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A review of LCA studies on bio-based products using an ecosystem services perspective

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Outline

Sommario

È ampiamente riconosciuto in termini globali che l'utilizzo di risorse non rinnovabili per la produzione e l'utilizzo di prodotti di uso comune come l'energia, i combustibili, i materiali plastici e i materiali di costruzione hanno portato a problemi ambientali globali come il cambiamento climatico, la modificazione dei cicli biochimici piuttosto che la distruzione della biodiversità. Da questa consapevolezza è nato negli ultimi anni il concetto di bioeconomia. La bioeconomia si riferisce a un'economia che utilizza risorse naturali rinnovabili come colture, foreste, animali e microrganismi per produrre cibo, energia e altri prodotti e servizi a base biologica al fine di garantire la biodiversità e la protezione dell'ambiente. Nonostante questa includa diversi settori come l'agricoltura e la pesca, in questa tesi ci si è focalizzati sui bioprodotti di origine forestale, o derivanti comunque da biomassa legnosa come la bioenergia (elettricità e calore), i biocombustibili, i componenti biochimici, i biomateriali ecc. La produzione e l'utilizzo di questi prodotti sono fondamentali per un mondo più sostenibile, ed è per questo che è necessario lo studio delle loro performance ambientali, economiche e sociali. A tal fine, una metodologia ampiamente utilizzata è l'analisi del ciclo di vita (Life Cycle Assessment, LCA) e gli approcci che da essa si sono sviluppati: Life Cycle Costing (LCC) e Social Life Cycle Assessment (SLCA). Questi strumenti permettono di identificare gli impatti ambientali, economici e sociali generati lungo tutto il ciclo di vita del prodotto, dall'estrazione delle materie prime, allo smaltimento del rifiuto e sono stati recentemente utilizzati anche nel campo della bioeconomia. Partendo da queste considerazioni, lo scopo della tesi è stato quello di raccogliere ed analizzare la letteratura scientifica pubblicata dal 2016 al 2019 che ha avuto come oggetto l'applicazione di approcci LCA al settore della bioeconomia. Con tale analisi non si è posto l'accento sulla magnitudo degli impatti generati dai prodotti e dai processi ma si è voluto tracciare lo stato dell'arte della letteratura scientifica in questo settore, delineando la localizzazione geografica degli studi, il tipo di prodotti analizzati e i metodi LCA utilizzati nonché gli indicatori di impatto che vengono solitamente stimati. Successivamente si è cercato di mettere in relazione tali indicatori di impatto con i servizi ecosistemici ovvero i benefici che le persone ottengono dagli ecosistemi.

I risultati hanno mostrato un numero consistente di studi pubblicati ogni anno tra il 2016 e il 2019, che hanno avuto come oggetto dei casi studio localizzati principalmente negli Stati uniti, Canada, Svezia, Finlandia, Germania e Italia. Gli approcci LCA (ed in particolare quello relativo alla stima degli impatti ambientali) sono ampiamente utilizzati in questo campo e questo evidenzia il fatto che la comunità scientifica, in risposta anche alle strategie nazionali ed internazionali di sviluppo della

bioeconomia) sta prestando attenzione al monitoraggio delle prestazioni ambientali dei bioprodotti ed in particolare di quelli a basso valore quali energia, calore e biocarburante di seconda generazione.

L'analisi dei metodi utilizzati ha chiaramente mostrato come in questo campo si preferisca utilizzare "midpoint methods" rispetto a "endpoint methods". Questo è un risultato positivo, considerando che i midpoint methods hanno una maggiore solidità scientifica. Tuttavia, i risultati che forniscono in termini di indicatori di impatto sono più difficili da spiegare a portatori di interesse non esperti. Infine, il collegamento proposto tra gli indicatori di impatto calcolati e i servizi ecosistemici ha permesso di evidenziare che è possibile descrivere gli indicatori di impatto in un'ottica di benefici persi a livello di servizi ecosistemici, dando così una più ampia interpretazione dei risultati ottenuti.

Summary

It is widely recognized in global terms that the use of non-renewable resources for the production and utilisation of commonly used products such as energy, fuels, plastics and construction materials have led to global environmental problems such as change climate change, biochemical cycles as well as biodiversity loss. From this awareness the concept of bioeconomy was born in recent years. Bioeconomy refers to an economy that uses renewable natural resources such as crops, forests, animals and micro-organisms to produce food, energy and other bio-based products and services in order to guarantee biodiversity and environmental protection. Although this includes various sectors such as agriculture and fishing, in this thesis we focused on bioproducts of forest origin, or deriving from woody biomass such as bioenergy (electricity and heat), biofuels, biochemical components, biomaterials etc. The production and utilisation of these products are fundamental for a more sustainable world, that is why it is necessary to study their environmental, economic and social performance. To this end, the widely used Life Cycle Assessment (LCA) methodology as well as the methodologies derived from it, i.e. Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA), could be adopted. These tools make it possible to identify the environmental, economic and social impacts generated throughout the life cycle of the product, from the extraction of raw materials to the disposal of waste and have recently been used also in the field of bioeconomy. Starting from these considerations, the aim of the thesis was to collect and analyse the scientific literature published from 2016 to 2019 focusing on the application of LCA approaches to the bioeconomy sector. In such analysis the emphasis was not placed on the magnitude of the impacts generated by products and processes, rather on tracing the state of the art of scientific literature in this sector, outlining the geographical location of the studies, the type of products analysed and LCA methods used as well as the impact indicators that are usually estimated. Subsequently we tried to relate these impact indicators with ecosystem services, which are benefits that people obtain from ecosystems.

The results showed a substantial number of studies published each year between 2016 and 2019, investigating case studies mainly located in the United States, Canada, Sweden, Finland, Germany and Italy. LCA approaches (and in particular the one related to the estimation of environmental impacts) are widely used in this field and this highlights the fact that the scientific community, in response also to national and international bioeconomy development strategies, is paying attention to the monitoring of environmental performance of bioproducts (in particular low-value ones such as energy, heat and second-generation biofuel).

The analysis of the adopted methods has clearly shown a preference for "midpoint methods". This is a positive result, considering that “midpoint methods” are scientifically more robust than “endpoint methods”, although the results they provide are more difficult to explain to non-expert stakeholders. Finally, the proposed link between calculated impact indicators and ecosystem services allowed to highlight that it is possible to describe impact indicators in a perspective of benefits lost at ES level, thus providing a wider interpretation of obtained results.

1 Introduction

In the last 40 years an increasing awareness and knowledge of different environmental problems related to the human activities such as losing biosphere integrity, climate change, modification of biochemicals flows, land system change, ozone layer depletion and ocean acidification (Steffen and Rockström, 2015) has led to the development of different sustainable development strategies (Purvis et al., 2019). The current international policies are largely based on the 17 Sustainable Development Goals (SDG) of Agenda 2030 adopted by the United Nation, which is currently made up of 193 countries. Such SDG include 169 targets to attain by 2030. Agenda 2030 is a plan for people, planet and prosperity which includes, in addition to the three pillars of sustainability, peace and partnership. It therefore aims to solve important issues such as to end poverty and promote health, to protect the planet from degradation, to foster peaceful, just and inclusive societies and to ensure that all human beings can enjoy prosperous and fulfilling lives (Smith et al., 2018). As an avenue to pursue these goals, “bioeconomy” has been conceived as an operative sustainable strategy and concept (EC, 2018). Bioeconomy consists on the utilisation of the biomass as a primary source of carbon replacing fossil fuels. Bio-based products and their derivates are considered as the best alternatives to replace petroleum products and mitigate their environmental issues. Starting from this point, the bioeconomy approach has been developed during the last 10 years (Patermann et al., 2018). It is based on the idea of the economy built from biomass derived from agriculture, forest and wood waste and these natural feedstocks are used for the production of high-tech value bioproducts such as bioenergy, biochemicals and biomaterials (Popa, 2018). Based on this consideration the aim is to move from a fossil based economy to a bioeconomy, although today these two economies already coexist (Morone, 2018). This transition can result in 26 trillion dollars in economic benefits worldwide, generate over 65 million new jobs and avoid over 700.000 premature deaths from air pollution (Global Climate Action Summit, 2018).

Despite the great potential of bioeconomy, it is still necessary to monitor the environmental, economic and social performance of bioproducts. Life cycle assessment (LCA) has been used for decades as an environmental management tool (International Organization for Standardization (ISO), 2006). Subsequently, other tools to monitor economic and social performance have been developed such as the life cycle cost (LCC) and the social life cycle assessment (SLCA). In particular, LCA methodology allows to assess the environmental impacts related to production processes and products, and it has been used also for bio-based products. This tool is commonly used, but as any method it has also some limitations. For instance, it does not fully account for all the environmental impacts and important indicators such as land use change, biodiversity loss and ecosystem quality, which are especially relevant for bio-based products (Martin et al., 2018). However, since the bioeconomy sector is increasingly gaining importance in national economies, it is crucial to consider such issues in LCA. In this context, assessing the bioeconomy sustainability with an ecosystem services perspective seems to be a promising approach. The ecosystem services concept has come to be a key reference in sustainability science and policy-making by highlighting the often invisible benefits that ecosystems provide to human beings, such as food, clean water, climate and water regulation, pest control and cultural values (Costanza et al., 2017). This kind of perspective can clarify the linkages between bioeconomy and the impacts on the environment and human wellbeing, thus informing about how the ecological components are affected by bioeconomy and how, in turn, this can affect our wellbeing, with the final aim to assist policy makers in identifying the trade-offs in biobased production (Gasparatos et al., 2011). Some scholars have indeed suggested that the inclusion of environmental problems and ecological issues in LCA can be supported by the ecosystem service concept (Bruel et al., 2016), also in the context of biofuels production, thus highlighting a new opportunity for ecosystem services assessment (Maia de Souza et al., 2018)

In this context, the aim of this thesis is to perform a comprehensive review of the scientific literature assessing the sustainability performance of bio-based products through LCA approaches (including environmental LCA, LCC and SLCA). In particular, the thesis addresses the following three research questions/objectives:

1. What is the state of the most recent literature, including its temporal distribution, the products and geographic areas in each study and the methods used?
2. Which impacts, and related midpoints are considered by the reviewed studies?
3. How do midpoints relate to ecosystem services?

The focus of the review is on bio-based products and processes from wood, as they represent a major source of biomass in the current bioeconomy (Roos and Stendahll, 2015). In addition to be a key of primary production systems for raw material used in bioeconomy, natural and semi-natural forests are critical for delivering multiple ecosystem services of vital importance to human wellbeing globally, such as water purification and carbon storage.

