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Combining ex-ante LCA and EHS screening to assist green design: A case study of cellulose nanocrystal foam

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ABSTRACT

The evaluation of environmental credentials for innovative products within the research and design phase of development presents a valuable yet challenging exploit. The research presented here aims to carry out the early-stage environmental assessment of a novel nano material – cellulose nanocrystals (CNC) foam by applying ex-ante life cycle assessment (LCA) supplemented by an environmental, health and safety (EHS) screening. LCA is applied to assess the cradle-to-factory gate environmental impacts along the R&D trajectory from the laboratory synthesis, conceptual design, bench-scale trial to the up-scaled process design. Non-renewable energy use (NREU), greenhouse gas (GHG) emissions and agricultural land occupation (ALO) are the three indicators analysed. The early-stage EHS screening provides a supplementary assessment since the toxicity information is usually missing in the ex-ante LCAs due to lack of information. The EHS screening was conducted in two steps: 1) the (eco)toxicological effects of CNC are analysed by applying *in vivo* zebrafish assays; and 2)A so-called "block list" scan is performed where all substances used in the production of CNC foam are scanned against valid regulations. The LCA results demonstrate that technology upscaling leads to a steady environmental impact reduction. It is observed that for per kg studied CNC foam, both NREU and GHG emissions were reduced by a factor of 10 along the R&D trajectory from lab scale to upgraded process design, as a result of the design improvements associated with energy-intensive processes and process energy optimisation. Along the studied R&D trajectory the potential ALO was decreased by 83% primarily due to a more efficient recycling of ethanol. The block list scan did not yield highly concerned substances in the manufacturing process. The *in vivo* zebrafish assay provided valuable insight into the ecotoxicological effects of CNC pointing towards the need for a more rigorous assessment.

1. Introduction

In 1949, Rånby demonstrated that controlled sulfuric acid hydrolysis of wood and cotton cellulose, resulted in degradation of the amorphous regions, producing nanocrystals (Beck-candanedo et al., 2005). These nanocrystals are termed cellulose nanocrystals (CNC), also called nanowhiskers or nanocrystalline celluloses, as elongated crystalline rod-like nanocrystals (Habibi et al., 2010; Siqueira et al., 2010; Siro, Istvan; Plackett, 2010). CNC has a typical diameter of 3–20 nm and length of 100–1000 nm dependent upon the preparation method and cellulose source (Beck-candanedo et al., 2005; Habibi et al., 2010; Moon et al., 2011). Benefiting from the small size and large length-to-width/diameter aspect ratio, CNC has exceptional mechanical properties. A single nanocrystalline cellulose typically has a Young's modulus of 110 GPa–220 GPa and a strength of 7–50 GPa (Azizi Samir et al., 2005; Brinchi et al., 2013; Hubbe et al., 2008; Moon et al., 2011). These values are comparable to common engineering materials, e.g. aluminium alloy and stainless steel with Young's moduli of 68–82 GPa and 189–210 GPa respectively (Ashby, 2005).

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Conjointly, CNC provides advantages of superior dispersibility and lower susceptibility to bulk moisture absorption, promoting its utilisation as an efficient reinforcing candidate (Klemm et al., 2011). Studies on the development of nanocomposites using CNC as a reinforcing component in natural polymeric matrixes have been intensively reported (Brinchi et al., 2013; Eichhorn et al., 2010; Habibi et al., 2010; Khalil et al., 2012; Klemm et al., 2011; Oksman et al., 2016). In particular, CNC has demonstrated its potential for applications surrounding the reinforcement of cell walls in polymer foams (Mi et al., 2014; Wik et al., 2011), and in the fabrication of high porosity foams (Dash et al., 2012; Zhou et al., 2014) and aerogels (Mueller et al., 2015). Impelled by the various application possibilities (Eichhorn et al., 2010; Zhou et al., 2014), an increase in research activity has been carried out to further develop processing technology suitable for the mass production of CNC porous materials (Oksman et al., 2016).

Despite developments in extracting CNC and its utilisation for new materials, environmental and health impacts of CNC and CNC-composites remain little understood. Merely a few health studies exist, highlighting the lack of knowledge on the toxicology of CNC (Roman, 2015). Furthermore, only two LCA (life cycle assessment) studies of CNC are available in the public domain (de Figueirêdo et al., 2012; Nascimento et al., 2016). In these two studies, CNCs were extracted from white cotton and coconut fibre through lab experiments. For materials incorporating CNC, studies on their environmental performance have not been conducted at present.

Within the EU FP7 project "NCC-Foam"[1] (http://ncc-foam.eu/), open-cell foams using CNCs were developed with practical dimensions ($0.6\,m \times 0.4\,m \times 0.01\,m$). They could potentially be infused with resins and subsequently incorporated as a lightweight core within sandwich composite modules. For the development of a new material, the closer the development is to the industrial production plant, the more costly and inflexible it will likely become to include performance targeted improvements within the production system, or alter feedstock and material composition (Köhler and Som, 2014; Piccinno et al., 2016). Thus, opportunities to progress the manufacture technology should be grasped in the early stages of development. Choices made during early development stages have a large influence on the associated environmental impacts of a final product (Broeren et al., 2017; Hauschild et al., 2005; Sheldrick and Rahimifard, 2013). For CNCs, LCA has been previously applied to evaluate various process technologies in a bid to identify sustainable choices of biomass feedstocks and to provide recommendations on technology pathway choices (de Figueirêdo et al., 2012; Nascimento et al., 2016).

The present study applies ex-ante LCA to assess the environmental impacts of CNC foam, a product in its early-stage development. Reported early-stage technology assessments (e.g. ex-ante LCAs) were typically built on the data collected from lab scale synthesis (e.g. de Figueirêdo et al., 2012; Li et al., 2013; Piccinno et al., 2015) or conceptual design (Fernández-Dacosta et al., 2015; Villares et al., 2016). In practice, results of these assessments are often overlooked (Broeren et al., 2017; Patel et al., 2012) due to large time-scales between R&D to final production. In the present study the environmental impacts of CNC foam have been continuously observed and monitored throughout the project, allowing for comparison of the impacts arising at different development stages (e.g. from lab scale, conceptual design to commissioned bench-scale production and up-scaled process design).

Three environmental indicators are analysed in this study, namely non-renewable energy use (NREU), Greenhouse gas (GHG) emissions and agriculture land occupation (ALO). Due to the lack of information at the early stage of product development, many previous LCA studies either neglected the toxicity impacts as a whole (e.g. by only selecting a limited number of impact categories based on available data and information (Arvidsson et al., 2015; Cok et al., 2014; Hermann and Patel, 2007; Hottle et al., 2013; Schrijvers et al., 2014), or solely reporting toxicity impacts from the input materials, without inclusions of the direct impacts from the nanomaterials and product system (de Figueirêdo et al., 2012; Li et al., 2013; Piccinno et al., 2015; Nascimento et al., 2016)).

Given the dynamics of the early stages of product innovation it is virtually impossible to perform detailed assessment of the potential adverse effects of chemicals to humans and the environment, even when considering possibilities of applying predictive tools like Quantitative Structure Activity Relationships (QSARs) (Silvia et al., 2010) for specific toxicity endpoints. Conversely, it is to be noted that especially for formulations containing nanomaterials virtually no information on the toxicity profile of the nanomaterials is available and clear guidance for efficient toxicity testing of nanomaterials is still lacking. In the present study, we propose an early-stage Environmental, Health and Safety (EHS) screening in accompaniment to the LCA, aiming to provide first insights in possible (eco)toxicological effects though exploiting the limited data available in the early stage of a product development. The screening consists of two parts: 1) a simplified eco-toxicological test of CNC suspensions, focussing on adverse effects induced by chemicals dissolved in the suspensions, and 2) a so-called "block list" scan where all input substances are screened subject to international regulatory frameworks, such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) (European Commission, 2006), and (UNEP) Stockholm convention on Persistent Organic Pollutants (UNEP, 2008). This approach allows for a broad screening of chemicals of severe concern without the need of detailed and tedious fate and toxicity assessment. It is acknowledged that the approach will fall short for chemicals used in the processing steps of CNC foam, for which no toxicity data are available. In the specific case of CNC suspensions, it turned out that the block list screening could be performed for all chemicals used within the various process steps. Simplified toxicity screening was possible only for the mixture of chemicals present in CNC suspensions and in paper pulp; the method did not allow to assess adverse effects of nanoparticles present in CNC suspensions.

2. Methodology

This early-stage sustainability assessment consists of two components: an ex-ante LCA and an early-stage EHS screening, see Fig. 1. The ex-ante LCA and EHS screening are applied simultaneously. The LCA was applied at each instance a new product system design was confirmed and was conducted in accordance with the standardized methodology defined by the ISO (ISO, 2006a, 2006b).

Because toxicity data for an environmental impact assessment are not available for the studied CNC product, it is not possible to include a toxicity impact assessment in the ex-ante LCA. EHS screening is conducted to gain the first insight into eco- and human toxicities of this type of new nanomaterial. EHS screening is applied at the earliest possible stages of product development and consists of two steps (see Fig. 1):

1) The "block list" scan may be performed in any of the development stages as it requires only information on substances used within the *manufacturing processes*. The "block list" only contains substances that are regulated by authorities. However, the "block list" does not include novel substances structures such as

[1] One of the former synonyms of CNC is NCC (nanocellulose crystalline).

