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Life Cycle Assessment

OPTICAL 3D PRINTING OF DENTAL MODELS USING ACRYLIC RESIN BASED ON SOYBEAN OIL

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Rathish Rajan and Egidija Rainosalo – Centria University of Applied Sciences, Finland
Migle Lebedevaite and Ostrauskaitė Jolita – Kaunas University of Technology, Lithuania
Vaidas Talačka – AmeraLabs Ltd, Lithuania

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centria
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CONTENTS

1 INTRODUCTION

To facilitate the current transition toward a circular economy, the availability of renewable materials for additive manufacturing also becomes increasingly important. Additive manufacturing started in the 1980s with the development of the stereolithography apparatus (SLA) by Hull at 3D Systems (Hull 1984, Gross 2014). SLA printing is the layer-by-layer curing of liquid photopolymer resins using a focused laser beam. When a light projector is applied instead, exposing the entire layer to UV light simultaneously, the process is named digital light processing (DLP). Additive manufacturing via SLA or DLP process is applicable for high-resolution prototyping and fabrication of biomedical devices, for example, dental implants (l'Alzit 2022). The commercialized photopolymer resins used in SLA/DLP process are expensive and fossil fuel-based (Gross 2014, Voet 2021).

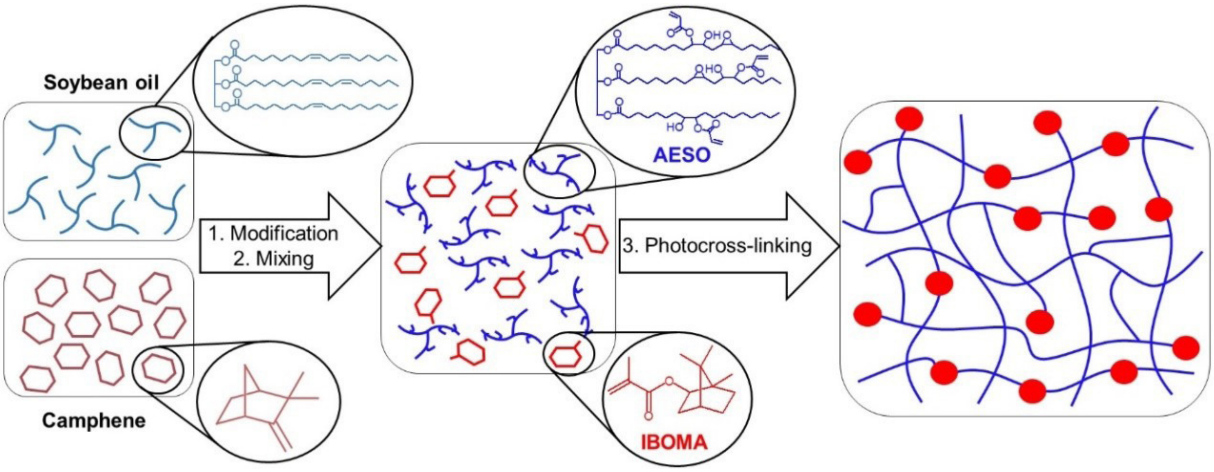

Figure 1: Schematic representation of curing of modified soybean oil-based resin during SLA/DLP method

The increased interest in bio-based products lead to active research and development that resulted in the development of vegetable oil-based 3D printable resin formulations. It is important to ensure that the new bio-based resin formulations do not have unintended environmental or health impacts from emissions during the production of novel ingredients, during the product use phase and during end-of-life disposal. Therefore, it is necessary to apply a holistic assessment tool to measure the sustainability of the resin formulation and the product made of it on a life cycle basis.

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, considering all potentially hazardous emissions and multiple categories of health and environmental impacts that result from those emissions (International Organization for Standartisation 2006). LCA can be used to investigate the most important contributors to environmental impacts by identifying the processes or materials in product life. Thus, it will provide data for designers to guide material selection, assist in supply chain management efforts, compare alternate designs or formulations, and provide product-level assessments that can be used for technology development and marketing (Montazeri 2018).

The advancement in digital technology has increased the options available for dental treatment. To produce solid casts from digital data, there are two types of 3D manufacturing processes. Subtractive manufacturing is one of the processes that can produce 3D models (Kafle 2021). The other fabrication method being used is additive manufacturing such as 3D printing. This method of fabrication includes many advantages such as a minimum material usage with diminished waste accumulation during the production and the ability to create multiple products at a time (Kafle 2021).