Results from the review carried out in this thesis work can be a useful reference for academia and industry professionals dealing with the issues related to assessing environmental impacts of bioeconomy. Moreover, the link to the concept of ecosystems services proposed in this study will contribute to provide a broader vision of LCA approaches to bio-based products, looking at the result in a perspective of affected benefits provide by natural systems (i.e. ecosystem services).

2 Conceptual background

2.1 Bioeconomy and sustainability

In our present economy we are using fossil fuels (petroleum/oil, natural gas, coal) for many different purposes such as for producing energy, chemicals, plastics, textile and other materials we use every day. Material consumption, especially for energy production, is still increasing worldwide (Abas et al., 2015). It has been estimated that the world population will increase constantly in the future, entailing a continued and major depletion of natural resources (United Nations, 2017). The knowledge that fossil fuels are non-renewable resources and that their use contributes to environmental problems such as climate change, wildlife and habitat destruction is necessary (Sinding-Larsen and Wellmer, 2012). With the goal to implement the concept of sustainable development (Brundtland, 1987), policy-makers, academia and companies worldwide have developed new sustainable strategies such as circular, green and bio economy (D'Amato et al., 2017) and solutions such as green chemistry and eco-design in order to change our current economy (Prashant Kumar, 2019; Song and Han, 2015) . Bioeconomy refers to an economy that uses renewable natural resources such as crops, forests, animals and microorganisms to produce food, energy and other bio-based products and services with the aim of ensuring biodiversity and environmental protection. It is considered as a revolution in our economic development, decreasing, as shown in Figure 1, our dependence on fossil resources and creating new economic growth, jobs and innovation (European Commission, 2018a).

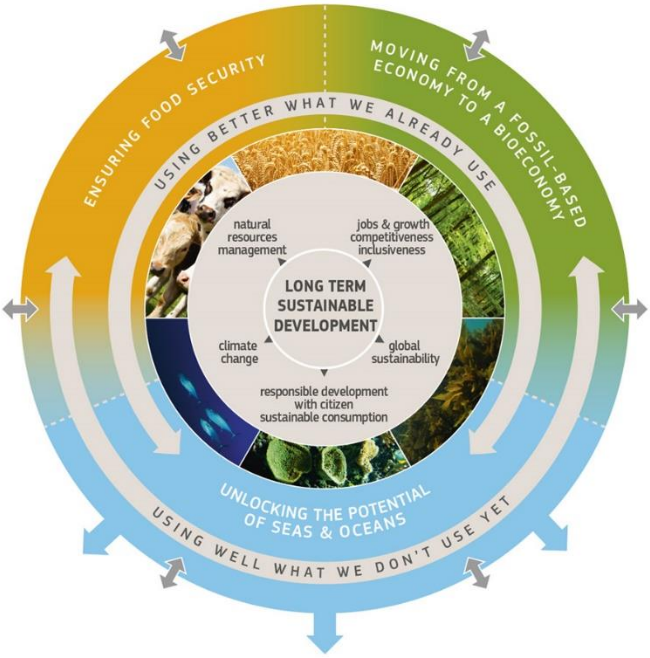

Figure 1: Representation of the bioeconomy concept (European Commission, 2018b).

Bioeconomy aims on direct act against climate change: for example just by using wood instead of fossil fuel, greenhouse gasses emission can be decreased because forest acts as carbon sink (van Renssen, 2014). People can also change life in the rural area through bioeconomy, as the pioneer *Novamont* company showed in a small rural area in Italy, where by using starch material from corn and other crops it developed the first new biodegradable bioplastic named Mater-Bi (Bastioli, 1998). As another example, in Finland, the Innovation Hub (Smarter Mobility) at the Helsinki Metropolia University of Applied Sciences, in co-operation with the forest-based bioindustry company UPM, designed and manufactured a passenger car (the Biofore Concept Car) that utilizes various wood-based materials. Those materials include thermoplastics (cellulose-polypropylene composite called UPM ForMi), composites obtained by regenerating cellulose reinforcement with a thermoset matrix and a plywood-thermoplastic composite (called UPM Grada); the vehicle itself runs on diesel made out of pulp-making process side-streams (called UPM BioVerno). Bioeconomy is thus central in our era and since 2010 it has grown continuously. Importantly, in the European Union it created around €2.2 trillion (10^{12}) of values added, generating 18.2 million employs of the Europe labour force in one year (Ronzon et al., 2017).

Bioeconomy is thus presented as a way to generate more wealth, well-being and growth from natural resources. Until 1970 economists saw the environment only as a source of resources, considering environmental problems as a consequence of market failure and a source of limitation of economic growth (Turner et al., 2013). The origin of bioeconomy started in 1970 when the economist Georgescu-Roegen developed the "decrease concept", stating that the unlimited growth would not be compatible with the biophysical law of nature (Georgescu-Roegen, 1971). In the 80s and 90s, there was a belief that biological advancement would transform the industry worldwide. The European Commission put an important effort to promote the concept of bioeconomy and its opportunities, starting from the biotechnology utilisation in the market towards the replacement of fossil resources by bio-based resources (Birner, 2017). In the early 2000s, there has been more investments on innovation and high technology industries. In the following years, there has been a push from the EU on transforming life science knowledge into new, sustainable, eco efficient and competitive products underlining the importance of this concept and the role of Europe as a worldwide leader in this field. Finally, in 2007 researches and companies from different fields such as biotechnology, bioenergy, crop production and biomedicine identified the fundamental role of biotechnology in the utilisation of crop as a renewable industrial feedstock to produce biofuel, biochemicals and biopolymers (Lewandowski, 2017).

Consequently, the developments in bioeconomy has been reflected in the increase of scientific publications as well as economic and policy strategies such as the European bioeconomy strategy of 2012.

2.1.1 Bioeconomy strategies in EU and worldwide

At the begin of 2018, almost 50 countries were pursuing bioeconomy development in their policy strategies. These strategies are present from North to South America, Europe, Russia, Asian countries Australia and Africa, as shown in Figure 2, and depends on the country level of development, resources and political system. For example, the developed countries can promote their bioeconomy through subsidies which fund bio-based research and development aiming at improving the competitiveness of bio-based products. In less developed countries they see their bioeconomy strategies as very large potential to foster their economic developments in a sustainable way. In addition, strategy implementation can proceed along one or more transformation path (TP) such as fossil fuel substitution, boosting primary sector productivity, new and more biomass uses, low bulk and high value application. Bioeconomy has become a strategic political goal in all the countries that have bioeconomic ambition (Dietz et al., 2018).

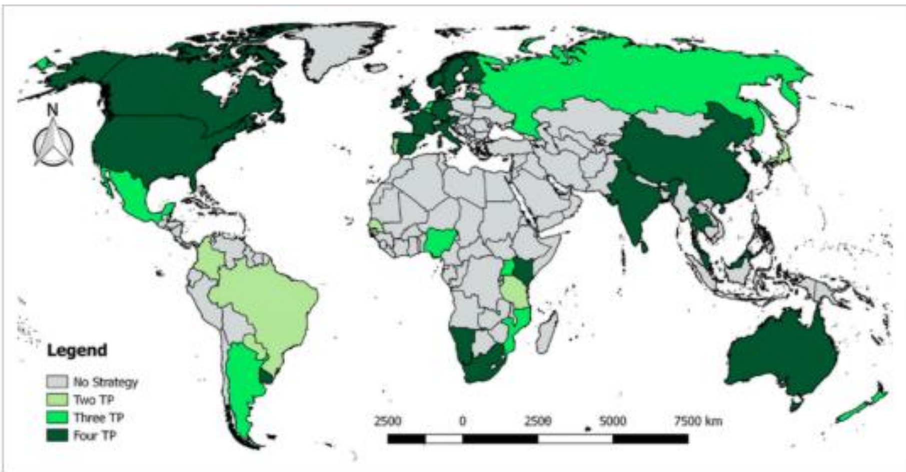

Figure 2: Bioeconomy strategies around the world (Dietz et al., 2018).

Europe and the United States were the first to launch bioeconomy strategies in 2012. United States bioeconomy strategies focus more on biofuel and biotechnology (House, 2012). The European bioeconomy strategy was design in that year and reviewed in 2018 in order to ensure food security, manage natural resources in a sustainable way, reduce dependence on non-renewable resources, mitigate climate change and create job, maintaining Europe competitiveness (Caudet and von Hammerstein-Gesmold, 2018; European Commission, 2012). In particular, in 2018 European Union focused its strategy on the circular bioeconomy that is the movement of bioeconomy toward the use of wastes, co-products and residue resources, thus ensuring the most efficient use of natural resources, shifting from virgin to secondary material production (Philp and Winickoff, 2018).

The goal of this strategy was the improvement of the sustainable use of renewable resources keeping the idea of the previous strategy. To achieve this goal three key objectives and related concrete actions were defined. Scaling up and strengthening the Biobased sector through an investment of € 100 million; Rapidly deploying bioeconomies around Europe through the development of a strategic agenda aimed at the distribution of bio-based products and sustainable agricultural food; Protecting the ecosystem and understanding the ecological limitation of the bioeconomy providing guidance and promoting good practices on how to operate as well as implementing an EU-wide monitoring system (European Commission, 2018a). The implementation of these actions may run until 2025.

This strategy has been implemented in individual European countries, even though to date not all member states have implemented it. The first countries in Europe adopting bioeconomy strategies were the Nordic countries such as Finland and Norway, followed by Germany, Austria, France, United Kingdom and Italy. Within the EU, national strategies vary, most likely depending of the self-sufficiency of domestic biomass (De Besi and McCormick, 2015). As an example, Finland is a pioneer in bioeconomy and bioeconomy strategy. It aims at economic growth and the creation of new jobs by increasing the bio-economy business and by producing high value products and services while ensuring the natural conditions of the ecosystem (MEE, 2014). On the other hand, Italy strategy is based on longer, more sustainable and locally routed activities in order to deliver a value product or service for the marker. It states that is possible improving the sustainable production of products in each sector, allowing an effective valorisation of the ecosystem (Presidency of Council of Ministers, 2017).

Following the logic of national strategies, private initiatives have been implemented by multinational leaders' companies such as the Coca Cola Company, IKEA, LEGO and others, which aim to switch their production from fossil-based chemicals to biochemicals. These simple examples shows the importance biochemicals and bioeconomy strategy have in the global market (Biddy et al., 2016).

2.1.2 Biobased resources: biomass as a core of bioeconomy

The bioeconomy strategies mentioned above took in consideration different kind of sectors such as forestry, agriculture, fishing and aquaculture. However, the focus of this thesis is on wood-based bioproducts, so the following chapters are emphasizing on these aspects. Within this context, bioeconomy strategies focus on the lignocellulosic biomass production or other kinds of bio-waste production subsequently converted into value added bioproducts such as bioenergy, biochemicals, biomaterials and others (Ragauskas et al., 2006). It was estimated by a model based projection that 476 million tons of lignocellulosic biomass is needed to ensure the production of energy, fuel and biobased material in Europe by 2030; this conversion is possible due to the extraction of the building block chemicals such as sugar and lignin from the biomass (S2Biom, 2016).