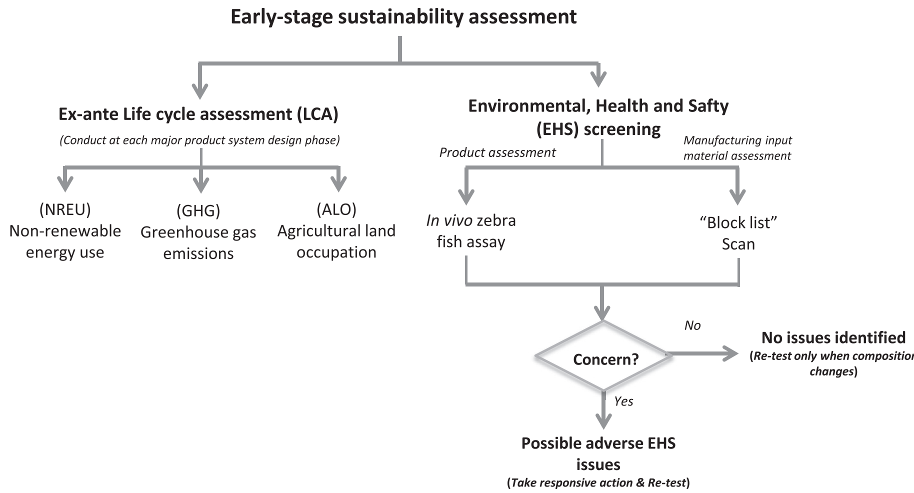


Fig. 1. Structure of the proposed early-stage assessment methodology.

nanomaterials. To gain insight into the toxicities impacts, the *in vivo* zebrafish assay was conducted.

2) The *in vivo* zebrafish assay was performed when it is difficult to predict the ecotoxicities of a new substance by using the existing toxicity simulation tools. Zebrafish was chosen as a standardized OECD test is available for testing the impact of chemical on the early life stages of zebrafish (OECD, 2012). Zebrafish represents an important trophic level within the food chain and there is about 70% genome similarity between zebrafish and humans. Thereupon, zebrafish embryos are sensitive to toxicants and they are considered as being invertebrate species. The latter implies that no additional ethical requirements are applicable upon zebrafish embryo testing. This method can be performed in any instance where enough sample material can be produced and submitted. It is also repeated when the product itself undergoes ingredient changes.

During the EHS screening process when adverse effects are observed or hazardous chemicals are identified, three options are available at each stage of development: (i) Substitution of the hazardous chemicals by less harmful compounds. This would contribute directly to safe production practises. (ii) Modification of the products shown to possess hazardous properties, including consideration of modification of the product being produced. (iii) Take precautions to warrant minimized exposure to the hazardous chemicals present, during all stage of development and application. Only in the worst case in which none of these options warrants sufficient reduction of potential risks, termination of product development is to be considered.

2.1. Life cycle assessment

2.1.1. Goal and scope definitions

The goal of the LCA is two folds:

1) To assess the environmental impacts and identify possible improvement potentials of CNC foam; and
2) To understand how the environmental impact changes along the various R&D stages.

The functional unit is defined as "1 kg of CNC foam". The system boundary is defined as "cradle-to-factory gate". It includes every process involved from resource extraction of raw materials and energy, to chemical/mechanical conversions and processing until the formation of the foam product. The packaging, use and disposal phases of the CNC foams are not included in this study.

Based on the goal, attributional LCA in the "accounting context" is chosen for the inventory modelling (i.e. "Type C" under the ILCD guidance) (European Commission, 2010). The foreground data for the manufacture of CNC foam is obtained during the project period (2013–2016). The background data is based on the available information averagely dated in the 2000s and 2010s. The geographical scope is Europe. For the raw materials, utilities and energy consumed in the production processes, status quo production technologies are assumed (i.e. less than 10 years old).

Three environmental indicators are selected: NREU (non-renewable energy use), GHG (greenhouse gas) emissions and ALO (agriculture land occupation). NREU strongly correlates with many energy-related environmental impacts (Huijbregts et al., 2006). NREU is calculated using the Cumulative Energy Demand method (Frischknecht et al., 2007a), covering primary fossil fuel and nuclear energy consumption. Cumulative fossil energy demand has a strong correlation with many other energy-related impact categories and is therefore a useful proxy of environmental impacts (Huijbregts et al., 2006).

GHG emissions have received much attention due to the societal concerns on climate change. The GHG emissions are calculated based on the Global Warming Potential (GWP) for a 100 year period from the IPCC 5th assessment report (IPCC, 2013). The carbon inventory is modelled in accordance with PAS 2050:2011 (BSI, 2011). Since CNC foam is a bio-based product, both biogenic carbon removals and emissions are taken into account. GHG emissions arising from direct and indirect land use changes are not taken into account.

Land use (indicated as "agriculture land occupation" here) is an important resource indicator for bio-based products. Many studies have shown that bio-based products have the benefits of reducing NREU and saving GHG emissions (Chen and Patel, 2011; Hermann et al., 2007; Weiss et al., 2012). However, the trade-offs between NREU/GHG emission reduction and land use are commonly overlooked in many LCAs (Broeren et al., 2017; Sheldon and Sanders, 2015). In this LCA, the impact category of ALO is chosen from ReCiPe Mid-point with Hierarchy perspective (Goedkoop et al., 2013). ALO includes various categories of land occupation, including a wide range of arable and forest land (Goedkoop et al., 2013).

2.1.2. Life cycle inventory analysis

2.1.2.1. Product systems. The raw material used in the production of CNC foam is dissolving grade pulp, which has a β-cellulose content higher than 90%. Dissolving pulp is commonly produced from wood via the sulfite process or the kraft process with an acid pre-hydrolysis step to remove hemicelluloses. The development of CNC foam production technology passed through four distinguishable stages within the time-scale of this study, namely, lab-scale production, conceptual design of a pilot plant, bench-scale trials and most recently the up-scaled process design. These four stages distinguish the four product systems (PS) investigated.

Fig. 2a shows the simplified scheme for the production of CNC foam. The process initiates with a controlled sulfuric acid hydrolysis of dissolving pulp at around 40 °C (Shoseyov et al., 2013b). In this step, cellulose amorphous domains are degraded while the crystalline domains remain intact. The amorphous cellulose is partially oxidised into CO_2 emitted to air and the remaining solid fraction consisting mainly of mono- and poly-saccharides is disposed of as solid waste. The CNCs are separated from the acid by centrifugation.

In the lab production, approximately 80% of the sulfuric acid is recycled. The obtained CNCs are washed before the solution is sonicated in an ice bath until the solution becomes optically clear, resulting in a stable suspension with uniformly dispersed CNCs. The CNC suspension is then mixed with a bio-based binder, and this mixture is subsequently frozen at −80 °C using liquid N_2. In the freezing step, the ice crystals that formed push the CNCs towards each other, forcing self-assembly and arrangement of CNCs into macro-structures. In the thawing step, the ice is removed via two ethanol exchange cycles. After removing ethanol by draining and natural drying, a foam consisting of CNCs was obtained (Fig. 1b shows the CNC foam produced in the lab) (Shoseyov et al., 2013a). In the **lab-scale production** (PS1), about 50% of the ethanol is recycled.

It is important to note that as the product is currently under development the common life cycle processes post production i.e. packaging, end-product transportation and distribution, use and end of life waste management are not explored in this early stage assessment due to lack of detailed information on the type of end products that the studied CNC material could lead to.

With the ambition of developing a pilot scale processing technology, the conceptual design of a pilot plant was first created with a target of producing 100 kg CNC foam per day. The main distinguishing feature of this **conceptual design** (PS2) is the incorporation of a tunnel refrigerator operating at −40 °C to replace liquid N_2 and a distillation process to recover 67% of the ethanol used during the solvent exchange process. These adapted measures are integrated into the system to reduce the energy consumption (especially from the freezing step) and production cost.

Developing a pilot plant to test the scalability of the production process presented a critical step within the project. Two acute bottlenecks were encountered: 1) the high production cost of CNCs, and 2) difficulties in finding suitable equipment to achieve the ambitious goal of 100 kg/day. These constraints led the project team to two important decisions: 1) changing the foam's constituent ingredients by adding a bio-based bulk filler to bring down the cost, and 2) curtailing the pilot design to a bench-scale process, in order to continue the development within the budget confinements. As a result, the foams produced from the **bench-scale trial** (PS3) consist of CNC, the bio-based binder and the bio-based bulk filler. In this way, the two bottlenecks are overcome without compromising the key properties of the foam (e.g. density and thermal conductivity). Further key process improvements in PS3 include an increased ethanol recycling rate (from 67% to 94%), a reduction in ethanol makeup by 71%, an elevated operation temperature (from −40 °C to −20 °C) and a shorter operation time in the freezing step via the use of a shock freezer.

The bench-scale trial successfully produced about 0.8 kg foam per day for a couple of weeks. Resulting individual foams weigh about 96 g each and have the dimension of 0.6 m × 0.4 m × 0.01 m, suitable for various mechanical property and fire property testing.