Dental model printing generally requires exceptional surface quality and very high accuracy as these models are used by dental technicians and dentists not only for a visual purpose but for the planning of dental treatment as well. Optical 3D printing here is also very beneficial as most of these prints are personalized, unique and applied to a specific customer only. Currently, the dental models are made from petroleum-based acrylic resins. Cradle-to-gate LCA results are compared across multiple impact categories to highlight potential environmental benefits or impacts of printing a batch of dental models from soybean oil-based resin formulation and provide recommendations for further improvements applicable to different life cycle phases of the product.

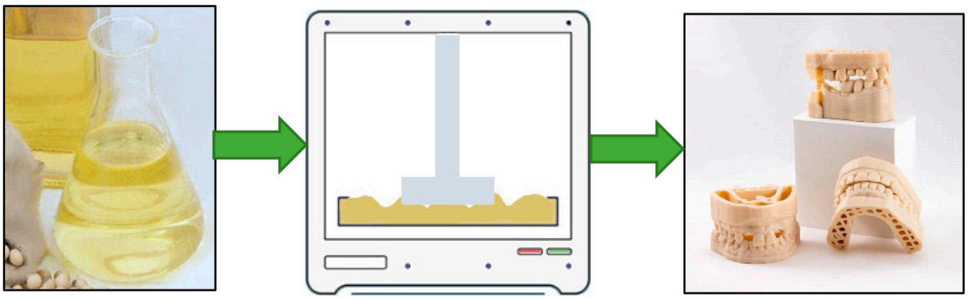

Figure 2: Representation of the SLA 3D-printing of dental models from resin formulation based on soybean oil

2 METHODS

The LCA model is built according to the international standards ISO 14040 and ISO 14044 (International Organisation for Standartisation, 2006). To conduct the LCA, the SimaPro 9.0 software and ILCD midpoint+ method was used.

2.1 GOAL AND SCOPE

The goal of this study is to compare the life cycle environmental impacts of bio-based photocurable acrylic resin for 3D printing dental models with existing conventional photocurable acrylic resins. The acrylated epoxidized soybean oil (AESO) is used as the main component of the bio-based photocurable resin with approx. 87.7% of bio-renewable carbon (BRC) content. The functional unit of this study is set to 3D-printing of a batch containing 17 dental models using 0.25 kg of photocurable acrylic resin (bio-based or conventional) by digital light processing method. The optical 3D printing using both resins consumes 0.24 kg of isopropanol (IPA) and 5 g of gloves.

Since this LCA aims to compare the environmental impacts in the production phase of bio-based and conventional acrylic resins used for the production of dental models, the use-phase and EOL (End of Life) of the dental models are excluded. These stages are excluded due to the lack of data about the emissions during production and because of similarities of end-of-life scenarios for both types of resins considered. Thus, a cradle-to-gate approach has been adopted which begins from the raw material extraction and ends with the printed part ready for packing. The life cycle phases and the unit processes of 3D printing dental models with bio-based resin and conventional resin are presented in Figure 3. Capital equipment, infrastructure and employee travel are excluded. Since the factories and infrastructure are used for producing vast amounts of 3D printed products, the environmental impacts allocated to one batch of the dental model are extremely low. Therefore, these processes are excluded.