Biomass is the biodegradable fraction of products, waste and residual generated by natural processes such as natural components originated from growing land vegetation via photosynthesis (Vassilev et al., 2010). Its chemical composition is ca. 70% polysaccharides, 20% lignin and 10% fats, proteins, terpenoids, alkaloids, nucleic acid and also a small number of inorganic compounds. Given its great availability around the world, biomass as lignocellulosic feedstock is considered to be the best source of polysaccharides and lignin for large-scale bioproducts production (Petrus and Noordermeer, 2006). Lignocellulosic feedstock can range from food/non-food crops to agroforestry residue and waste. Food crops such as sugarcane, corn and rapeseed crops, also called first generation feedstock, was commonly used to produce these bioproducts, but the debate about intensive land use for energy and oil crops at the expense of food crops became more pronounced so nowadays the utilisation of second generation feedstock is promoted (Thompson, 2012). Second generation feedstock include non-food crops (non-food terrestrial biomass) and lignocellulosic wastes (agroforestry residues and processing). Non-food terrestrial biomass includes short rotation woody crops and herbaceous crops. Woody crops are crops that grow faster, such as 4-5 years and they are so called “short rotation woody crops”. They are hard wood such as willow, poplar, black locust and eucalyptus and compared with the long-term woody crops (12 years) are better in term of sustainability supply and weed control. Using this feedstock does not overcome the problems related to land use at the expense of other crops, so land use competition still remains (Popa, 2018). In the near future, a solution to this problem could be to integrate the pulp and paper production industries with the production of other bio-based products, using its side streams or by-products. This would be possible if we consider that these industries extract only 47% of the potential value from lignocellulosic materials (Chakraborty et al., 2019). On the other hand, herbaceous perennial crops are also used in biorefinery; they include herbaceous crops such as *Miscanthus* and *Sorghum* and are most used for energy production (Lee et al., 2018).

In addition, other important second generation feedstock used in bioeconomy sector are agroforestry residues and processing that include primary forestry residues and secondary forestry wasted. Forestry residues are generated during forest activities such as harvesting, shaping, weeding, trimming and pruning. These products have low economic value. These residues are stumps, branches, needles and leaves (Thorenz et al., 2018). Secondary forestry wastes are derived from industrial processes such as cutting, veneer, sawdust and sludge, e.g. for the production of furniture, panels pulp and paper.

Starting from this feedstock, biorefinery represents a sustainable process and cost-effective conversion of it into a number of bioproducts such as chemicals and materials, as well as bioenergy such as biofuel, power or heat (Cherubini, 2010), as shown in Figure 3.

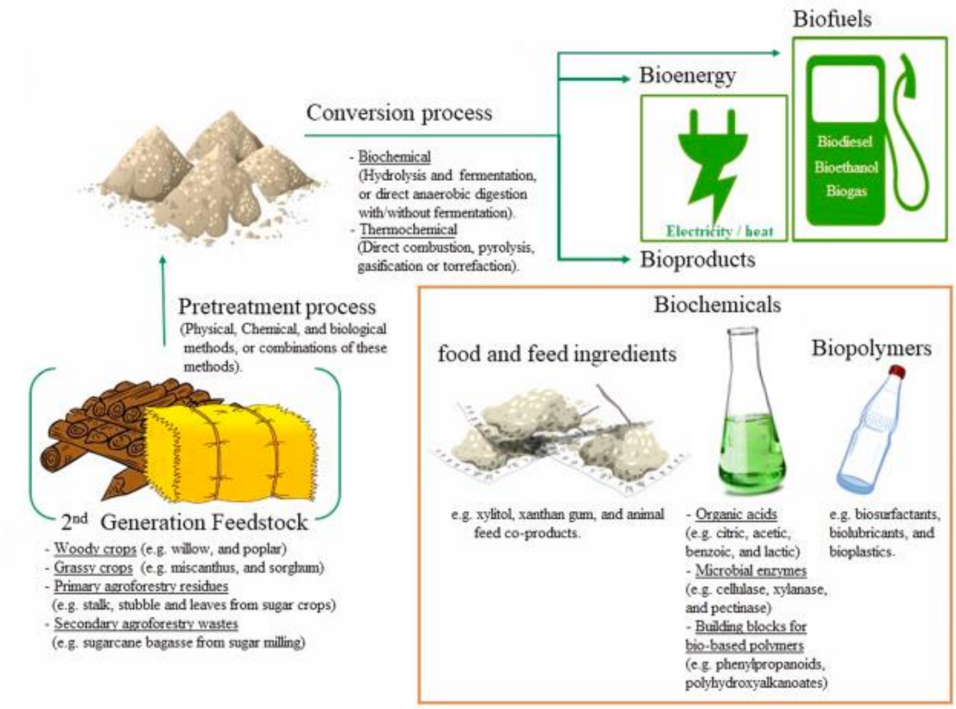

Figure 3: From second generation feedstock to bio-products (adapted from (Hassan et al., 2019)).

Biorefining is still an emerging production process (there are only 224 biorefineries in Europe (Biobased industries consortium, 2019)), and its aim is to replace the oil refinery product and at the same time be competitive in the market. Biorefinery processes are, in some respects, similar to the petrochemical ones, but different for the resources used and for other technical aspects. One of the main problem about biorefinery is the heterogeneous composition of biomass so, different pre-treatments are needed in order to have an high yield of simply sugar released (Sillanpää et al., 2017). As stated above, bioeconomy products include a variety of energy, material, compounds and chemicals. An example of the main products derived from the bioeconomy sector, focusing on forest sector only, are shown in Figure 4, representing the so-called bioeconomy pyramid (Toppinen et al., 2018). This pyramid has been developed in six levels and each of them represents different products. In particular, the products on the bottom have low value added and their production needs a lot of biomass. Going up in the pyramid the products have more value added and less biomass is needed for their production.

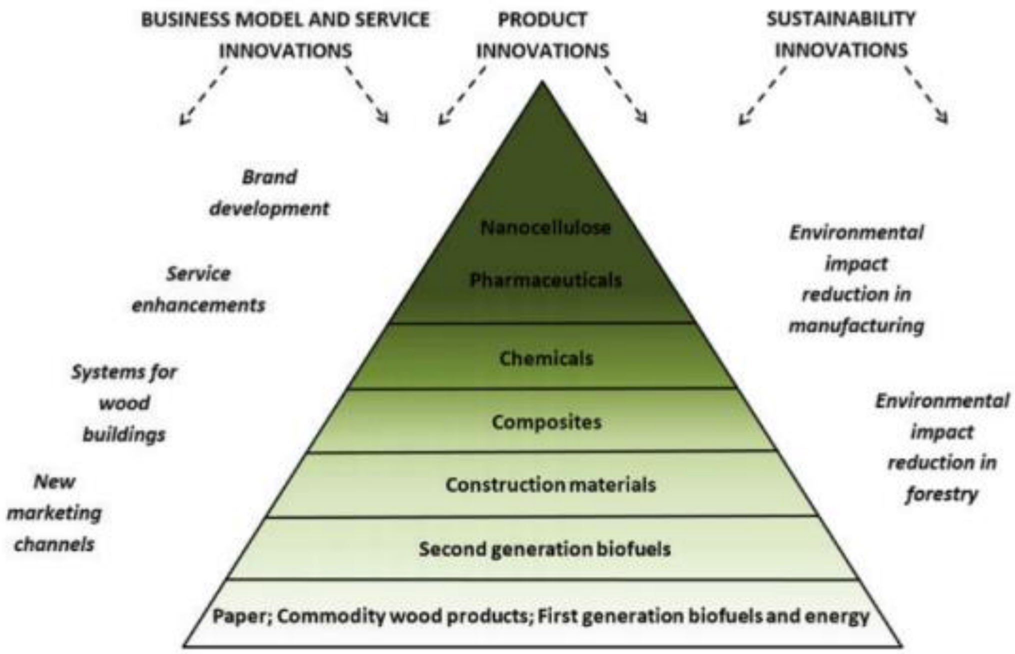

Figure 4: representation of bioeconomy pyramid (Toppinen et al., 2018a).

For example, starting from the bottom there are *Paper*, *commodity wood products*, *first generation biofuels and energy*. This level contains products that are widely used globally, e.g. paper or commodity wood products such as tables, chairs, cabinets, as well as first generation fuels (i.e. fuel derived from first generation feedstock.) The second level includes *second generation biofuel* which in turn includes biofuel for transportation and bioenergy in terms of heat and power. Such categories include several products such as bioethanol, biodiesel, biogas and syngas and they are the results of different lignocellulosic conversion technologies that can be classified as biochemical and thermochemical. Biochemical conversion includes hydrolysis followed by fermentation or anaerobic digestion in order to release bioethanol and biogas (Alrefai et al., 2017; Brethauer and Studer, 2015;

Nwakaire et al., 2013). Thermochemical conversion use temperature as the main means of conversion and different methodologies such as combustion, pyrolysis, torrefaction (van der Stelt et al., 2011) or gasification (Cheng et al., 2017), to produce solid fuel such as biochar and liquid fuel such as syngas, bio-oil, biomethane, bioethanol and gasoline (Basu, 2018; Chen, 2015). The third level, *construction materials* also play an important role in the bioeconomy sector. They can be of various type, from building structure to different furniture, boards, panels etc. Nowadays policymakers want to increase the utilisation of wood in the construction, making them more environmental friendly and supporting wood utilisation in public procurement in building sector (Toppinen et al., 2018b). The fourth level, *composites*, refers to wood material mixed by other components in order to improve their properties. An example could be wood-plastic composites i.e. material made by plastic component with wood particles. Typical example is the mixing of wood fibre with bio polylactic acid bioplastic or polypropylene (Sommerhuber et al., 2017). These wood-plastic composites replace neat plastic products and solid wood products and they are used mainly for some parts of automotive interior but also in the building sector e.g. for decking (Beigbeder et al., 2019). Last three levels include chemicals, pharmaceuticals and nanocellulose and they represent the most added value in the market inside this bioeconomy pyramid representation. *Biochemicals* represent high value chemicals derived from biomass such as fine chemicals (organic acid), fuel additives, precursor for plastic, pharmaceuticals, cosmetics and others (Sillanpää M., 2017). *Pharmaceuticals* are biochemical compounds manufactured for use as medicinal drugs; typical example is Aspirin from Willow tree and used as analgesic, anti-inflammatory and antypiretic but also many others such as betulinic acid, extracted from birch bark and used to limit the activity of HIV virus having strong antibacterial properties (Huang et al., 2018). *Nanocellulose* is considered also a high value added product. It is a fibrous material at nanometre scale which has a strength close to steal with the difference that its weight is more or less one-fifth the weight of steel. For that reason it is used in automotive part industries, medicine manufacturing, electronic parts and other (Moon et al., 2017)

2.1.3 Relation between bioeconomy and the concepts of circular economy and green economy

Bioeconomy is a part of the strategies adopted by multiple societal actors worldwide to tackle sustainability issues and improve social, environmental and economic conditions as required by the United Nation Sustainable Development Goals.