Based on internal knowledge developed within the project, a detailed **up-scaled process design** (PS4) aiming at producing 30 kg foam per day was established using engineering tools. In comparison to PS3, ethanol makeup is reduced by 18% in the thawing step due to the scaling factor. Even though extra electricity consumption is added for pumping ethanol in the thawing step due to the design of the automatic production line in PS4, the total electricity consumption is reduced by 42% compared to PS3. This is mainly due to the more energy efficient ethanol distillation and drying. The main characteristics of the four product systems are summarized in Table 1.

2.1.2.2. Data and assumptions. For PS1 and PS3, the foreground data was measured based on physical measurements taken from actual productions. For PS2 and PS4, the foreground data is obtained from engineering partners design simulation models, used to provide a best estimate for quantities of materials and energy used within the production process.

Ecoinvent v3.0 is used as the database for the background data. For PS3 which was carried out in Italy, the site-specific background data is used. For the other product systems, the European data is used whenever the average production technology in Europe is available. If the European data is not available, the average global production is assumed and the global data is used. For data which is not available in Ecoinvent v3.0, unit process models are developed based on peer-reviewed articles and industrial confidential data. Table 2 provides an overview of the sources and assumptions of the background data.

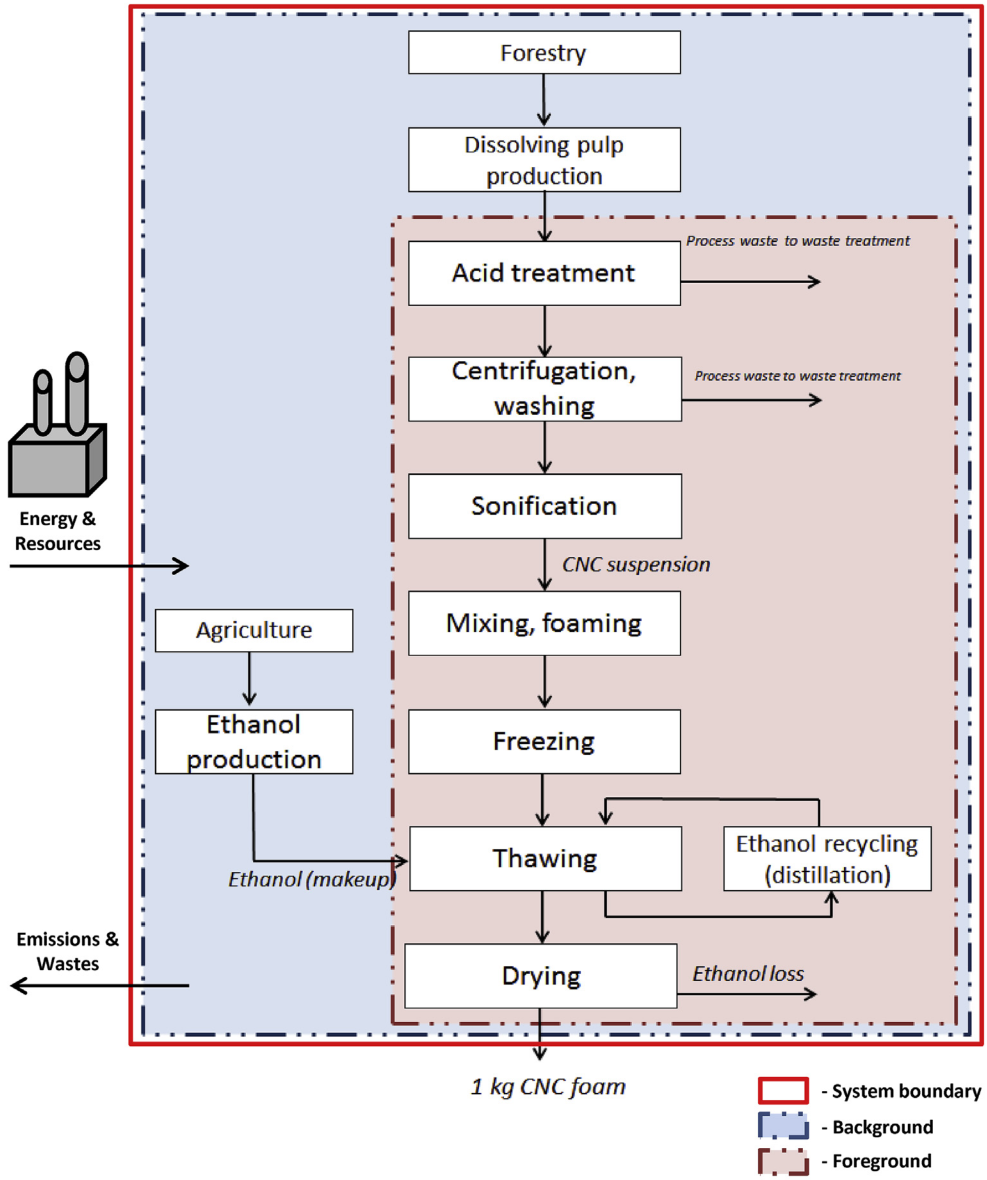
The default allocation from the Ecoinvent database is selected due to the attributional nature of this LCA. For process inputs which are produced from waste streams (e.g. the production of bio-based binder), the environmental impact of that waste is assumed to be zero. The environmental impacts of solid waste generated from the acid treatment are cut off for two reasons: 1) very small quantities generated 2) the solid waste mainly consists of oligo- and mono-polysaccharides which likely have low impacts on the energy requirement and GHG emissions.

2.2. Environmental health and safety screening

2.2.1. Ecotoxicity assessment - in vivo assay using zebrafish embryos Danio rerio and daphnia magn

To provide a preliminary assessment on the health and safety aspects of CNC suspension in the early stage development, the potential adverse effects of CNC were investigated by exposing zebrafish embryos (*Danio rerio*) and waterfleas (*Daphnia magna*). The testing was performed by integrating two methods, namely passive sampling and passive dosing. Equilibrium partitioning passive sampling extracts a negligible concentration of potentially toxic compounds from a substrate into a suitable polymer (Mayer et al., 2003; Vrana et al., 2005). Reversely, passive dosing is releasing compounds into an unpolluted medium (Butler et al., 2013). By performing passive sampling in the jars used for toxicity testing, the passive sampling devices can directly be used for passive dosing. In this way the test organisms are exposed to available concentrations of complex mixtures of potentially toxic substances (range log octanol-water partitioning coefficient, log Kow from 2.5 to 5.5) present in the substrate of interest.

For the passive sampling testing, 10 test jars were coated with 50 mg of Low V.O.C. Conformal Coating 1–2577 obtained from Dow



a

b

Fig. 2. (a) Schematic diagram of the CNC foam product system. (b) Image of CNC Foam (image provided by Melodea and Hebrew University within the EU FP7 project CNC Foam).

Table 1
Main characteristics of the four product systems.

Product systems [a]	Development stages	Capacity [kg/day]	Foam ingredients	Main process characteristics		Geographic scope
				Freezing	Ethanol recycling rate	
PS1	Lab-scale production	0.005	CNC + bio-based binder	liquid N_2 (−80 °C)	50%	W. European
PS2	Conceptual design	100	CNC + bio-based binder	Tunnel refrigerator (−40 °C)	67%	W. European
PS3	Bench-scale trial	0.8	CNC + bio-based binder + bulk filler	Shock freezer (−20 °C)	94%	Italy
PS4	Up-scaled process design	30	CNC + bio-based binder + bulk filler	Shock freezer (−20 °C)	94%	W. European

[a] PS1 and PS3 are real production processes, PS2 and PS4 are process designs.

Corning. 5 mL of a 3% CNC suspension obtained after sonification was added to each of the jars followed by 20 ml of demineralised water containing 25 mg L^{-1} sodium azide. Jars were allowed to equilibrate for 28 days on a tilting shaker and flushed twice with 5 ml demi water. After equilibration, 10 mL of zebrafish medium (100 mg L^{-1} $NaHCO_3$, 20 mg L^{-1} $KHCO_3$, 180 mg L^{-1} $MgSO_4$ and 200 mg L^{-1} $CaCl_2$) were added and the jars were allowed to equilibrate for 24 h at 26 °C under a 14/10 h light/dark cycle to reach equilibrium. Subsequently, a toxicity test with zebrafish embryos was performed. Ten eggs were placed in each jar and checked for phenotypic malformations daily up to 120 h post fertilization (OECD, 2013). Toxicity testing (21 days) of *Daphnia magna* was performed according to OECD guideline 211 (OECD, 2012). Zebrafish embryos and waterflea are two commonly used test animals representing biota from two trophic levels. Similar toxicity tests with phenanthrene and dichloroaniline served as positive controls. The positive controls did yield normal dose-response curves, with EC_{50} values within the range normally found in our labs.

2.2.2. *"Block list" scan*

The health and safety aspects of a product are not only related to the product ingredients but also related to the substances/chemicals used in the *manufacturing process*. Therefore, a "block list" scan has been carried out to identify substances in the production process of very high concern regarding their adverse effects to man and the environment. There are national and international regulations and directives on the monitoring and registration of substances. A list of important European and International regulations and directives, such as REACH was compiled for such a "block list" scan. This screening provides a quick overview of any relevant restrictions and/or provisions relating to the CNC foam production at the very early stage of the product development, helping to rule out the potential environmental and business risks.