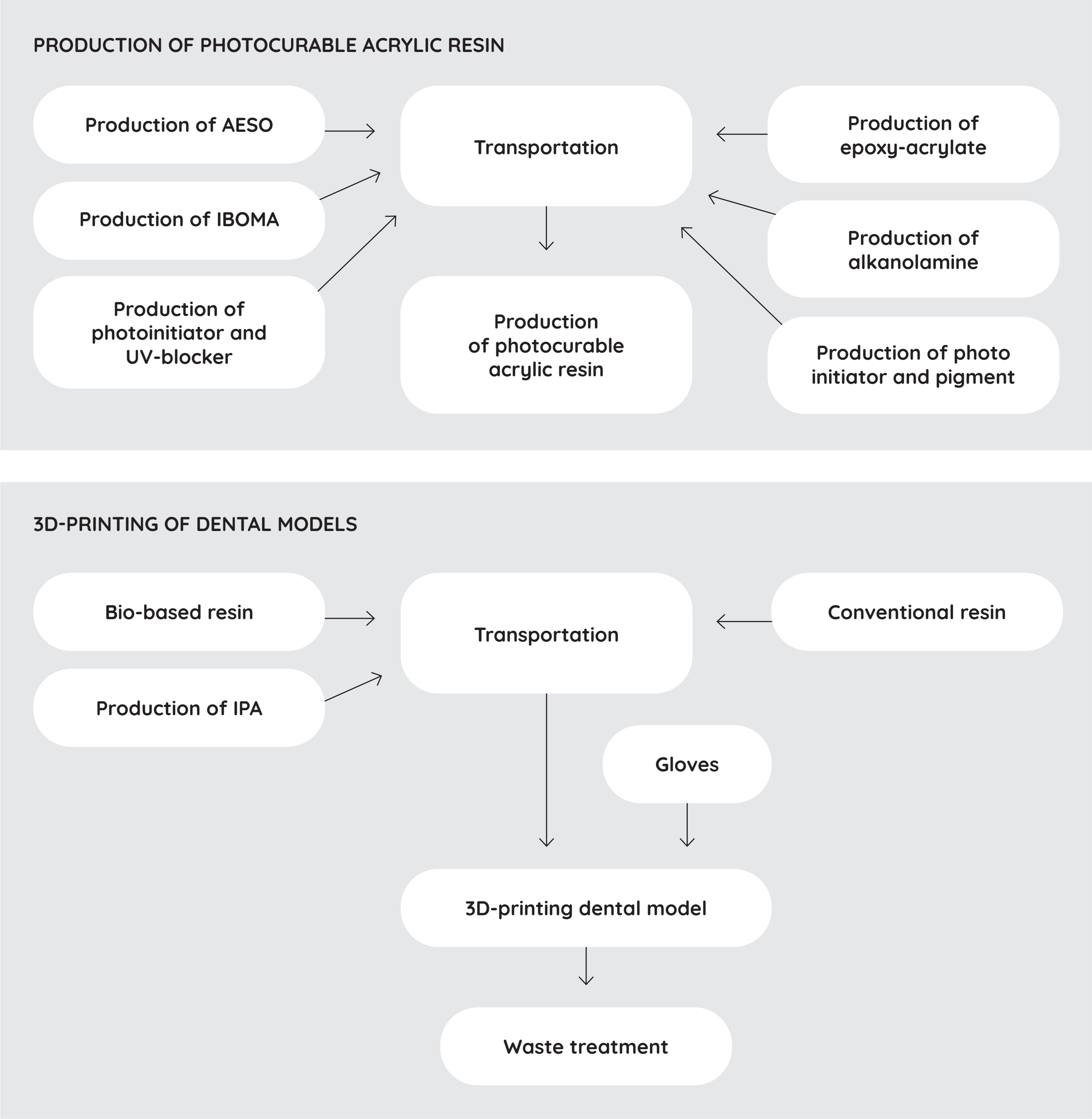

Figure 3: System boundary considered for 3D printing dental models from soybean oil-based resin and conventional acrylic resin

2.2 LIFE CYCLE INVENTORY

The main processes modelled for the study are described in the following sub-sections. Priority was given to measured/calculated data obtained from the ECOLABNET partners (KTU and AMERALABS). Other secondary data used in the study is collected from Ecoinvent 3.1. database and the literature. Literature and internet pages, as well as expert judgement and personal communications, were used as a source of information to construct the needed processes and materials. When the secondary data was not available or data was not available, estimates are applied to ensure the completeness of the study. Simapro 9.1 software was used to model the cradle to gate life cycle of 3D printing the dental models. The country-specific Ecoinvent datasets of the electricity grid mix have been used for modelling the electricity consumed during the 3D printing, and production of the photocurable acrylic resin. The inventory results and the impact assessment are calculated using Simapro 9.1.

2.2.1 MODELLING OF BIO-BASED PHOTOCURABLE ACRYLIC RESIN

The resins were prepared by mixing AESO (58.45%) with bio-based reactive diluent (IBOMA) (38.97%) to achieve the required resin viscosity for DLP 3D printing technology. The added amount of photoinitiator was 2.5%. 0.08% of UV blocker was used to control the UV light absorption.