Recently, both in scientific literature and policy-making, bioeconomy has been associated to and integrated with the concept of circular economy (Carus and Dammer, 2018; D'Amato et al., 2018). In particular, the two concepts are closely related to each other, so that they can be defined as complementary. For example, they both share the same area of intervention as food, biomass and products of biological origin. Furthermore, they share some common concepts such as sustainability, the chain approach, biorefinery and cascading use of biomass. Finally, both converge towards innovation and research, environmental and economic problems and societal transition to sustainability (European Environmental Agency, 2018). The integration of the two concepts was perfectly applied in the European bioeconomy strategy of 2018 as explained above. However, Circular economy is also an important sustainability concept for many societal actors worldwide: it is promoted by the European Union and national governments, and adopted by several companies (D'Amato et al., 2019b; Kirchherr et al., 2017). Circular economy is inspired by the circularity of material and energy in nature, where everything is recycled: plants adsorb light, leaves grow, animals eat plans, the soil is enriched with their waste, and from the soil seed sprouts ready for the new cycle. So, there is no waste and everything is reused. The circular economy promotes using waste as a raw material. In addition, this economy is based on reducing, sharing, leasing, repairing, reusing, refurbishing and recycling in an (almost) closed loop, which aims to retain the physical characteristic and value of re-used products, materials and raw material as much as possible (Korhonen et al., 2018). Economic benefits include saving millions of euros and creating millions of jobs, helping to reduce greenhouse gas emission and support sustainability, in line with the principle of sustainable development. For example, it has been estimated that the global economy would benefit 1US$ trillion dollar annually in preventing waste, material cost saving and job creation (Ellen MacArthur Foundation and McKinsey & Company, 2014).

Another concept with international strategic relevance is green economy, focused more on the relation between environmental conservation and poverty mitigation. The United Nations Environmental Program (UNEP) in 2011 defined the concept as "results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. In its simplest expression, a green economy can be thought of as one which is low carbon, resource efficient and socially inclusive" (United Nations Environment Programme, 2011, p. 1). Green economy is also the overall framework for the concept of ecosystem services (D'Amato et al., 2017; Gasparatos and Willis, 2015), as it will be better explained in Section 2.3.

All the three concepts, bioeconomy, circular economy and green economy are based on the three pillars of sustainability, even though with different priorities and solutions. For example, on the economic dimension all the three concepts aim to improve economic sustainability through the implementation of different strategies. On the environmental dimension, bio and circular economy propose which resources should be used and how. Finally all the three concepts focus more on the economic and environmental aspects than on the social ones (D'Amato et al., 2019a). In terms of scientific research, bioeconomy is most popular in Europe and in the United States, circular economy has a strong dominance in China, and green economy is more evenly distributed worldwide (D'Amato et al., 2017).

2.2 Life cycle assessment (LCA)

2.2.1 Definition, history and applications

Life Cycle Assessment (LCA) is an environmental management tool and its main goal is to assess the environmental impacts of products, industrial processes or human activities along the whole life cycle, from raw material extraction through production and to utilisation and waste management (Fig. 5.). LCA allows to identify the main environmental impacts and thus improve products or processes. It is also called as an assessment "from the cradle to the grave", even though other formulas are also common (see Section 2.2.2) (ISO 14040, ISO14044). This methodology assesses both direct and indirect impacts. Direct impacts are those directly related to the products or process activities, while indirect ones are those correlated to the activity of secondary processes or organizations such as the transportation of raw material (or final product) and the consequent emission of exhaust gas. LCA is globally accepted and used in many companies as a strategic tool due to its applicability in different fields such as mining and oil extraction, construction materials sector, plastic, personal care products and many others (Jacquemin et al., 2012). Currently, the approach is largely used to support the development of bioeconomy, assessing the potential environmental impacts of bio-based products (Weiss et al., 2012) .

Figure 5: Scope of analysis of life cycle assessments: from raw material extraction to end of life.

LCA has been utilized since 1960 when the scientific community emphasized the complexity and gravity of environmental issues. On the early 1970 it was focusing mainly on raw material and energy, while shortly after it focused on atmospheric emissions. In the late 1970 and early 1980 mainly addressed waste management (Hunt and Franklin, 1996) .

The Society of Environmental Toxicology and Chemistry (SETAC) played a key role in the development of the concept of LCA. In the early 1990 they were leading agents in the development, harmonisation and early standardisation of LCA and during a SETAC workshop in Smugglers Notch in Vermont a Technical framework for LCA was developed and presented. It was named “LCA triangles” and can be defined as the first LCA ever. It was divided in three main phases: inventory, improvement and interpretation (Klöpffer, 2006). Following this, LCAs also entered scientific research. For example, since 1996, *The International Journal of Life Cycle Assessment* has been a key platform for promoting LCA studies. Other important journals promoting LCA approaches are also the *Journal of Cleaner Production* and *Integrated Environmental Assessment and Management* (Almut B. Heinrich, 2014). Finally, starting from 1997 and still nowadays, the international normative reference for LCA is represented by the International Standard Organisation series ISO 14040-44: UNI EN ISO 14040 (2006) and UNI EN ISO 14044 (2006) are the main LCA standard guiding practise (Lehtinen et al., 2011). These standardisations have contributed to the drafting of good practices to conduct LCA, making it easy to compare different types of LCA methods (see Section 2.2.2).

2.2.2 Structure and steps to perform LCA

ISO 14040 and ISO 14044 are the methodological references to conduct LCA studies; as shown in Figure 6 they prescribe four steps: 1. Goal and Scope definition; 2. Life Cycle Inventory (LCI); 3. Life Cycle Impact Assessment (LCIA); and 4. Life Cycle Interpretation.

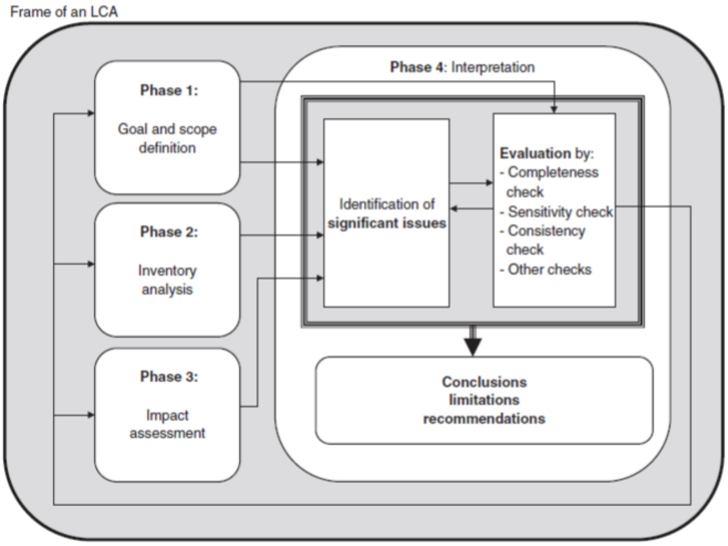

Figure 6: LCA phases and their interrelations (according to ISO 14040).

In the first step, the aim is to define: purpose of the study, functional unit, system boundary, data, assumption and limits. The goal definition is done by the institution commissioning the LCA study, which can include companies, environmental officers, industries or other; they must explain what the objective of the study is, why and for whom the LCA is conducted, and if the study will be published and made public or not. The functional unit and system boundaries are also identified at this stage. The functional unit (FU) is a reference unit for all data in the study. Its definition is very important because then the impacts are evaluated for that functional unit. It quantifies the performance of a product or process such as its functionality, appearance, stability, durability, ease of maintenance, thus defining the reference object of study with respect to which all input and output data are normalized. A typical example of FU in the bioeconomy sector can be “1 kWh of heat generated from the wood pellets”, or “1 m^3 of roundwood”. The system boundary represents the boundary within which the LCA study is conducted. It is necessary in order to define the spatial, temporal and production chain limits of the analysis. A typical system boundary used is cradle to grave but also other are common such as cradle to gate (also called cradle to factory-gate), cradle to cradle, gate to gate, gate to grave and well to wheel (Curran et al., 2014; Lehtinen et al., 2011),

- *Cradle to grave*: is an assessment on the overall stage in the lifecycle of the product such as raw material extraction (cradle), manufacture, distribution, use and disposal (grave) and it embodies a complete Life Cycle Assessment.
- *Cradle to gate*: is an assessment from raw material (cradle) to the production process until the product is ready to be distribute in the market from factory. This valuation is also the bottom for the Environmental Product declaration (EPD) called even EDP business to business.
- *Gate to gate*: it's a partial LCA; it is an assessment of the process within all production chain. Single gate to gate modules should than be link within the production chain to form a complete cradle to gate assessment. It is also called input output analysis.
- *Cradle to cradle*: it is a specific cradle to grave assessment where the product used and present in its end of life is then recycling and use in one or more of the previous processes. It can be summarized as closed loop production. This method is used to minimise the environmental impact caused by the products, using sustainable production and disposal system. It aims to include social responsibility in the developing of products.
- *Well to wheel*: it is a specific LCA used for fuel applied in vehicles and transport. This analysis is frequently divided in phases such as well to station, well to tank, station to wheel, tank to wheel or plug to wheel. First phase includes feedstock extraction, transport, refining and deliver to pump station. Phase pump to wheels consist of the working of the vehicle.

The data availability is also considered in the first LCA phase; it is necessary to state which kind of data is needed for the analysis, as well as how to collect and compute them (Curran M.A., 2017).
The second phase, i.e. "life cycle inventory (LCI)" also called data collection, focuses on the collection, verification and analysis of all data defined on the first phase. Its objective is to list and quantify all the input and output of material and energy related to a product or process through its life cycle. There are two types of data that can be used: primary and secondary data. Primary data include direct measurements and annual reports and are collected directly in the field. It is preferable to use this type of data as they are more representative of the case under examination. Secondary data can also be used; they are taken from literature, database or Input-Output Analysis. More specifically, databases that are commonly used are Ecoinvent V3 and ELCD (European Life Cycle Database). An important point in the inventory step is the data quality evaluation. Data must be precise, complete, representative, substantial and reproducible. There are no standardized methods to assess the quality of data but usually Monte Carlo Analysis is used (Klöpffer and Grahl, 2014).