It is important to notify the reader that when a compound is not restricted by any of these regulations, it does not necessarily imply that they are not harmful and always safe to use. Environmental health and safety properties may not (yet) be known and restrictions are updated regularly to include new compounds or new insights. Also, the lists give information for certain substances on how to use them safely. However, these lists do provide useful preliminary information on compounds that should be avoided or which specific applications are restricted. The directives and regulations should therefore be regularly checked for any updates. The following Directives and Regulations were scanned in this study:

1. Biocidal Products Directive 98/8/EC 1998–2013 consolidated version
2. Biocidal Product Regulation (EU) 528/2012
3. Directive 2000/60/EC (WFD, 2014 consolidated version)
4. Plant Protection Products 91/414/EEC 1991–2011
5. Regulation (EC) No. 1272/2008 Annex VI (CLP)
6. Regulation (EC) No. 1907/2006 Annex XIV (Authorisation)
7. Regulation (EC) No. 1907/2006 Annex XV (Candidate List)
8. Regulation (EC) No. 1907/2006 Annex XVII (Restriction)
9. Regulation (EC) No. 166/2006 Pollutant Release (EPRTR)
10. Danish List of Undesirable Substances (LOUS)
11. Dutch Substances of High Concern (ZZS)
12. Japanese Priority Assessment Chemical Substances (PACs) list
13. Directive Industrial Emissions 2010/75/EU (IPPC Annex II list)
14. Convention for the protection of the North East Atlantic Marine Environment (OSPAR)
15. (UNEP) Stockholm convention (POPs Protocol)

Table 2
Data sources and assumptions associated with the background data.

Inputs/Outputs	Data sources	Note/Assumptions
Dissolving pulp	Confidential data from industry	Production of commercial grade dissolving pulp made from wood
Sulfuric acid	Ecoinvent v3.0 (Althaus et al., 2007)	Mixed production from global commodity market[a]
Biobased binder	Own LCI model based on literature data	Produced from agricultural waste. Confidential ingredient
Liquid N_2	Ecoinvent v3.0 (Althaus et al., 2007)	Average European commodity market[b]
Ethanol	Ecoinvent v3.0 (Jungbluth et al., 2007)	From fermentation, 36% from Brazil (sugarcane-based), 36% from the US (corn-based), the rest are from rest of the world based on the global commodity market[c]
De-ionized water	Ecoinvent v3.0 (Althaus et al., 2007)	Average global commodity market[d]
Grid electricity	Ecoinvent v3.0 (Frischknecht et al., 2007b)	For PS1, PS2 and PS4: the average European grid electricity is assumed[e] (92% from non-renewables). For PS3 (located in Italy): the average Italian grid is assumed[f] (87% from non-renewables).
Wastewater treatment	Ecoinvent v3.0 (Doka, 2007)	Average waste water treatment for households globally[g]

[a] Unit process "Sulfuric acid {GLO}| market for | Alloc Def".
[b] Unit process "Nitrogen, liquid {RER}| market for | Alloc Def".
[c] Unit process "Ethanol, without water, in 99.7% solution state, from fermentation {GLO}| market for | Alloc Def".
[d] Unit process "Water, deionised, from tap water, at user {GLO}| market for | Alloc Def".
[e] Average European electricity mix is modelled based on Ecoinvent (for individual country mix) and share of the electricity production during 2010–2014 of EU28 based on EuroStat (Eurostat, 2016): Germany 19%, France 15%, UK 11%, Italy 11%, Spain 9%, Sweden 5%, Poland 4%, NL 4% and the remaining countries together 22%.
[f] Unit process "Electricity, low voltage {IT} | market for | Alloc Def".
[g] Unit process "Wastewater, from residence {GLO}| market for | Alloc Def". Average European data is not available.

Chemicals on the “block list” have a (specific) negative impact on EHS or are of concern regarding their potential harm. This can vary from expected acute adverse effects on workers during labour exposure to concerns about environmental persistency, potential for bioaccumulation or chronic toxicity, including carcinogenic, mutagenic and reproductive toxicity. If a substance is listed in one of the regulations, this does not mean necessarily that it is a problematic substance. It may well be that a chemical can be used without causing harm, if appropriate precaution measures are taken. Alternatively, certain effects might not be relevant when the compound is used as an intermediate. However, this is still useful information that should be considered, especially when upscaling the production process becomes relevant in a later stage and a classical LCA does not take occupational health and safety into account.

3. Results and discussion

3.1. LCA results

Figs. 3 and 4 present the identified cradle-to-factory gate life cycle NREU and GHG emissions for 1 kg CNC foam produced via the four product systems. It can be seen that for all four systems the impacts of CNC foams predominantly originate from the process energy and the production of ethanol.

The extremely high impacts of the lab scale production (PS1) are caused by the use of a large amount of liquid N_2, which contributes 88% of the total NREU and 82% of the GHG emissions. The impact of liquid N_2 was primarily caused by the large amount of electricity used for cryogenic air separation. In the conceptual design (PS2) replacing liquid N_2 with a tunnel refrigerator leads to substantial decrease in NREU (by 86%) and GHG emissions (by 82%). In PS2, the production of makeup ethanol is the biggest impact contributor, accounting for 48% of NREU and 63% of GHG emissions, followed by ethanol distillation, accounting for 35% of NREU and 26% of GHG emissions.

In the bench scale trial (PS3), an increased ethanol recovery rate (from 67% to 94%) leads to a lower ethanol makeup but higher electricity consumption in the distillation. The high ethanol recovery rate was succeeded in the bench trial (PS3) as a result of improved process design. The reduced ethanol makeup results in a large decrease of NREU (−34%) and GHG emissions (−45%), although the increased electricity consumption (of distillation) leads to an increase in these impacts (24% and 28% respectively). As a result, PS3 in total achieved a 13% decrease in NREU and 16% decrease in GHG emissions compared to those of PS2. In PS3, the biggest impact contributor is ethanol distillation, accounting for 67% and 65% of NREU and GHG emissions respectively, followed by the production of makeup ethanol, accounting for 16% and 22% of the impacts.

The environmental impacts of the CNC foam in the up-scaled design (PS4) are the lowest of all systems studied. The NREU and GHG emissions are reduced by 32% and 42% respectively in comparison with PS3 due to a substantial reduction in electricity consumption. In PS4, devices have better energy efficiencies due to the scaling factor (e.g. the specific final energy consumption for ethanol distillation is reduced by 18% compared PS4 to PS3). The total electricity consumption in PS4 reduces by 42% compared to PS3. In PS4, ethanol distillation is still the biggest contributor (62% of NREU and 57% of GHG emissions), followed by the production of makeup ethanol (20% of NREU and 31% of GHG emissions).

Fig. 5 shows the result of the agricultural land occupation. It can be seen that the production of ethanol takes the lion's share of the land use; it accounts for 83–96% of the total ALO. In contrast, the impact from the raw material production (dissolving pulp) is nearly negligible. Ethanol is produced via sugar fermentation primarily from sugarcane and corn (see Table 2). PS1 has a high ALO due to both ethanol and liquid N_2. The latter is produced via cryogenic air separation which requires a large amount of electricity input. The ALO of liquid N_2 is caused by the renewable content of the electricity (especially in Germany, Sweden and Finland where a substantial part of the fuel is from biomass). The ALO from PS1 to PS4 continuously decreases with the decreasing amount of ethanol makeup in the production processes.

3.2. Sensitivity analysis of the LCA results: future optimisation

Sensitivity analysis is carried out to check the robustness of the key assumptions and to identify future improvement potentials. The results presented in Section 3.1 show that process energy

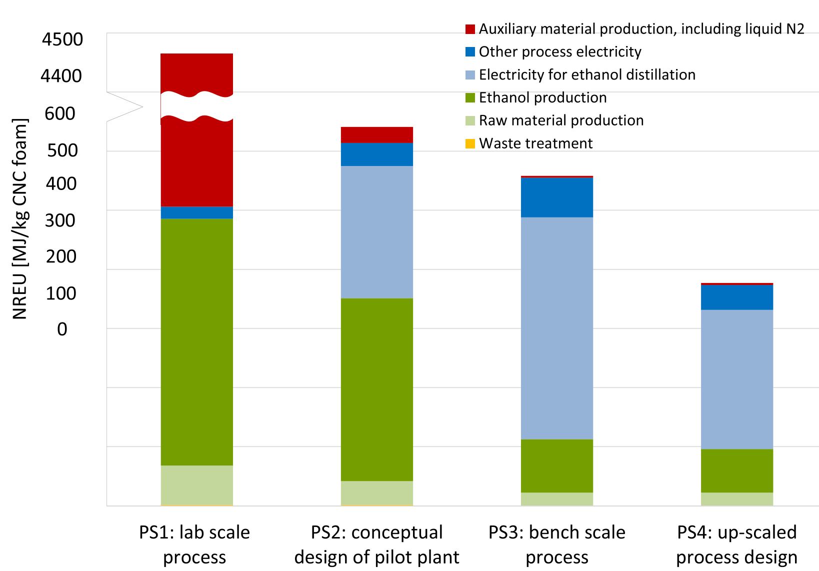


Fig. 3. Cradle-to-factory gate NREU of 1 kg CNC foam at four R&D stages.