Table 1. Composition of photocurable AESO resin

Formulation	(%)
acrylated epoxidized soybean oil (monomer)	58,45
isobornylmethacrylate (monomer)	38,97
diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (photoinitiator)	2,5
2,5-bis(5-tert-butyl-benzoxazol-2-yl)thiophene (UV blocker)	0,08

The modelling of the bio-based acrylic resin was done based on the data provided by the resin producer (KTU). The composition of the photocurable AESO resin is tabulated in Table 1. The AESO and IBOMA were not available in the Ecoinvent database. The AESO was modelled using epoxidized soybean oil (ESO), acrylic acid, hydroquinone and triethylamine (Habib 2011, Saithai 2011). In addition, epoxidized soybean oil was modelled and used in the modelling of AESO. The literature data was followed for the selection of raw materials for AESO. The modelling of the process for the production of 1 kg of AESO is tabulated in Table 2. The electricity and heat data required for producing 1 kg of organic chemical excluding the upstream process is included in the modelling due to lack of data (Kim 2003).

The production of IBOMA was modelled using methacrylic acid, camphene, hydroquinone, and zirconia sulfuric acid. Camphene and zirconia sulfuric acid are not modelled but replaced with 'chemical organic' available in the Ecoinvent database. The raw materials used for modelling are based on the process of preparation of IBOMA in the US. Patent US5719314A (Riondel 1998). The material input and the data used can be found in Table 3.

Table 2: Modelling of the process for producing 1 kg AESO

Materials/fuels	Data used	Amount	Unit
Epoxidized soybean oil	Epoxidized soybean oil (Modelled)	1000	g
Acrylic acid	Acrylic acid {RER}| production | Cut-off, U	141	g
Hydroquinone monomethyl ether	Hydroquinone {RER}| production | Cut-off, U	0,45	g
Triethylamine	Triethyl amine {RER}| production | Cut-off, U	5,7	g
Production			
Electricity	Electricity, medium voltage {LT}| electricity voltage transformation from high to medium voltage | Cut-off, U	0,166	kWh
Heat - steam	Heat, from steam, in chemical industry {RER}| steam production, as energy carrier, in chemical industry | Cut-off, U	7,7	MJ
Heat - fuel	Heat, district or industrial, other than natural gas {LT}| heat and power co-generation, oil | Cut-off, U	0,15	MJ

Table 3: Modelling of the process for producing 1 kg of IBOMA

Materials/fuels	Data used	Amount	Unit
Zirconia sulfuric acid (catalyst)	Chemical, organic {GLO}| market for | Cut-off, U	121	g
Hydroquinone monomethyl ether	Hydroquinone {RER}| production | Cut-off, U	0,107	g
Methacrylic acid	Methacrylic acid {RER}| production | Cut-off, U	554,34	g
Camphene	Chemical, organic {GLO}| market for | Cut-off, U	808,05	g
Production			
Electricity	Electricity, medium voltage {LT}| electricity voltage transformation from high to medium voltage | Cut-off, U	0,166	kWh
Heat - steam	Heat, from steam, in chemical industry {RER}| steam production, as energy carrier, in chemical industry | Cut-off, U	7,7	MJ
Heat - fuel	Heat, district or industrial, other than natural gas {LT}| heat and power co-generation, oil | Cut-off, U	0,15	MJ

The modelling of the bio-based acrylic resin was done according to the formulation provided by KTU (Table 1). The UV-blocker (0.08%) and diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (2.5%) was not modelled. It was replaced with the 'chemical organic' unit process from the Ecoinvent database. The data used for the production of bio-based photocurable resin can be seen in Table 4.

Table 4: Modelling of the process for producing 1 kg of photocurable bio-based acrylic resin

Materials/fuels	Data used	Amount	Unit
AESO (Monomer)	Acrylated epoxidized soybean oil (Modelled)	584,5	g
IBOMA (Monomer)	Isobornyl methacrylate (Modelled)	389,7	g
diphenyl(2,4,6-trimethylbenzoyl phosphine oxide (photoinitiator) +UV-blocker	Chemical, organic {GLO}| production | Cut-off, U	25,8	g
Production			
Electricity	Electricity, medium voltage {LT}| electricity voltage transformation from high to medium voltage | Cut-off, U	0,166	kWh
Heat - steam	Heat, from steam, in chemical industry {RER}| steam	7,7	MJ

2.2.2 MODELLING OF CONVENTIONAL PHOTOCURABLE ACRYLIC RESIN

The modelling of conventional acrylic resin was done by following formulations of a commercial resin's material safety data sheet from Ameralabs. The average energy consumption for 1 kg of organic chemicals was also included in modelling (Kim 2003).