The aim of the third phase, “Life Cycle Impact Assessment (LCIA)” is to understand and evaluate the magnitude and significance of potential environmental impacts caused by product, process or organization under investigation. In particular, data from LCI are assigned to different impact categories (such as climate change, acidification, eutrophication and many others, as shown in table 1) in order to translate the information collected in the inventory phase into environmental indicators related to impact categories.

In particular, data from LCI are assigned to different impact categories (such as climate change, acidification, eutrophication and many other, see table 1) in order to translate the information collected in inventory step in environmental indicators or impact categories

Table 1. Typical impact categories in LCA (Hauschild, 2015).

Impact category	Description	Socio-ecological relevance
Climate change (of global warming potential GWP)	The anthropogenic release of greenhouse gasses (GHG) such as CO_2, CH_4, N_2O, halocarbon HFCs, PFCs and SF6 is the main cause of an increase of solar radiation reaming inside the atmosphere and resulting global climate change. This is due to the chemical properties of these gas that adsorb infrared wavelength radiation reflected from the Earth surface and cloud, releasing energy in form of heat.	An increasing in the global temperatures causes sea level rise, extreme weather phenomena and threats to the health of ecosystems and human beings.
Stratospheric ozone depletion	Ozone (O_3) is a natural constituent of atmospheric earth. Is a very reactive molecule shifting in O_2 and O radical by chemical and photochemical dissociation reaction, resulting in ozone breakdown. This layer has been depleted for long time due to the utilization of chlorofluorocarbon (CFC), specially CFC_{11} and $CFC_{12,}$ in the refrigerator system, air conditioning system and solvent. When released to the atmosphere this component (CFC) react with UVB radiation, forming Chloro radicals that rise in the atmosphere and react with ozone, causing ozone layer depletion	It is a fundamental layer that protect the surface of Earth by adsorbing the solar ultraviolet B radiation (UVB) and that are the main cause of skin cancer when excessive exposure occurs.
Photochemical Ozone Formation	Is the formation of ozone in the tropospheric (0-15km above the ground level) layer forming during photochemical reaction driven by solar radiation with chemicals released in the atmosphere. These chemicals are mainly emitted by anthropogenic source and include NOx as a sum of NO_2 and NO and different component of Non-Methane Volatile Organic Carbon (NMVOC) such as alkanes, alkenes, alcohols, aromatic and so on. For example, NO_2 dissociate in NO and O, the oxygen released react with the oxygen (O_2) present in the atmosphere forming O_3 and NO can react with the ozone forming again molecular oxygen and nitrogen dioxide. On the other hand, NMVOC once in the troposphere are subjected to degradation forming intermediate RO_2 and	This layer is also known as summer smog because it occurs especially in summer when the solar radiations are high. The ozone is a strong oxidant which effects the human health, both acute and chronic effects but also it has effect on the crop and vegetation such as forest. Finally, it has been shown that ozone acts as a direct greenhouse gas and that affects the lifetime of methane and other greenhouse gasses.

Impact category	Description	Socio-ecological relevance
	HO_2 radicals where R correspond to the remaining part of the VOC. These by-products react then with NO formed during the previous photochemical reaction forming again NO_2, that again can be photochemically modify forming the tropospheric ozone layer.	

Acidification	Acidification is a process where the protons H^+ are released and cause changing in pH and alkalinity. It is caused by disposal of atmospheric inorganic gasses on earth surface and can occur in different ecosystem such as terrestrial, freshwater and less in marine. Main components that cause acidification are NOx, NH_3 and SO_2, less contribution is due to the presence of pyrite FeS_2, hydrogen sulphide H_2S and hydrogen chloride HCl ± hydrogen fluoride HF. These gasses can occur naturally by a volcanic eruption or emissions from the ocean but one of the most significant contributors is the combustion of fossil fuel	One direct impact is the formation of so the called “acid rain” caused by the reaction of SO_2 with water H_2O forming sulfuric acid H_2SO_4. Sulfuric acid dissolved then in $2H^+$ and $SO4^{2-}$ causing acidity
Eutrophication	Represents a change in aquatic and terrestrial ecosystem due to the anthropogenic released of nutrient such as Nitrogen (N) and Phosphor (P). These nutrients mainly came from the fertilizers (N source) and detergents (P source) but also as from human and animal defecation.	Aquatic environments grow fast biomass such as Algae. After their life cycle these plants die, consuming oxygen due to their decomposition subtracting it from the water, forming so a hypoxic condition (low levels of dissolved oxygen in the water column) resulting in fish killing or dead zone. Terrestrial eutrophication causes a changing in nutrient cycling and change in plant community even if the mechanism is not jet well known
Ecotoxicity	Cause-effect mechanism caused by chemicals in the environment. These impacts can be divided in four parts as chemical fate, exposure, effect and severity. Chemical fate refers to the chemical behaviour and distribution in the environment compartment (air, water, soil etc.). Exposure refer to bioavailability in term of contact between target (such as human, fish or other species) and a pollutant trough an exposure for a specific duration and frequency.	These process, results in chemical exposure on the species. These effects are described by lab test results, where it is used to identify the fraction of individuals affected from increasing the pollutant concentration. Severity explain the forcefulness of the effect and it quantify how many species are disappearing from the ecosystem
Human Toxicity	Refers on the impact that chemicals released in the environment such as in the air, water soil and biota affect the Human health. The environment chemicals can be adsorbed in human body by different ways such as: directly by drinking water, inhaling the air, indirectly by in digesting food that contain chemicals pollutant due to bioaccumulation. Other way to can be by directly dermal contact with the products.	Once in the body these chemicals can cause various disease, disability or also death.

Land Use	Impact category describes the impact caused by the utilisation of natural land by human activity such as agriculture, forestry, mining and construction. Operations in land for human purpose imply modification of the natural environment and significant effect and damage as a result.	Loss of biodiversity, modification in soil fertility, physical and chemical soil condition and other causing finally impact on the ecosystem services that are than related to Natural resources, human health and wellbeing and ecosystem quality
Particulate matter formation	Impact category discusses the particulate matter (PM) present in the environment. With the term PM we refer to small size matter that can be both directly emitted to the atmosphere by anthropogenic and natural processes such as $PM_{2.5}$, PM_{10} and 1-4, dichlorobenzene (primary PM) and form in the atmosphere by precursor such as volatile organic compound, sulphur oxides (SOx), nitrogen oxides (NOx) and ammonia (NH_3) forming a so called secondary PM.	All of these substances once inhaled can cause a serious illness such as lung cancer, chronic and acute mortality, reduced life expectancy and so on. Particular attention has to be done with $PM_{2.5,}$ particulate matter with dimension less than 2.5 µm that are the only particle that can pass through the nose and accumulate on the lung in the bronchi (secondary and terminal) and alveoli. Matter with bigger dimension stopped on the nose, pharynx, trachea and primary bronchi
Abiotic Resource Use	Environmental impact caused by the utilisation of abiotic resources such as metals, fossil energy, nuclear energy and flow energy resources as wind energy. To evaluate this category in LCA is common to split it in three categories: resource accounting methods, resource depletion methods at midpoint level and resource depletion methods at endpoint level.	Utilisation of the natural resources along all the life cycle of the product and the scarcity of the resources at midpoint and endpoint level
Water Use category	Water is a global resource that is continuously recirculated by the water cycle. It has been estimated that the global amount of water is about 1,386 million cubic Kilometres and that within this huge number almost 97,5% is saline water and 2,5% is fresh water. In addiction only 0.3% of the fresh water is visible as river and lake, the 30% is ground water and both are available for human activities. The remaining amount is representing by ice and perennial snow.	After the extraction of this resources, water can be seen as abiotic resources or a compartment receiving emission for example by industrial processes. In LCA study nowadays, only freshwater is accounted in the studies and the main categories used are water scarcity, resource depletion, impact on human health and impact on ecosystem quality

According to ISO, impact category is a class representing an environmental problem. Different impact categories are calculated by different methods. For example, TRACI, EDP, CML 2001 are mostly used as “midpoint” methods while ReCiPe, Eco-Indicator 99 and EPS used as “endpoint” methods. Midpoints are environmental indicators that express the relative severity of an impact category, focusing on a single environmental problem. As an example, greenhouse gas emission and global warming potential are environmental indicators that express the relative gravity on climate change impact category. On the other hand, some methods such as ReCiPe provide an aggregation of midpoints in endpoints that show the environmental impact on three higher aggregation levels such as human health, biodiversity and lack of resources. All in all, there are also methods that provide only endpoints without midpoints aggregation such as Eco-Indicator 99 and EPS (Hauschild and Huijbregts, 2015). Figure 7 summarizes the concept of midpoints and endpoints.

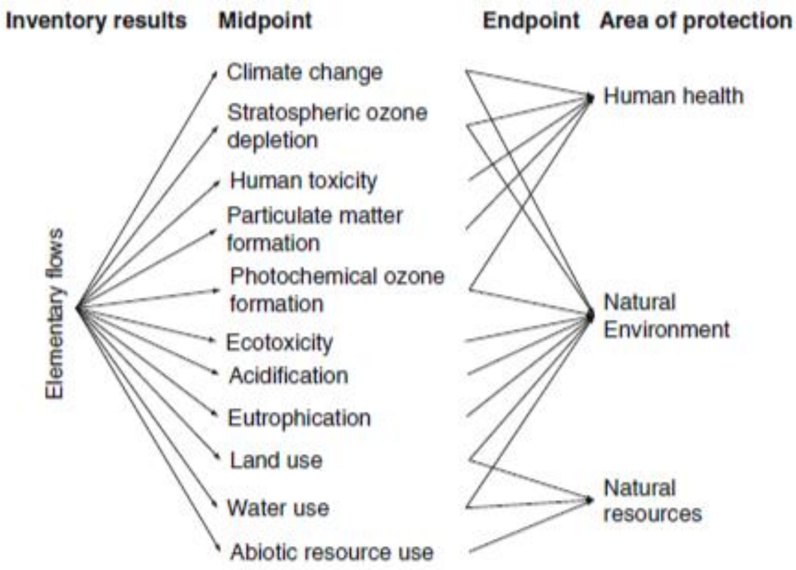

Figure 7: representation of midpoints and endpoints (Hauschild et al., 2013).

The third phase can also contain two non-mandatory steps such as Normalisation and Weighting. Normalisation is a comparison between the impacts produced and those that would occur in systems of similar production (generally average data on a global, European or regional scale with reference to a specific temporal scale). Finally, each impact score can be weighted to aloe aggregation and thu to obtain a unique value on which to base the evaluation (Pizzol et al., 2017).