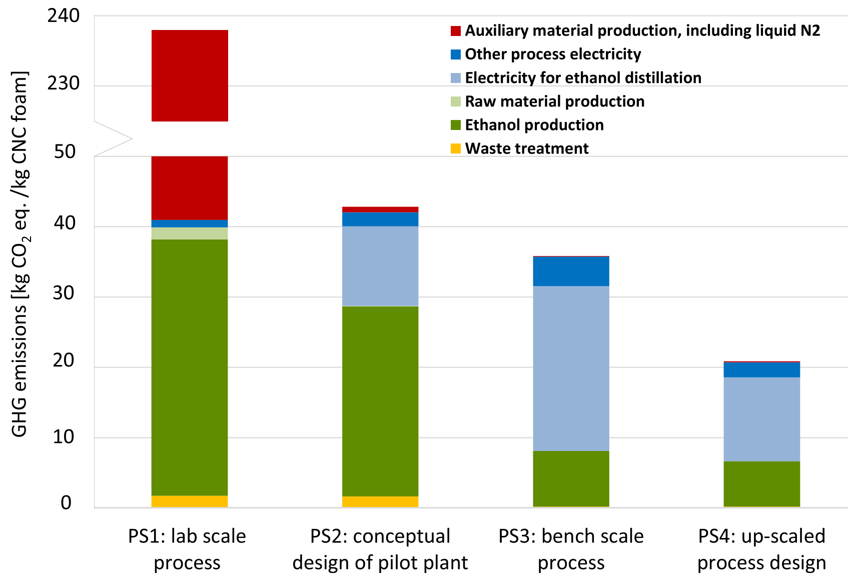


Fig. 4. Cradle-to-factory gate GHG emissions of 1 kg CNC foam at four R&D stages.

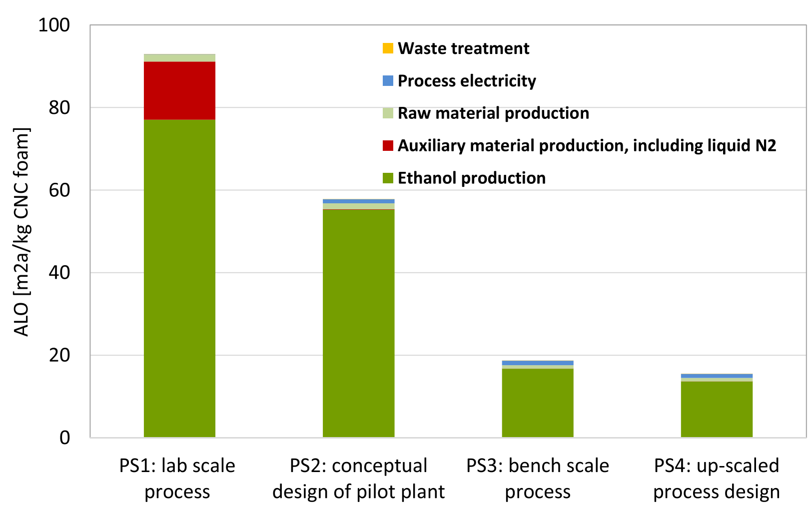


Fig. 5. Agricultural land occupation for producing 1 kg CNC foam at different stages of the R&D.

associated with ethanol recycling and the production of ethanol makeup are the crucial aspects for the environmental impacts of the CNC foam. These two aspects are influenced by two factors: 1) the ethanol recycling rate, which affects the total demand of makeup ethanol and 2) the energy source used, especially for distillation.

Firstly, in chemical industry solvents are highly recycled in order to minimize the operational costs in a commercialised production. There is no commercial CNC production to borrow experience. The industrial partners in the project suggested that a 98% recycling rate of ethanol was a reasonable prognosis for a large scale production of CNC foam. Secondly, in chemical industry, process heat is usually not supplied by electricity but rather from industrial boiler operated on fossil fuels (Boustead, 2005). In the second sensitivity analysis, the parameter of process heat is changed to “industrial steam” instead of generating heat from electricity. Lastly, considering that CNC is a future material, a future energy infrastructure in the production process should also be investigated. In the third sensitivity analysis, a low-carbon electricity future is assumed by using Swedish electricity (only 8% from combusting fossil fuels) as a proxy to replace the average EU electricity mix as assumed in the baseline. Taking PS4 as the baseline, key assumptions related to ethanol recycling and the energy sources are varied with three sensitivity analyses performed. The overview of these assumptions is summarized in Table 3.

Fig. 6 shows the results of the sensitivity analyses for NREU (6a) and GHG emissions (6b). Increasing the ethanol recycling rate to 98% would lead to an impact reduction of 7% for NREU and 11% for GHG emissions (see SA1). Whereas using industrial steam for ethanol distillation (SA2) and using Swedish electricity mix (SA3) have a significant influence on the NREU. However, their influences on the GHG emissions are quite different (Fig. 6b). Using Swedish electricity mix to provide all process energy (SA3) leads to a much larger reduction of the GHG emissions than only replacing

Table 3
Overview of the sensitivity analyses.

Sensitivity analysis	Key aspects	Assumed variation	Baseline "value" in PS4
SA1	Ethanol recycling rate	98%	94%
SA2	Source of heat for ethanol distillation	Industrial steam[b]	Electricity for heat demand (European average electricity mix[c])
SA3	Source of electricity for ethanol distillation and all remaining process[a] energy demand	Swedish electricity mix[d]	European electricity mix[c]

[a] Including the energy demand for centrifugation, sonification, mixing, freezing, pumping, cooling and drying.
[b] Fuel mix of 99% non-renewable energy, ecoinvent unit process "1 kWh Heat, in chemical industry {RER}| market for | Alloc Def" (Frischknecht et al., 2007b). Industrial steam is commonly used for large chemical production (e.g. to supply the distillation heat).
[c] The same source as described in footnote **e** in Table 2.
[d] Fuel mix: 32% of renewable and 60% nuclear and 8% fossil, ecoinvent unit process "1 kWh Electricity, low voltage {SE}| market for | Alloc Def" (Frischknecht et al., 2007b). The Swedish electricity is assumed here as an example of low carbon electricity.

European electricity with industrial steam for ethanol distillation (SA2). This is because the GHG emission factor of the Swedish power mix (0.07 kg CO_2 eq./kWh) is substantially lower than that of average industrial steam (0.41 kg CO_2 eq./kWh). The Swedish power mix has a very low GHG emissions factor due to the fuel mix of 60% nuclear power, 22% hydropower, 10% biomass and only 8% fossil fuels (Frischknecht et al., 2007b).

3.3. Results of EHS screening

3.3.1. Ecotoxicological analysis of CNCs: in vivo zebrafish assay

The toxicity of CNC was tested by exposing zebrafish embryos and *Daphnia magna* to passive samplers equilibrated in CNC suspensions and in paper slurry. Unloaded passive dosing vials were used as the control group. Inspection of abnormalities of zebrafish embryos revealed no signs of toxicity upon 120 h of exposure of the zebrafish embryos to either test samples or to controls, indicating lack of effects of chemicals dissolved in either the CNC suspensions or the paper slurry. Fig. 7 shows the results of two independently performed tests on the effects of CNC and paper slurry on the reproduction of Daphnia magna. Results of both tests were examined with a one-way analysis for variance (ANOVA). Neither the first experiment [$F(2,28) = 0.275$, $p = .761$] nor the second experiment [$F(2,29) = 1.427$, $p = 0{,}257$] showed a significant effect of the two substrates tested on the reproduction of Daphnia magna during 21 days of exposure.

3.3.2. "Block list" scan

Table 4 presents the results of the "block list" scan for all substances used in the manufacture process of CNC foam against (inter)national chemical regulatory lists. Table 4 contains an overview of the most relevant international chemical regulations dealing with hazardous substances. Non-compliance with any of these implies in general that additional efforts need to be undertaken in order to minimize adverse effects to man and the environment. Such efforts vary, dependent on the regulation of interest. As can be seen from this table, no highly undesirable substances were found in the manufacture process of CNC foam, albeit that sulfuric acid, liquid nitrogen and ethanol are included. In all cases, however, the inclusion is not due to considerations affecting the safe use of the chemicals in CNC foam production. As an example, the case of liquid nitrogen may be mentioned: nitrogen is a virtually inert chemical present in the atmosphere at relatively high concentrations that cause no environmental and human health hazards unless highly elevated levels are induced or when present as a liquid, in which case skin burning might occur as with any substance when present at a temperature of −70 °C.

Please note that when a compound is not restricted by either of these regulations, this does not imply that they are not harmful and always safe to use (see also Materials and Methods). This screening provides a quick overview of any relevant restrictions and/or provisions relating to the CNC foam production. It also gives information on how certain chemicals have to be used, for example in relation to occupational safety and health and on possible exposure scenario's and prevention measures.