Table 5: Modelling of the process for producing 1 kg of photocurable conventional acrylic resin

Materials/fuels	Data used	Amount	Unit
Epoxy-acrylate	Conventional photocurable_Epoxy acrylate (Modelled)	950	g
Alkanolamine	Triethanolamine {RER}| ethanolamine production | Cut-off, U	20	g
Photoinitiator	Chemical, organic {GLO}| production | Cut-off, U	10	g
Pigment	Chemical, organic {GLO}| production | Cut-off, U	20	g
Production			
Electricity	Electricity, medium voltage {LT}| electricity voltage transformation from high to medium voltage | Cut-off, U	0,166	kWh
Heat - steam	Heat, from steam, in chemical industry {RER}| steam production, as energy carrier, in chemical industry | Cut-off, U	7,7	MJ
Heat - fuel	Heat, district or industrial, other than natural gas {LT}| heat and power co-generation, oil | Cut-off, U	0,15	MJ

2.2.4. MODELLING OF PRODUCTION STAGE

The details about modelling of 3D printing of 1 batch of dental models by DLP method using bio-based and conventional, photocurable acrylic resins are provided in this sub-section. One batch of dental models containing 17 models takes 38 minutes to complete DLP 3D printing. The resin consumed during the printing of one batch of dental models and the final weight of the cured models is 255 g. There is assumed to be 30 g/batch wastage of resin during printing. Around 3.7 L of isopropanol (IPA) is used for washing and IPA is assumed to be replaced after the production of 200 parts (Mele 2020). The modelling of bio-based and conventional acrylic resin can be seen in Table 6 and Table 7.

Table 6: Modelling of the process for 3D printing 1 batch of dental models using bio-based resin

Materials/fuels	Data used	Amount	Unit
Bio-based acrylic resin	Bio-based (Modelled) acrylic photo resin	255	g
IPA for washing	Isopropanol Cut-off, U {RER}| production |	245,86	g
Gloves	Latex {RER}| market for latex | Cut- off, U	5	g
Production			
Electricity - Printing	Electricity, low voltage {LT}| electricity voltage transformation from medium to low voltage | Cut- off, U	0,0361	kWh
Waste treatment			
Waste treatment IPA	Process-specific burdens, hazardous waste incineration plant {CH}| processing | Cut-off, U	245,86	g
Waste treatment gloves	Process-specific burdens, hazardous waste incineration plant {CH}| processing | Cut-off, U	5,0	g
Waste resin during printing	Process-specific burdens, hazardous waste incineration plant {CH}| processing | Cut-off, U	30,0	g
Transportation			
Transportation of resin from a distance of 100 km	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U	0,025	tkm
Transportation of IPA from a distance of 100 km	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U	0,024	tkm

Table 7: Modelling of the process for 3D printing 1 batch of dental models using conventional resin

Materials/fuels	Data used	Amount	Unit
Conventional acrylic resin	Conventional photo curable acrylic resin (Modelled)	255	g
IPA for washing	Isopropanol {RER}| production | Cut-off, U	245,86	g
Gloves	Latex {RER}| market for latex | Cut- off, U	5	g
Production			
Electricity - Printing	Electricity, low voltage {LT}| electricityvoltage transformation from medium to low voltage | Cut- off, U	0,0361	kWh
Waste treatment			
Waste treatment IPA	Process-specific burdens, hazardous waste incineration plant {CH}| processing | Cut-off, U	245,86	g
Waste treatment gloves	Process-specific burdens, hazardous waste incineration plant {CH}| processing | Cut-off, U	5,0	g
Waste resin during printing	Process-specific burdens, hazardous waste incineration plant {CH}| processing | Cut-off, U	30,0	g
Transportation			
Transportation of resin from a distance of 100 km	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U	0,025	tkm
Transportation of IPA from a distance of 100 km	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, U	0,024	tkm

3 LIFE CYCLE IMPACT ASSESSMENT METHOD

The life cycle impact assessment method chosen in this study is ILCD Midpoint+. The full title of this method is ILCD recommendations for LCIA in the European context. The European Commission analysed several methodologies for LCIA and made some effort toward harmonization. The endpoint methods, however, are not included in the ILCD method in Simapro, because the list is far from complete. However, in this study, all the type of LCI results are linked to 16 midpoint categories and is connected through endpoint indicators to the areas of protection such as human health, natural environment and natural resources as per the ILCD handbook recommendation (Figure 4).