The fourth and final phase of LCA consists of the interpretation of the findings from the inventory analysis and the impact assessment. The interpretation phase should deliver results that are consistent with the defined goal and scope and which reach conclusions, explain limitations and provide recommendations. There are three main steps that is commonly used in Life cycle interpretation and that are defined by ISO 14044. They consist in *identification* of the important topics based on the result of LCI and LCIA; *evaluation* of completeness, sensitivity and consistence of the study; and *conclusion, limitation and recommendation* (Hauschild and Huijbregts, 2015).

LCA has its strength as its limitation. This method allows the estimation of the total impact of the product, process or service analysed. Therefore, it can support to set priorities for improvement. The tool also allows to compare different products and improving the existing ones, and it is ideal for the design of new products. Finally, it supports environmental strategies. As for the limitations, LCA is a model and thus a simplification of reality. LCA does not give absolute answers: assumption have to be made and this causes uncertainties (International Organization for Standardization (ISO), 2006).

2.2.3 Different types of LCA approaches

Along with LCA, different tools are used to gather useful information for the sustainability assessment of products and processes and their related decision-making (Gundes, 2016). These include Life cycle costing (LCC) also called life cycle cost assessment (LCCA) or life cycle economic analysis (LCEA), social LCA (SLCA), life cycle sustainability assessment (LCSA), and life cycle carbon dioxide assessment (LCCO2), which are briefly described below.

Life cycle costing (LCC) is the counterpart of LCA for economical assessment and the process is governed by the ISO 15686 standard (BSI ISO 15686-5, 2008). LCC is used to compare different design strategies in term of initial, maintenance and operation cost occurring in a specific period of time. Only values that can be expressed in monetary term are considered in LCC calculation, thus environmental load are neglected (Gluch and Baumann, 2004).
Social Life cycle assessment (SLCA) is a method that evaluate the social and socio-economic aspect of products. It aims to assess the social impact by helping to understand the positive and negative effect on the society along the product's life cycle. Typical impact categories utilised are Human right, Labour practices and decent work conditions, Society and product responsibility (Jørgensen, A. et.al., 2007). SLCA has not been used as well as LCA since social conditions vary geographically and it's difficult to link social impact indicators to the functional unit of the product-system (Andrews et al., 2009). Moreover, life cycle sustainability assessment (LCSA) has been developed with the aim to have a comprehensive and global overview about the sustainability of the product or process. It includes all the LCA approaches, usually LCA, LCC and SLCA. The utilisation of this practise enhances to apply the "triple bottom line" approach where it basically said that to reach a more sustainable future, environment, economy and society impact activities have to be taken into account all together (Guinée J., 2016). To conclude, Life cycle carbon dioxide assessment (LCCO2) considers all the carbon-equivalent emission output in the different phases of the product's life cycle. This tool is particularly useful to evaluate how much CO2 emission has been emitted and comparing with other products or processes how much CO2 emission can be avoided (Chau et al., 2015).

2.3 Ecosystem services

Ecosystem services (ES) are defined as benefits for people to obtain from natural and semi-natural ecosystems (MA, 2005). ES-can be simply explained as the capacity of the ecosystem to provide raw materials, biochemical products and clean water, regulate the air quality and climate respectively capturing fine dust and sequestering carbon, maintaining soil fertility and nutrient cycle as well as contributing to aesthetic, spiritual and recreation experiences (De Groot et al., 2002). Ecosystem services contribute to human well-being in multiple ways. They can have multidimensional values and be perceived differently from person to person. Moreover ecosystem services range from basic material for good life (such as food and vary products) to psycho-physical health, good social relation, security and freedom of choice and action (Costanza et al., 2017). On May 2019, the United Nations released a 40 pages summary of the report on biodiversity and ecosystem services in the world, stating that "Nature and its vital contributions to people, which together embody biodiversity and ecosystem functions and services, are deteriorating worldwide" and that biodiversity is declining faster than at any time in human history due to the human activity (Díaz et al., 2019; pg 2). This report was prepared for policymaker and underlined the importance to act through transformative change and reorganisation of technologic, economics and social factors (Díaz et al., 2019). The topic of ecosystem services is thus increasingly relevant in sustainability science and policy-making.

2.3.1 Evolution of application and implementation

The application and implementation of ecosystem services (ES) is still under development. In the 1970s, ecologists started to describe ecological issues such as environmental pollution and resource scarcity with the aim to underline the societal dependence on natural ecosystem and to raise awareness on biodiversity importance and the need for conservation. The first author that used the concept of natural capital was Schumacher (Schumacher, 1973) in 1973 and shortly after, in 1977, Westman published a paper in *Science* entitled "How much are nature's service worth?" where he examined for the first time the link between economic and ecological system (Westman, 1977). Some years later, in 1981 Ehrlich and Ehrlich coined the term "ecosystem Services" (Ehrlich, Paul ; Ehrlich, 1981) and in the following decade the ecosystem ecology community and the environmental and resource economic community have started to work together building the new concept of 'ecological economics' using the ecosystem services approach as an explicit part of the research (Costanza, 1989).

Keystone literature for the ecological economics community include an article published in *Nature* by Costanza and co-authors in 1997. The publication, titled as ‘The Total Value of the World’s Ecosystem Services and Natural Capital’, aimed at synthetizing a quantitative global assessment of the monetary value of ecosystem services globally. Results showed, as a first approximation, that the ES value is in the range of US $16-54 trillion ($10^{12}$) per year. This estimation demonstrates how much ES are important for human well being in contrast to what economists thought. That’s because in conventional economic it is common to account ecosystem value only if it gives some direct products that can be sold in the markets (e.g. timber) (Costanza et al., 1997). As a result, an increasing interest on ES from both the scientific and regulatory communities have occurred and is still ongoing.

In the beginning of the new millennium two international initiatives were promoted to advance ES research: The Millennium Ecosystem Assessment (MA) and The Economics of Ecosystem and Biodiversity (TEEB). MA represent a global assessment regarding the state of art and relevance of ecological system and related benefits for society (MA, 2005); TEEB, instead, is an ongoing process aiming at emphasising the social and economic value of the loss of biodiversity and ES, thus supporting the policy makers and the business community to take action (TEEB, 2008). In the frame of such initiatives, a cascade framework representing the links between natural and human systems (later further developed by Potschin and Haines-Young, 2018) as well as classification approaches were developed as will be explained in the following.

The cascade framework by Potschin and Haines-Young (2018) (figure 8) represents the links between natural and human systems. At the core of the figure, “service” is the benefit human derive from nature and it can be interpreted as a link between the environment and the socio-economic systems (MA, 2005). The illustration explains the steps from biophysical structure and related processes to ES and to human well being (Potschin-Young et al., 2018). In the biosphere side, the biophysical structure and the ecological processes within it hold potential to deliver services which can directly and indirectly contribute to the human well-being. For example, woodland habitat (= biophysical structure) is needed to maintain a viable biomass production (= function) which can be used to provide bioenergy in form of electricity and heat (= service). The utilisation of bioenergy contributes to environment and human health care and earn (benefit) for example reducing greenhouse gas (GHG) emissions compared with fossil fuel utilisation and finally this benefit is contributing nowadays to create new markets, after the production and selling of this product (Value).

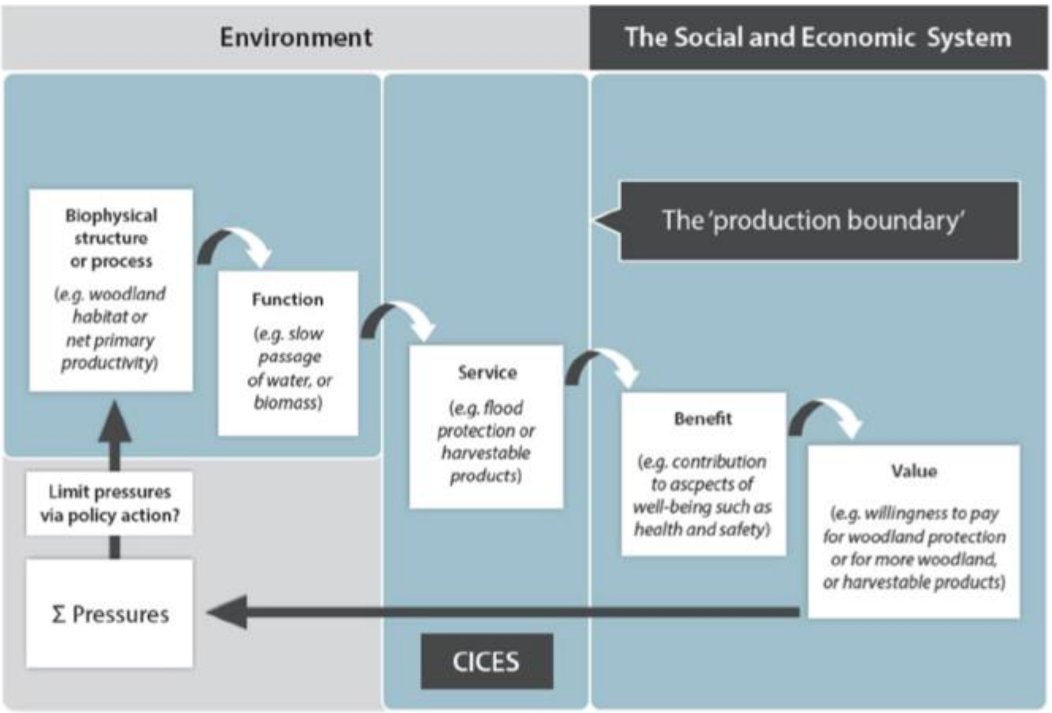

Fig.8. Cascade framework: from structure to functions, to services to benefits to value (modified after Potschin and Haines-Young, 2018).

As anticipated, a number of ecosystem services' classification approaches were developed in order to clearly aid scientific analysis, economic valuation and policymaking. The first classification approach was proposed by the Millennium Ecosystem Assessment (2005); starting from the list of 17 ESs created by Costanza et.al (1997), ecosystem services were grouped into four main categories: provisioning, regulating, supporting, cultural.

- **Provisioning services** are represented by tangible items obtained from ecosystems, which humans mostly use to satisfy material needs. This include, for instance, fiber as timber used for building or heating, fuels such as bioethanol and biodiesel, but also biochemicals as acid acetic, lactic acid, glucose and other sugars as well as other fatty acid and amino acid. Other important products in this category are natural medicine and pharmaceutical as the antitumoral taxol extracted from the bark of the yew tree (Exposito et al., 2012). A relevant item is also freshwater for drinking or other uses (MA, 2005).
- **Regulating services** are less tangible items related to the regulation of ecosystem processes such as climate regulation. Ecosystems act on climate in different form: warming effect caused by natural greenhouse gas production, cooling effect generated by the GHG absorption and effect on the precipitation distribution. Another important regulating service is for instance air quality regulation, due to the fact that ecosystems can act as sinks for various trace

gases. Other important services are water regulation, water purification and pest regulation (MA, 2005).