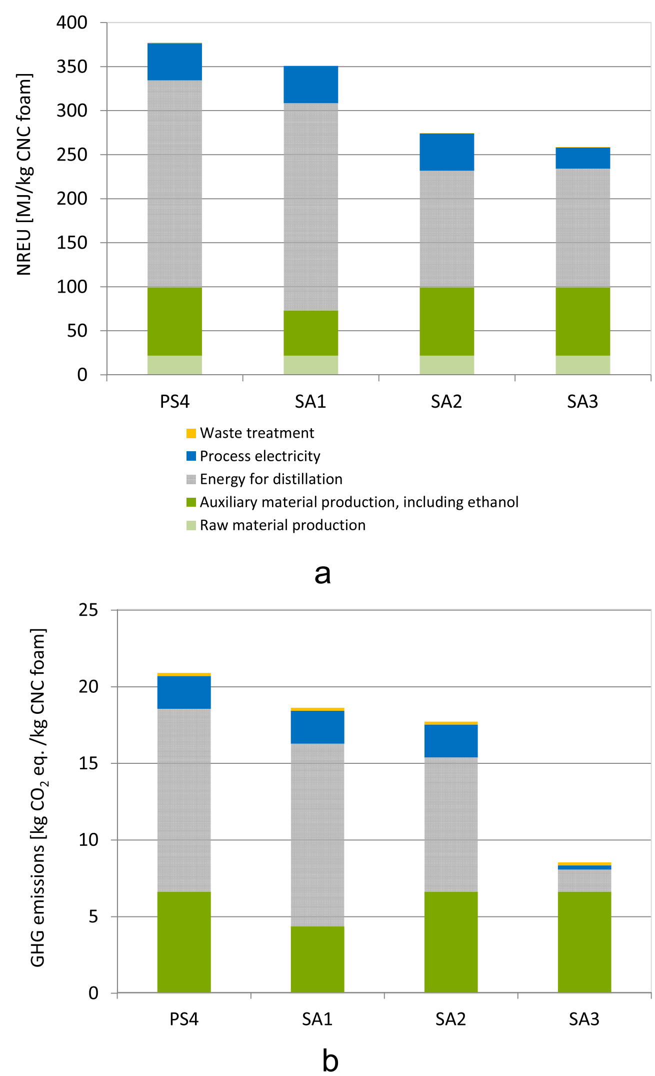


Fig. 6. Results from sensitivity analyses for a) NREU and b) GHG emissions for producing 1 kg CNC foam. Please refer to Table 3 for the three cases of the sensitivity analyses.

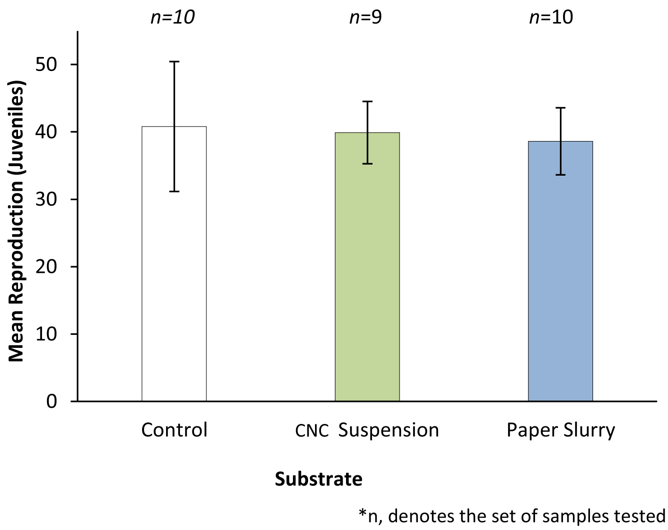


Fig. 7. Fecundity of bio indicator Daphnia magna when exposed to CNC and paper slurry.

3.3.3. Summary and discussion of early-stage EHS screening

No adverse effects were observed in acute aquatic toxicity testing of emulsions of CNC. This implies lack of release of hazardous chemicals and lack of acute toxicity of the CNC present in the suspensions tested. Based on these results, a preliminary conclusion to be drawn is that the studied CNC suspensions do not give rise to safety considerations at the initial stages of development. As a matter of course, this conclusion does not rule out possible adverse risks further on in the development chain as enhanced exposure might occur. The "block list" scan shows that no hazardous chemicals are being employed in the current stage of product development. Hence, at this stage no adaptation of the development process is needed to cope with release of hazardous substances and to secure compliance with international chemical regulations.

4. Conclusions

In this study, the cradle-to-factory gate environmental impacts of a CNC foam product are assessed along the R&D trajectory from laboratory synthesis, conceptual design, bench-scale trial to the up-scaled process design. NREU, GHG emissions and agricultural land occupation are the three indicators analysed. Along the R&D trajectory a steady reduction of the environmental impacts is observed as the result of upscaling the production technology. The NREU and GHG emissions of the up-scale process design (PS4) are only less than 10% of the impacts analysed for the lab scale production (PS1). The nature of lab research that focuses on providing proof-of-concept for a new product without considering process efficiency and cost inevitably leads to very high environmental impacts.

When the R&D advances into the engineering phase, improving process efficiency and reducing the production cost become the key focus of the technology/product development. As a consequence, substantial impact reduction can be expected by the first process design. In the case study of CNC foam, the impacts (NREU and GHG emissions) are reduced by at least 80% when comparing the conceptual design of a pilot process to the lab synthesis. This reduction is largely attributed to the replacement of liquid N_2 with a tunnel freezer (see Section 3.1). Further engineering in upscaling the production process provides process optimisation and improvements and results in further reduction

Table 4
"Block list" scan of all substances appearing in the manufacture process of CNC foam (+/− indicates that an ingredient is not listed in regulatory lists and directives).

Substance	CAS nr ↓	Regulatory framework ↓ EC nr/ EINECS ↓	European: Biocidal Products Directive 98/8/EC 1998–2013	Biocidal Product Regulation (EU) 528/2012 EC nr[a]	Directive 2000/60/EC (WFD, 2014 cons.)[b]	Plant Protection Products 91/414/EEC 1991–2011	Regulation (EC) No. 1272/2008 Annex VI (CLP)	Regulation (EC) No. 1907/2006 Annex XIV (Authorisation)	Regulation (EC) No. 1907/2006 Annex XV (Candidate List)	Regulation (EC) No. 1907/2006 Annex XVII (Restriction)	Regulation (EC) No. 166/2006 Pollutant Release (EPRTR)[b]	National: Danish List of Undesirable Substances (LOUS)	Dutch Substances of High Concern (ZZS)[b]	Japanese PACs list	Directive Industrial Emissions 2010/75/EU (IPPC Annex II list)[b]	International: OSPAR[b]	(UNEP) Stockholm convention (POPs Protocol)
Dissolving grade pulp	9004-34-6	232-674-9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sulfuric acid, 98%	7664-93-9	231-639-5	–	–	–	–	+	–	–	–	–	–	–	–	+ (sulfuric)	–	–
Bio-based binder	37294-28-3		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Liquid nitrogen	7727-37-9	231-783-9	+	+	–	–	+	–	–	–	–	–	–	–	+ (nitrogen)	–	–
Ethanol, 97%	64-17-5	200-578-6	–	–	–	–	+	–	–	–	–	–	–	–	+ (carcinogen)	–	–

[a] Compounds that are included in the Biocidal Product Regulation (EU) 528/2012, are listed by EC number i.s.o. CAS number.
[b] These regulations are all included in the search engine of the RIVM database "risks of compounds" (risico's van stoffen). http://www.rivm.nl/rvs/.

of measured impacts. In this case study, the further impact reductions obtainable through process optimisation and improvement are at relatively marginal level compared to the impact reduction leap achieved with the first upscaling process design.

Impacts related to biomass feedstock production (e.g. land-use related impacts) are often considered as an important trade-off of biobased products (Broeren et al., 2017; Weiss et al., 2012). However, in this case study, the ALO of the CNC foam is dominated by the biobased solvent (ethanol) but not the biobased raw material (wood pulp). This gives an important signal that more awareness should be raised and greater attention should be paid to the selection of solvent in the early-stage of product design.

The impacts of the furthest evolved design modelled in this study might be very close to the actual impacts of the future commercialised product system. The sensitivity analysis of the upscaled process design provides several outlooks by taking into account some of the features of commercial scale production (e.g. a high solvent recycling rate and low carbo-intensive energy sources). Although these features lead to further reduced impacts, it should be noted that the impacts of the future commercialised product could be still higher, as the actual industrial production is often larger than the theoretical design. However, this doesn't mean the impacts of future commercialised product will be definitely higher. Any possibilities of using heat integration and process optimisation in the commercial scale could considerably increase the process efficiency and result in a decrease in the environmental impacts.

An early-stage EHS screening was firstly adopted as a supplement to the LCA to assist the sustainable development of a nanoproduct and its production technology. There is in general a lack of data and assessment methodology in order to perform a full EHS assessment for many novel products in their early-stage development. In this case study, the "known" substances which enter the product systems are scanned against the current legislations to clear up the legislation barriers during early-stage R&D. No highly undesirable substances are found in the manufacturing process. Attention should be paid to sulfuric acid, liquid nitrogen and ethanol to determine how these chemicals should be used in regards to occupational health and safety.

The "unknown" substance in this case study is CNC. There is in general a lack of studies on the (eco)toxicity or environmental health and safety of CNC. Some previous studies show no adverse effects (Kovacs et al., 2010; Vartiainen et al., 2011) but other studies give discordant results (Endes et al., 2016). In this study, the actual risk of CNC was assessed by applying passive sampling by exposing zebrafish embryos and daphnia magna to CNC suspensions and paper slurries. No signs of toxicity were observable upon 120 h of exposure of the zebrafish embryos to either test samples or to controls, indicating lack of effects of chemicals dissolved in either the CNC suspensions or the paper slurry. For a reliable and more complete assessment of the EHS of CNC, careful sample characterization is crucial, as factors such as the morphology, but also endotoxins or chemical impurities influence observed health effects. Particle charge and degree of aggregation are important factors in determining the shape and dimensions of the CNC and in turn its toxicity. The source of the CNC, preparation procedure, and/or post-processing also influence the toxicity of CNC (Roman, 2015). Therefore, further efforts are required to generate solid conclusions on the toxicity of CNC, for example by applying total extraction to assess the potential risk of CNC, by performing more extensive dose-response assessment and by testing the CNC particles, whilst being aware that these particles will not be present as such in the final product formulations.

