIX A

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