- **Cultural Services** are non-material items characterised by intangible human-nature experiences, such as psycho-physical health, aesthetic value, recreation and ecotourism, reflection and inspiration (MA, 2005).
- **Supporting Services** are those necessary for the production of all other ecosystem services and include photosynthesis, water cycling and nutrient cycling so element such as nitrogen and phosphor needful for the organism growth and development (MA, 2005).

In addition, other classification approached were created, based on the one by MA (2005). For instance TEEB (2010), maintained the same structure of the MA classification, adding other five ES and substituting supporting services with habitat services in order to underline the importance of the ecosystem to maintain genetic diversity and life cycle of migratory species (Unep, 2008). Other types of classification include the UK National Ecosystem Assessment (Assessment, 2011), the Final Ecosystem Goods and Services Classification System (DH Landers and Nahlik AM., 2013) and they focused more on monetary valuation and on benefit and beneficiaries, respectively.

The classification currently mostly used and updated in Europe by scientists and regulators, and which is also used in the current study (see section 3.2), is The Common International Classification of Ecosystem Services (CICES). It is a hierarchically organized classification developed in order to provide the users with a highly detailed level of information. The classification includes five hierarchically organized levels (i.e. section, division, group, class, and class type), each one presenting more specific and detailed information than the previous one. The classification uses three main categories such as provisioning, regulating and cultural, but does not include supporting services because they are considered as part of the ecosystem structure, process and function (see Figure 8) (Haines-Young and Potschin, 2018).

There are no ideal classifications, but the choice of the classification to use depends on the purpose of the research. According to Wallace (2007), there are three main components affecting the classification of ecosystem services. First, there is no explanation of the term that effectively encompass the topic. Second, different school of thought use different words, but the meaning is almost the same, so clarity concerning the term used to characterise services are needed, if not ambiguity can occur. Third, a single ecosystem service is difficult to classify due to the amount of linkages occurring among different ESs. To overcome this problem a specification of the point at which linked processes deliver a service is needed (Wallace, 2007).

2.3.2 Assessment (valuation) of ecosystem services

Identifying and classifying ecosystem services is propaedeutic for their assessment or valuation. Value of ES is often "invisible" and that is why we need to highlight it. In addition, assessment and valuation are important because the decision process affects human wellbeing in different ways. When the society needs to make choices, an evaluation process is thus necessary or recommended. For example, when we build a biorefinery, that is fundamental to move from a fossil-based economy to bioeconomy and related human welfare, unavoidably impacts on natural capital occurs. Being clearer about the value of ES can help policy and decision making as well as society to take better decisions for managing them (De Groot et al., 2012). The Oxford Dictionary define valuation as 'an estimation of the worth of something' so compared with an assessment is more related with an economic and social value. The ES value requires that a series of complementary methods are used. These methods are qualitative and quantitative (both monetary and non-monetary). For example, in the conventional economic approach (monetary valuation) various valuation methods are applied to ecosystem services and mainly four are used: production function methods, damage cost avoided, revealed preference methods and stated preference methods (Bateman et al., 2011). An alternative approach to value the Ecosystem services is non-monetary valuation. This aims to give value through qualitative, quantitative and deliberate measures, examining the importance, demand and preference people give to the nature and ecosystem services. Within the different approaches the most typically used in qualitative measures are survey of preference assessment such as the people perception of changes in ES and its spatial representation (ES demand mapping), so they represent the perception of stakeholder. On the other hand, quantitative measures are more related with semi structured and deep interviews while deliberate measures are delivered by a group of stakeholders that meet discussing the value of the public goods and service (Kelemen et al., 2014).

LCA has potential as a tool to integrate the valuation of ecosystem services in the impact performance of products and service. However, the typical framework used in LCA does not allow a simple incorporation of ecosystem services in the study. First, because LCA account linear relationships between mechanisms but it does not take in consideration the multidimensional interactions, so accounting the ecosystem services it is quite difficult considering that they are dynamic and vary in time and space (Koch et al., 2009). Second, impacts in LCA does not include those from the ecosystem functional level up to impact on human welfare. However, using a classification method, where the intermediate service (ecosystem process) and final service (Human wellbeing) are separated (FEGS-CS method), can be useful to understand the relationship between impact on ecosystem process and human wellbeing (Othoniel et al., 2016). Third, simplification of complex impact and uncertainties associated with inventory data need to be used carefully. Finally, production system impacts the environment and ecosystem services not in a single way, differing by space and time. Modelling only one service does not reflect the real impact on the huge ecosystem services delivered in that place (Bakshi and Small, 2011).

To overcome these problems, D.Maia de Souza et al. (2018) proposed a conceptual framework to link ES and LCA in order to have a more complete evaluation of impacts by processes and activity, focusing on the biofuel sector (figure 9).

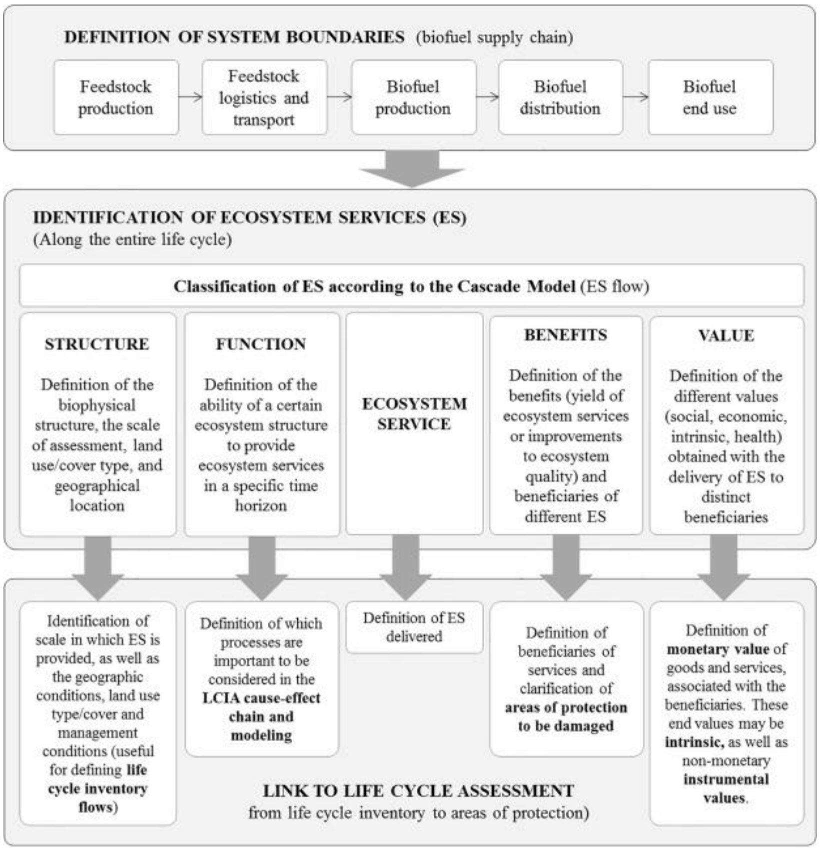

Figure 9: The cascade model-LCA integrated framework to identify ES at multiple scales, associated with the life cycle of biomass-based products (D.Maia de Souza et al. 2018).

This work shows that it can be possible, starting from the ecosystem services cascade model to define the information useful to conduct an LCA in which ES are included. The idea is that starting from the definition of System Boundary (in this case Cradle to grave) it is possible to identify the ecosystem services that plays an important role within the context (system boundary) and subsequently, utilize this information to derive input and output that can be useful to include in the LCA process. For example, knowing the scale of the assessment as well as the land use covered (for example forest) we can derive the scale in which ES is delivered and as consequence we can have an overview of which inputs are needed for the LCA (i.e. which data are needed to be taken into account in order to include a specific ES). Secondly, knowing the potential (yield) of the ecosystem to deliver ecosystem services is helpful to define which processes within the life cycle of the product have the potential to influence the ability of ecosystem to deliver ecosystem services. So, if one process decreases the yield of the ecosystem to deliver a specific ES, that process needs to be improved or changed until the yield does not remain constant. Finally, knowing the benefit obtained and the value people assigned to these services, derived information can be used as a measure to improve various damage indicators in LCA (Maia de Souza et al., 2018) .

This new way of thinking about how to include ES in LCA can be a helpful tool to improve the gaps that there are nowadays between these two topics. However, the studies present in the literature, follows the classic approach of LCA, not including ES. For that reason, in this thesis I propose a new method to relate the environmental impacts calculated by an LCA study with ecosystem services and therefore to indirectly understand which effects (positive or negative) a product or process may have on ESs along its life cycle.

3. Methods

3.1 Data collection

To conduct the literature review of life cycle assessment approaches (LCA, LCC, LCSA) applied to forest bio-based products, I referred to the steps described by Khan et al. (2003) to conduct a systematic review. These steps can be summarised as follows: the definition of the questions for the review; the identification of relevant work and selection of relevant criteria that are linked with the questions; summarization of the evidence synthetizing the data collected; and finally, interpretation of the findings.

The literature search was conducted in January 2019, targeting English language publications in Scopus (https://www.scopus.com/). Different search strings were tested and refined during the process of identifying the one that could synthetically capture all the relevant information. Such process was based on the keywords included in recent scientific articles exploring the bioeconomy phenomenon (e.g. Karvonen et al. (2017); Hurmekoski et al. (2018); (Martin et al., 2018)). In particular, Karvonen et al. (2017) identified a list of LCA approaches evaluated as important tools in assessing the sustainability of bioeconomy products; Hurmekoski et al. (2018) identified new wood-based products with considerable potential for markets, by taking into account the four major forest industry countries such as Finland, Sweden, USA and Canada; and (Martin et al., 2018) focused on the impact tools and sustainability indicators used or missing in the Swedish forestry bioeconomy sector.

The final search string is shown in table 2. was inserted in the advanced search option in Scopus and resulted in 941 documents. The search then was further refined by selecting years from 2016 to 2019, which resulted in 644 documents. The reason for selecting such a time period is that the bioeconomy is a recent phenomenon, which has shown a consistent increase in scientific literature after 2015 (D’Amato et al., 2017).

Table 2: String used for the search of publications in Scopus between 2016 and 2019.