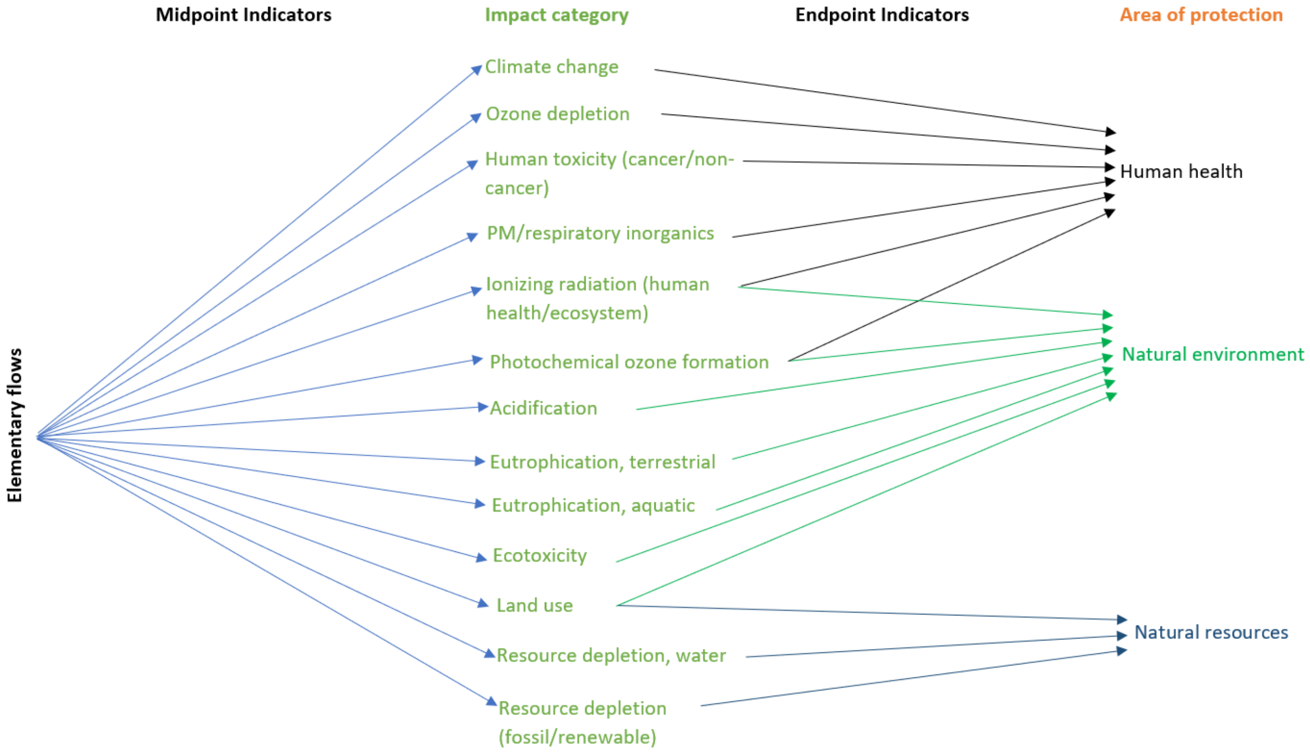

Figure 4: Overall scheme of the ILCD Midpoint+ method showing the link through midpoint indicators and endpoint indicators towards three areas of protection

4 LIFE CYCLE IMPACT ASSESSMENT

Life cycle impact assessment (LCIA) results are presented in this section. The results of the inventory analysis have been characterized, and impact assessment results are calculated using Simapro. LCIA results are always relative expressions and represent the potential environmental impact. According to ISO 14040 and ISO 14044, normalization and weighting are voluntary parts of the impact assessment phase. In this study, the LCIA results have not been weighted or normalization has been done.

In the characterization step, all the impacts are sorted into 16 midpoint categories according to the effect they have on the environment. The global warming potential is calculated for each of the different greenhouse gases and expressed relative to the CO2 which is therefore defined as unity. The results show that there is a small savings of 0,15 kg CO2 eq in terms of the climate change category. The main process contributing to this impact category in terms of bio-based resin is crude soybean oil. The lower savings in this category is due to the modification process of soybean oil. The main midpoint categories that showed increased impact for bio-based resin were land occupation, marine eutrophication and water resource depletion. This is obviously due to the land occupation and other agricultural practices during the cultivation of the soybean. The fertilizer run-off into the water bodies due to agricultural practices is accountable for the increased impact of bio-based resin in the eutrophication category. However, the dental models printed with bio-based resin showed reduced impact in 12 out of 16 categories when compared to those made from conventional acrylic resin.