The case study demonstrated a novel early-stage assessment approach – by combining ex-ante LCA with an early-stage EHS screening when the impact assessment of (eco)toxicity is limited in the early-stage development. The early-stage EHS screening offers a first insight in the ecotoxicity of CNC and gives the direction of the preventive measures for occupational health and safety for the future upscaling of the technology. This combined approach can be particularly interesting for the sustainability assessment of novel material/chemicals in their early-stage development where little or no toxicity information is available. The proposed approach requires a multi-disciplinary team to conduct such an assessment, which requires to involve R&D scientists, LCA practitioners and toxicology scientists. It does require more resources than a conventional ex-ante LCA. But the effort pays off. It leads to significant insight in the environmental performance of a novel material in its early-stage development, much more than an LCA with absent information on toxicity information. The "block list" is a publically-available resource. It can be used by any industrial or academic EHS experts to assist in R&D. It is also applicable for any stages in R&D. Since occupational EHS are usually not included in a LCA, the "block list" scan provides a simplified way to make a first observation for the EHS issues associated with the ingredients used in the manufacturing process. To conduct *in vivo* zebrafish assay expertise in toxicology is required. However, the effort is still small compared to a full-fledged ecotoxicity test of CNC. It is proven tool to flag important toxicity information and identify the attention points for nanomaterials at the earliest possible development stages.

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References

Althaus, H., Hischier, R., Osses, M., Primas, A., Hellweg, S., Jungbluth, N., Chudacoff, M., Ökoscience, C., 2007. Life Cycle Inventories of Chemicals. Ecoinvent Report No. 8. EMPA Dübendorf. Swiss Cent. Life Cycle Invent, Dübendorf, CH.

Arvidsson, R., Nguyen, D., Svanström, M., 2015. Life cycle assessment of cellulose nanofibrils production by mechanical treatment and two different pretreatment processes. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.5b00888, 150515094259005.

Ashby, M.F., 2005. Materials Selection in Mechanical Design. Elsevier, Oxford.

Azizi Samir, M.A.S., Alloin, F., Dufresne, A., 2005. Review of recent research into cellulosic whiskers, their properties and their application in nanocomposite field. Biomacromolecules 6, 612–626. https://doi.org/10.1021/bm0493685.

Beck-candanedo, S., Roman, M., Gray, D.G., 2005. Effect of Reaction Conditions on the Properties and Behavior of Wood Cellulose Nanocrystal Suspensions. https://doi.org/10.1021/bm049300p.

Boustead, I., 2005. Eco-profiles of the European plastics industry: steam (On-site). Plast. Eur. Assoc. Plast. Manuf. 1–18.

Brinchi, L., Cotana, F., Fortunati, E., Kenny, J.M., 2013. Production of nanocrystalline cellulose from lignocellulosic biomass: technology and applications. Carbohydr. Polym. 94, 154–169. https://doi.org/10.1016/j.carbpol.2013.01.033.

Broeren, M.L.M., Zijp, M.C., Waaijers-van der Loop, S.L., Heugens, E.H.W., Posthuma, L., Worrell, E., Shen, L., 2017. Environmental assessment of bio-based chemicals in early-stage development: a review of methods and indicators. Biofuels, Bioprod. Biorefining. https://doi.org/10.1002/bbb.1772 n/a-n/a.

BSI, 2011. Publicly Available Specification PAS 2050: 2011 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services,