Table 8: Characterization results expressed in 16 midpoint categories for a batch of dental models printed with conventional and bio-based acrylic resins

Midpoint Impact category	Unit	Dental model-Conventional acrylic resin	Dental models-Bio-based acrylic resin
Climate change	kg CO2 eq	2,30E+00	2,15E+00
Ozone depletion	kg CFC-11 eq	2,72E-07	1,55E-07
Human toxicity, non-cancer effects	CTUh	4,26E-07	4,56E-08
Human toxicity, cancer effects	CTUh	8,93E-08	7,37E-08
Particulate matter	kg PM2.5 eq	1,25E-03	1,01E-03
Ionizing radiation HH	kBq U235 eq	1,68E-01	1,24E-01
Ionizing radiation E (interim)	CTUe	5,73E-07	4,48E-07
Photochemical ozone formation	kg NMVOC eq	7,80E-03	6,46E-03
Acidification	molc H+ eq	1,00E-02	8,94E-03
Terrestrial eutrophication	molc N eq	1,78E-02	1,58E-02
Freshwater eutrophication	kg P eq	5,71E-04	4,09E-04
Marine eutrophication	kg N eq	1,70E-03	3,45E-03
Freshwater ecotoxicity	CTUe	3,13E+01	2,01E+01
Land use	kg C deficit	1,85E+00	1,32E+01
Water resource depletion	m3 water eq	3,09E-03	4,63E-03
Mineral, fossil & renewable resource depletion	kg Sb eq	3,66E-05	6,60E-05

A reduced impact was found in terms of freshwater ecotoxicity for bio-based resins. The process that influences this impact category was crude soybean oil used in the modelling of bio-based acrylic resin. Chemicals can be emitted to the environment (air, water, soil) during all life cycle stages of products. Emission inventories of different products may contain hundreds of chemicals, of which many will have the potential to cause ecotoxic impacts on aquatic and terrestrial ecosystems, leading to damage to ecosystem quality. It can be concluded that by using the soybean-based resin, fewer chemicals are emitted into the environment during resin production. This should eventually improve the ecosystem quality.

The three areas of protection linked through midpoint indicators are human health, natural environment and natural resources as seen in Figure 4. As seen in Figure 5, the dental models based on bio-based resin have a negative environmental impact on endpoint indicator natural resources. This is because the midpoint categories (land use, water resource depletion and mineral, fossil & renewable resource depletion) assigned to this endpoint indicator are related to soybean oil cultivation. The bio-based resin seems to be a better option than conventional resin in the case of endpoint indicator human health.