978 0 580 71382 8.
Butler, J.D., Parkerton, T.F., Letinski, D.J., Bragin, G.E., Lampi, M.A., Cooper, K.R., 2013. A novel passive dosing system for determining the toxicity of phenanthrene to early life stages of zebrafish. Sci. Total Environ. 463–464, 952–958. https://doi.org/10.1016/j.scitotenv.2013.06.079.
Chen, G.-Q., Patel, M.K., 2011. Plastics derived from biological sources: present and future: a technical and environmental review. Chem. Rev. 112, 2082–2099. https://doi.org/10.1021/cr200162d.
Cok, B., Tsiropoulos, I., Roes, A.L., Patel, M.K., 2014. Succinic acid production derived from carbohydrates: an energy and greenhouse gas assessment of a platform chemical toward a bio-based economy. Biofuels, Bioprod. Biorefining 8, 16–29. https://doi.org/10.1002/bbb.1427.
Dash, R., Li, Y., Ragauskas, A.J., 2012. Cellulose nanowhisker foams by freeze casting. Carbohydr. Polym. 88, 789–792. https://doi.org/10.1016/j.carbpol.2011.12.035.
de Figueirêdo, M.C.B., Rosa, M. de F., Ugaya, C.M.L., Souza Filho, M., de S.M. de, Silva Braid, A.C.C. da, Melo, L.F.L. de, 2012. Life cycle assessment of cellulose nanowhiskers. J. Clean. Prod. 35, 130–139. https://doi.org/10.1016/j.jclepro.2012.05.033.
Doka, G., 2007. Life Cycle Inventories of Waste Treatment Services. ecoinvent report No. 13. Swiss Cent. Life Cycle Invent, Dübend.
Eichhorn, S.J., Dufresne, A., Aranguren, M., Marcovich, N.E., Capadona, J.R., Rowan, S.J., Weder, C., Thielemans, W., Roman, M., Renneckar, S., Gindl, W., Veigel, S., Keckes, J., Yano, H., Abe, K., Nogi, M., Nakagaito, A.N., Mangalam, A., Simonsen, J., Benight, A.S., Bismarck, A., Berglund, L.A., Peijs, T., 2010. Review: current international research into cellulose nanofibres and nanocomposites. J. Mater. Sci. https://doi.org/10.1007/s10853-009-3874-0.
Endes, C., Camarero-Espinosa, S., Mueller, S., Foster, E.J., Petri-Fink, A., Rothen-Rutishauser, B., Weder, C., Clift, M.J.D., 2016. A critical review of the current knowledge regarding the biological impact of nanocellulose. J. Nanobiotechnol. 14, 78. https://doi.org/10.1186/s12951-016-0230-9.
European Comission, 2006. Regulation (EC) 1907/2006 of the European parliament and of teh council of 18 December 2006-REACH. Off. J. Eur. Union 396–849. L: 2006:396:0001:0849:EN: PDF. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ.
European Commission, 2010. ILCD Handbook: General Guide for Life Cycle Assessment - Provisions and Action Steps. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Ispra, Italy.
Eurostat, 2016. Electricity Production Consumption and Market Overview.
Fernández-Dacosta, C., Posada, J.A., Kleerebezem, R., Cuellar, M.C., Ramirez, A., 2015. Microbial community-based polyhydroxyalkanoates (PHAs) production from wastewater: techno-economic analysis and ex-ante environmental assessment. Bioresour. Technol. 185, 368–377. https://doi.org/10.1016/j.biortech.2015.03.025.
Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., Wernet, G., 2007a. Overview and Methodology. Ecoinvent report No. 1.
Frischknecht, R., Tuchschmid, M., Emmeneger, M.F., Bauer, C., Dones, R., 2007b. Ecoinvent report No. 6-XVI, v2.0. In: Dones, R. (Ed.), Strommix und Stromnetz, Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Duebendorf, CH.
Goedkoop, M., Heijungs, R., De Schryver, A., Struijs, J., van Zelm, R., 2013. ReCiPe 2008. A LCIA Method Which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level. Characterisation. A life cycle impact …, p. 133. http://www.lcia-recipe.net.
Habibi, Y., Lucia, L.A., Rojas, O.J., 2010. Cellulose nanocrystals: chemistry, self-assembly, and applications. Chem. Rev. 110, 3479–3500. https://doi.org/10.1021/cr900339w.
Hauschild, M., Jeswiet, J., Alting, L., 2005. From life cycle assessment to sustainable production: status and perspectives. CIRP Ann. Manuf. Technol. 54, 1–21. https://doi.org/10.1016/S0007-8506(07)60017-1.
Hermann, B.G., Blok, K., Patel, M.K., 2007. Producing bio-based bulk chemicals using industrial biotechnology saves energy and combats climate change. Environ. Sci. Technol. 41, 7915–7921.
Hermann, B.G., Patel, M., 2007. Today's and tomorrow's bio-based bulk chemicals from white biotechnology: a techno-economic analysis. Appl. Biochem. Biotechnol. 136, 361–388.
Hottle, T.A., Bilec, M.M., Landis, A.E., 2013. Sustainability assessments of bio-based polymers. Polym. Degrad. Stabil. 98, 1898–1907. https://doi.org/10.1016/j.polymdegradstab.2013.06.016.
Hubbe, M. a, Rojas, O.J., Lucia, L. a., Sain, M., 2008. Cellulosic nanocomposites: a review. BioResources 3, 929–980. https://doi.org/10.15376/biores.3.3.929-980.
Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S.,R.,F., Hendriks, A.J., de Meent, D., Ragas, A.M.J., Reijnders, L., Struijs, J., 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ. Sci. Technol. 40, 641–648.
IPCC, 2013. Working Group I Contribution to the IPCC Fifth Assessment Report Climate Change 2013: the Physical Science Basis.
ISO, 2006a. Environmental Management - Life Cycle Assessment - Requirements and Guidelines.
ISO, 2006b. Environmental Management - Life Cycle Assessment - Principles and Framework.
Jungbluth, N., Chudacoff, M., Dauriat, A., Dinkel, F., Doka, G., Faist emmenegger, M., Gnansounou, E., Kljun, N., Schleiss, K., Spielmann, M., Stettler, C., Sutter, J., 2007. Life Cycle Inventories of Bioenergy. ecoinvent report No. 17. Swiss Cent. Life Cycle Invent, Dübendorf, CH.
Khalil, H.P.S.A., Bhat, A.H., Ireana Yusra, A.F., 2012. Green composites from sustainable cellulose nanofibrils: a review. Carbohydr. Polym. 87, 963–979. https://doi.org/10.1016/j.carbpol.2011.08.078.
Klemm, D., Kramer, F., Moritz, S., Lindström, T., Ankerfors, M., Gray, D., Dorris, A., 2011. Nanocelluloses: a new family of nature-based materials. Angew. Chem. Int. Ed. 50, 5438–5466. https://doi.org/10.1002/anie.201001273.
Köhler, A.R., Som, C., 2014. Risk preventative innovation strategies for emerging technologies the cases of nano-textiles and smart textiles. Technovation 34, 420–430. https://doi.org/10.1016/j.technovation.2013.07.002.
Kovacs, T., Naish, V., O'Connor, B., Blaise, C., Gagné, F., Hall, L., Trudeau, V., Martel, P., 2010. An ecotoxicological characterization of nanocrystalline cellulose (NCC). Nanotoxicology 4, 255–270. https://doi.org/10.3109/17435391003628713.
Li, Q., McGinnis, S., Sydnor, C., Wong, A., Renneckar, S., 2013. Nanocellulose life cycle assessment. ACS Sustain. Chem. Eng. 1, 919–928. https://doi.org/10.1021/sc4000225.
Mayer, P., Tolls, J., Hermens, J., Mackay, D., 2003. Peer reviewed: equilibrium sampling devices. Environ. Sci. Technol. 37, 184A–191A. https://doi.org/10.1016/S0889-8561(03)00030-4.
Mi, H.Y., Jing, X., Peng, J., Salick, M.R., Peng, X.F., Turng, L.S., 2014. Poly(ε-caprolactone) (PCL)/cellulose nano-crystal (CNC) nanocomposites and foams. Cellulose 21, 2727–2741. https://doi.org/10.1007/s10570-014-0327-y.
Moon, R.J., Martini, A., Nairn, J., Simonsen, J., Youngblood, J., 2011. Cellulose nanomaterials review: structure, properties and nanocomposites. Chem. Soc. Rev. https://doi.org/10.1039/c0cs00108b.
Mueller, S., Sapkota, J., Nicharat, A., Zimmermann, T., Tingaut, P., Weder, C., Foster, E.J., 2015. Influence of the nanofiber dimensions on the properties of nanocellulose/poly(vinyl alcohol) aerogels. J. Appl. Polym. Sci. 132, 1–13. https://doi.org/10.1002/app.41740.
Nascimento, D.M. do, Dias, A.F., Araújo Junior, C.P. de, Rosa, M. de F., Morais, J.P.S., Figueirêdo, M.C.B. de, 2016. A comprehensive approach for obtaining cellulose nanocrystal from coconut fiber. Part II: environmental assessment of technological pathways. Ind. Crop. Prod. https://doi.org/10.1016/j.indcrop.2016.02.063.
OECD, 2013. Test No. 210: Fish, Early-life Stage Toxicity Test. Test 1–21. https://doi.org/10.1787/9789264203785-en.
OECD, 2012. Test No. 211: Daphnia Magna Reproduction Test. OECD Guidel. Test. Chem.. - Eff. Biot. Syst. Section 2, p. 23. https://doi.org/10.1787/9789264070127-en.
Oksman, K., Aitomäki, Y., Mathew, A.P., Siqueira, G., Zhou, Q., Butylina, S., Tanpichai, S., Zhou, X., Hooshmand, S., 2016. Review of the recent developments in cellulose nanocomposite processing. Compos. Part A Appl. Sci. Manuf. 83, 2–18. https://doi.org/10.1016/j.compositesa.2015.10.041.
Patel, A.D., Meesters, K., den Uil, H., de Jong, E., Blok, K., Patel, M.K., 2012. Sustainability assessment of novel chemical processes at early stage: application to biobased processes. Energy Environ. Sci. 5, 8430. https://doi.org/10.1039/c2ee21581k.
Piccinno, F., Hischier, R., Saba, A., Mitrano, D., Seeger, S., Som, C., 2016. Multi-perspective application selection: a method to identify sustainable applications for new materials using the example of cellulose nanofiber reinforced composites. J. Clean. Prod. 112, 1199–1210. https://doi.org/10.1016/j.jclepro.2015.06.105.
Piccinno, F., Hischier, R., Seeger, S., Som, C., 2015. Life cycle assessment of a new technology to extract, functionalize and orient cellulose nanofibers from food waste. ACS Sustain. Chem. Eng. https://doi.org/10.1021/acssuschemeng.5b00209, 150518111053007.
Roman, M., 2015. Toxicity of cellulose nanocrystals: a review. Ind. Biotechnol. 11, 25–33. https://doi.org/10.1089/ind.2014.0024.
Schrijvers, D.L., Leroux, F., Verney, V., Patel, M.K., 2014. Nanocomposites using organo-modified layered double hydroxides for potential application in agricultural films. Green Chem. 16, 4969–4984. https://doi.org/10.1039/c4gc00830h.
Sheldon, R. a, Sanders, J.P.M., 2015. Toward concise metrics for the production of chemicals from renewable biomass. Catal. Today 239, 3–6. https://doi.org/10.1016/j.cattod.2014.03.032.
Sheldrick, L., Rahimifard, S., 2013. Evolution in ecodesign and sustainable design methodologies. In: 20th CIRP Int. Conf. Life Cycle Eng, pp. 35–40. https://doi.org/10.1007/978-981-4451-48-2_6.
Shoseyov, O., Heyman, A., Lapidot, S., Meirovitch, S., Nevo, Y., Gustafsson, T., 2013a. US20130171439-cellulose-based Composite Materials.
Shoseyov, O., Heyman, A., Lapidot, S., Meirovitch, S., Nevo, Y., Rivkin, A., 2013b. Method for Production of Cellulose Nanocrystals from Cellulose-containing Waste Materials.
Silvia, L., Mojca, F.G., Andrew, W., 2010. Review of QSAR Models and Software Tools for Predicting Acute and Chronic Systemic Toxicity. https://doi.org/10.2788/60766.
Siqueira, G., Bras, J., Dufresne, A., 2010. Cellulosic bionanocomposites: a review of preparation, properties and applications. Polymers (Basel) 2, 728–765. https://doi.org/10.3390/polym2040728.
Siro, Istvan, Plackett, D., 2010. Microfibrillated Cellulose and New Nanocomposite Materials ;: a Review, pp. 459–494. https://doi.org/10.1007/s10570-010-9405-y.
UNEP, 2008. Stockholm Convention on Persistent Organic Pollutants. United Nations Environ. Program. https://doi.org/10.1111/1467-9388.00331.
Vartiainen, J., P??hler, T., Sirola, K., Pylkk??nen, L., Alenius, H., Hokkinen, J., Tapper, U., Lahtinen, P., Kapanen, A., Putkisto, K., Hiekkataipale, P., Eronen, P.,

Ruokolainen, J., Laukkanen, A., 2011. Health and environmental safety aspects of friction grinding and spray drying of microfibrillated cellulose. Cellulose 18, 775–786. https://doi.org/10.1007/s10570-011-9501-7.

Villares, M., Işıldar, A., Beltran, A.M., Guinee, J., 2016. Applying an ex-ante life cycle perspective to metal recovery from e-waste using bioleaching. J. Clean. Prod. 129, 315–328. https://doi.org/10.1016/j.jclepro.2016.04.066.

Vrana, B., Allan, I.J., Greenwood, R., Mills, G.A., Dominiak, E., Svensson, K., Knutsson, J., Morrison, G., 2005. Passive sampling techniques for monitoring pollutants in water. TrAC Trends Anal. Chem. 24, 845–868. https://doi.org/10.1016/j.trac.2005.06.006.

Weiss, M., Haufe, J., Carus, M., Brandão, M., Bringezu, S., Hermann, B., Patel, M.K., 2012. A review of the environmental impacts of biobased materials. J. Ind. Ecol. 16 https://doi.org/10.1111/j.1530-9290.2012.00468.x.

Wik, V.M., Aranguren, M.I., Mosiewicki, M.A., 2011. Castor oil-based polyurethanes containing cellulose nanocrystals. Polym. Eng. Sci. 51, 1389–1396. https://doi.org/10.1002/pen.

Zhou, Y., Fu, S., Pu, Y., Pan, S., Ragauskas, A.J., 2014. Preparation of aligned porous chitin nanowhisker foams by directional freeze-casting technique. Carbohydr. Polym. 112, 277–283. https://doi.org/10.1016/j.carbpol.2014.05.062.