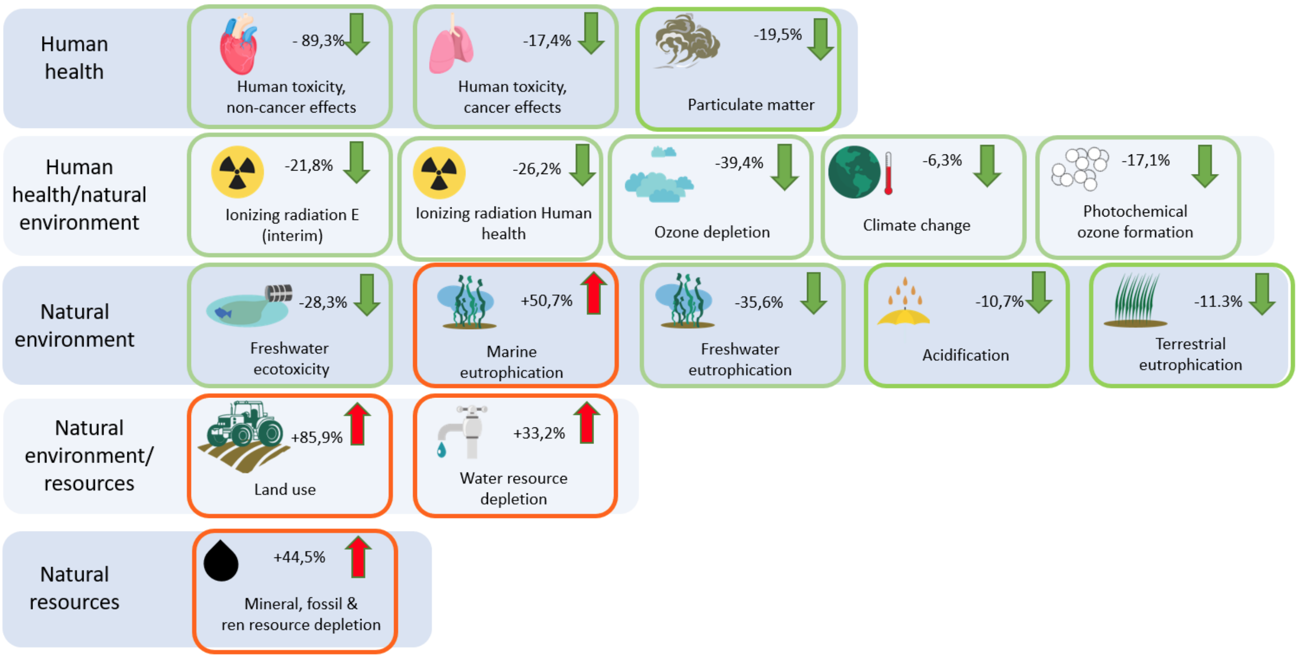

Figure 5: The environmental impacts of using bio-based resin compared to conventional resin to print the dental models presented in terms of three areas of protection

5 CONCLUSIONS

A cradle-to-gate life cycle assessment of optical 3D printing a batch of dental models by using bio-based and conventional acrylic resin was conducted to compare the environmental impact of both resins. The inventory compilation was based on Ecoinvent 3.1. database in Simapro software. Literature and internet pages, as well as expert judgement and personal communications, were used as a source of information. The life cycle impact assessment method chosen in this study is ILCD Midpoint+.

The bio-based resin has shown reduced impact on human health but increased impact on natural resources. The emissions from agricultural activities, especially the sulphur-containing diesel burned in farm equipment and the surface runoff of nitrogen and phosphorus compounds to water bodies due to fertilizer use, deteriorating air and water quality as seen from the overall LCIA results. Additionally, aromatic, aliphatic and chlorinated compounds added during soybean crushing and degumming, oil refining, and resin production all contribute to the increased environmental impacts when the soybean oil-based resin is considered. Land use is the major contributor to the endpoint indicator, natural resources and is due obvious reason for land occupation for soybean cultivation.

The results from this study clearly show the benefit of using bio-based chemicals for formulating the resin. However, replacing petrochemical components with renewable chemical substitutes in new bio-based resin formulations should not just consider the amount of bio-based content, but ideally should consider more sustainable bio-based feedstock and the processing conditions with low environmental impact to ensure environmentally preferable resin formulations.

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Life Cycle Assessment

OPTICAL 3D PRINTING OF DENTAL MODELS USING ACRYLIC RESIN BASED ON SOYBEAN OIL

Green chemistry and green engineering concepts have been combined to develop novel sustainable polymeric materials by formulating bio-based UV-curable 3D-printable resins. The bio-based resin is composed of acrylated epoxidized soybean oil (AESO), isobornyl methacrylate (IBOMA), photo-initiator and UV-blocker. Our previous studies have shown that these resins show comparable properties to the fossil-based optical 3D printing resins by providing the additional benefit of using bio-based feedstock materials.

Life cycle assessment is a tool used to measure environmental sustainability. This study aims to compare the environmental impact of 3D printing a batch of dental models using UV-curable, bio-based and fossil-based acrylic resins. This is a cradle-to-gate study which covers the raw material extraction and production of a batch of the dental model that is ready to pack. The software used for modelling the study is Simapro 9.1. The life cycle impact assessment (LCIA) method used is ILCD midpoint+. All the 16 midpoint impact categories are linked to three areas of protection (Human health, natural environment, and natural resources).

The dental models printed with bio-based resin show reduced impact in 12 out of 16 categories when compared to those made from conventional petroleum-based acrylic resin. There was no large difference between the two resins when the climate change impact category is considered. The four impact categories in which bio-based resin had relatively higher environmental impact are eutrophication, land-use, water resource depletion, mineral, fossil & renewable resource depletion. This is certainly due to the cultivation practices, processing of soybean oil, and production of AESO which contributes to the higher environmental impact of dental models printed by bio-based resin. The results from this study clearly show the benefit of using bio-based materials for formulating the UV-curable 3D-printing resin. In addition, the results also point out the importance of selecting more sustainable bio-based feedstock and processing conditions with low environmental impact when formulating new bio-based resins.

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