Search string (limited to 2016-2019)	Number of articles found (18.01.2019)
TITLE-ABS-KEY(“life cycle” OR “LCA” OR “SLCA” OR “S-LCA” OR “LCC” OR “ELCA” OR “E-LCA” OR “LCSA” AND “bio*” AND “forest” OR “wood*” AND “*fuel*” OR “*diesel*” OR “*gas” OR “*ethanol” OR “*plastic*” OR “wood-plastic*” OR “*composite*” OR “*packaging” OR “*film*” OR “*chemical*” OR “lactic acid” OR “furfural” OR “*ethylene” OR “building*” OR “construction” OR “fertilizer*” OR “heating” OR “pellet*” OR “chip*” OR “textile*” OR “cup*” OR “coating*”)	644

The bibliometric information related to these studies were exported from Scopus to an excel file. The information related to the documents’ title, authors and abstract was screened using a web-based software named Abstrackr (Byron et.al, 2012), a software developed by Brown University (Rhode Island, USA) that facilitate the process of acceptance/rejection of the documents under review. Before starting the screening processes, three main criteria for the selection were decided:

1. The document had to use LCA approaches directly and in empirical way (i.e. literature reviews on LCA were rejected);
2. Only scientific articles written in English were accepted, while books, book chapters and conference proceedings were rejected;
3. Article had to analyse bio-based products;
4. Biomass of product had to have a forest and/or wood-based origin.

Of the 644 documents screened, only 216 met the inclusion criteria and were admitted to the full text screening. Several documents were rejected because they dealt with life cycle of plant animals or bacteria or of plastics and other material and chemicals not derived by biomass; or because they did not use LCA despite investigating the treatment and pre-treatment of lignocellulosic feedstock, the synthesis of bio-based chemicals, different industrial processes and methodologies for bioproduct production. During the reading of the full-text, further refining was done by rejecting other articles as they were not available (no access or payment was needed to access), or as they did not meet the criteria cited above. So, the final sample of articles was 155. Figure 10 summarize the key stages in the review process.

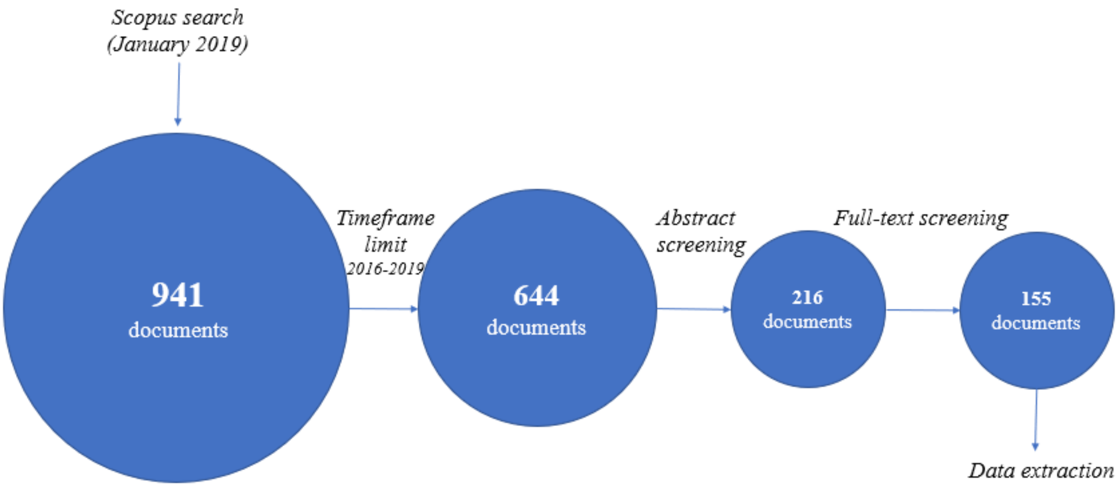

Figure 10: Literature search and screening of the results.

3.2 Analysis

The full text of the articles accepted for the review (N=155) were then read thoroughly and coded. The data extracted from the articles include the following: type of product or process; geographical location of the study; type of analysis (LCA, LCC, LCSA or others); system boundaries; functional unit; method used for the analysis (e.g. ReCiPe or others); type of midpoints or/and endpoints calculated; number of midpoints calculated compared to the number of midpoints available in the method.

Descriptive statistics were used to analyse the data. In order to correctly interpret and categorize bioeconomy products, I referred to the bioeconomy pyramid as a classification system (Toppinen et al., 2018a). However, it was not possible to strictly follow that classification, so I modified it to include also categories such as bioenergy, feedstock, biomaterials, bioeconomy related industrial processes, biochemical and management of different products. Therefore, the classification used in this work is the following: paper, bioenergy (including power and/or heat and second generation biofuels), industrial processes, feedstock (for bioenergy, for biomass, for industrial processes), biomaterial (including construction material, bioplastics, composites), biochemicals, nanocellulose and management. Moreover, in order to correctly interpret and categorize LCA approaches, methods and midpoints, I referred to Karvonen et al., 2017; Klöpffer and Grahl, 2014. Finally, in order to identify the relation between midpoints/endpoints categories and ecosystem services, I referred to the ecosystem services classification by the Common International (CICES) (Haines-Young and Potschin, 2018).

4. Results

4.1 Overview of the collected literature

155 publications have been used for data extraction. The number of articles was evenly distributed between 2016 and 2018. A smaller number of articles was found in 2019 but this result is reasonable considering that the search was performed in January 2019, so only one month of this year has been accounted.

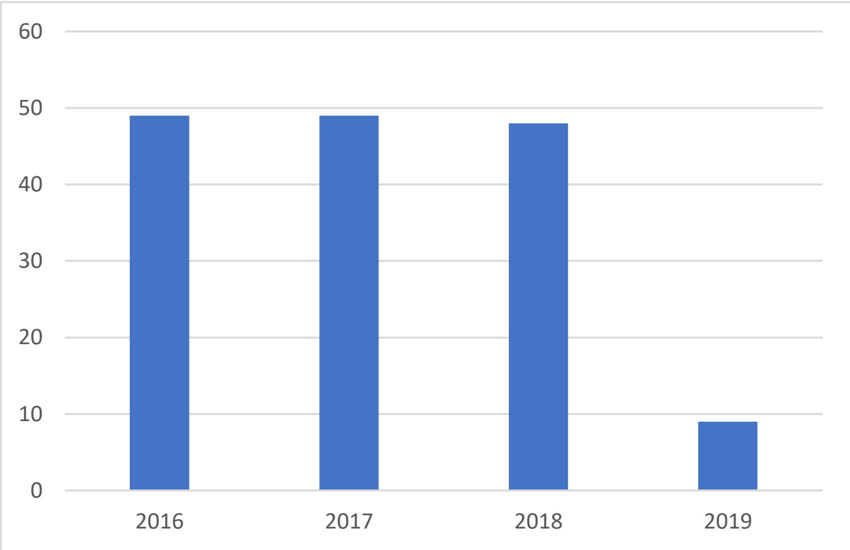

Figure 11: Timeline of the reviewed studies dealing with LCA approaches to forest-based products.

Within these articles, the geographical distribution identified has global coverage, including all continents (Figure 12). Note that the geographical location means the location where the study was conducted (not the authors' affiliation).

The results suggested that several studies (N=51) were performed in North America, focusing in particular on the bioenergy products (see table A.1. in appendix). Within this continent, the United States focused more on biofuel generation and less on power and heat. In addition, it is important to underline in the United States the utilisation of LCA approaches in management, to search for the economic and environmental impacts on introducing woody biomass in the processes (Jackson et al., 2018) as well as to reach out which is the best possible use of biomass (Morris, 2017). Studies conducted in Canada focused more on power and heat, and less on biofuel (even though some authors assessed the synthesis of bio-based diesel addictive, (Mahbub et al., 2019, 2017)). Moreover, both

United States and Canada consider feedstock as an important part of their research, used both for energy production and biomaterial.

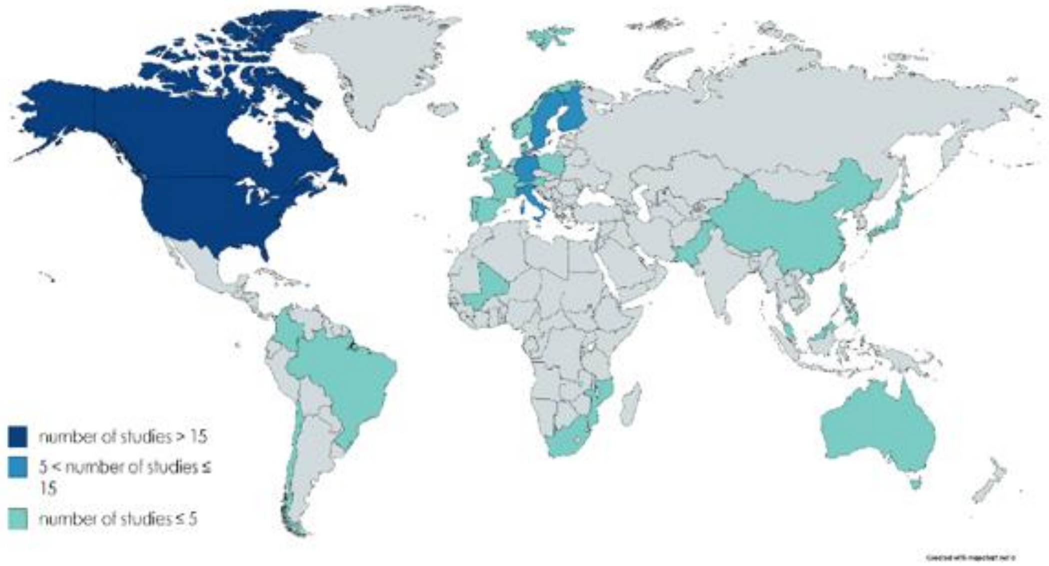

Figure 12: Geographical distribution of the reviewed studies dealing with LCA approaches to forest-based products (own representation, using mapchart.net).

Moving on to Europe, four countries were identified as mainly at study, such as the Nordic countries Finland and Sweden, the south of Germany and Italy. Finland and Sweden focused their studies on energy generation, especially on power and feedstock for energy generation, or biomass used for paper, construction material or composite. In Sweden an industrial cluster is being studied in order to replace a share of the fossil feedstock used with forest-based feedstock. On the other hand, in Germany works regard evenly bioenergy, biomaterial, feedstock and industrial processes. Bioenergy studies were focused on heat and power generation and, also in this country, LCA approach was used to assess the industrial symbiosis of the wood-based economy. Finally, studies in Italy, similarly to Canada, focused more on bioenergy generation (more on power heat and less on biofuels), as well as on feedstock for energy generation, biomass production and bio-solvent as acetonitrile. Only few studies (less than five per country) were recorded from other countries in the world.

The collected articles were then assessed to identify the bioeconomy products investigated in the different LCA studies, which were then classified as described in paragraph 3.2. Obtained results are shown in Figure 13.

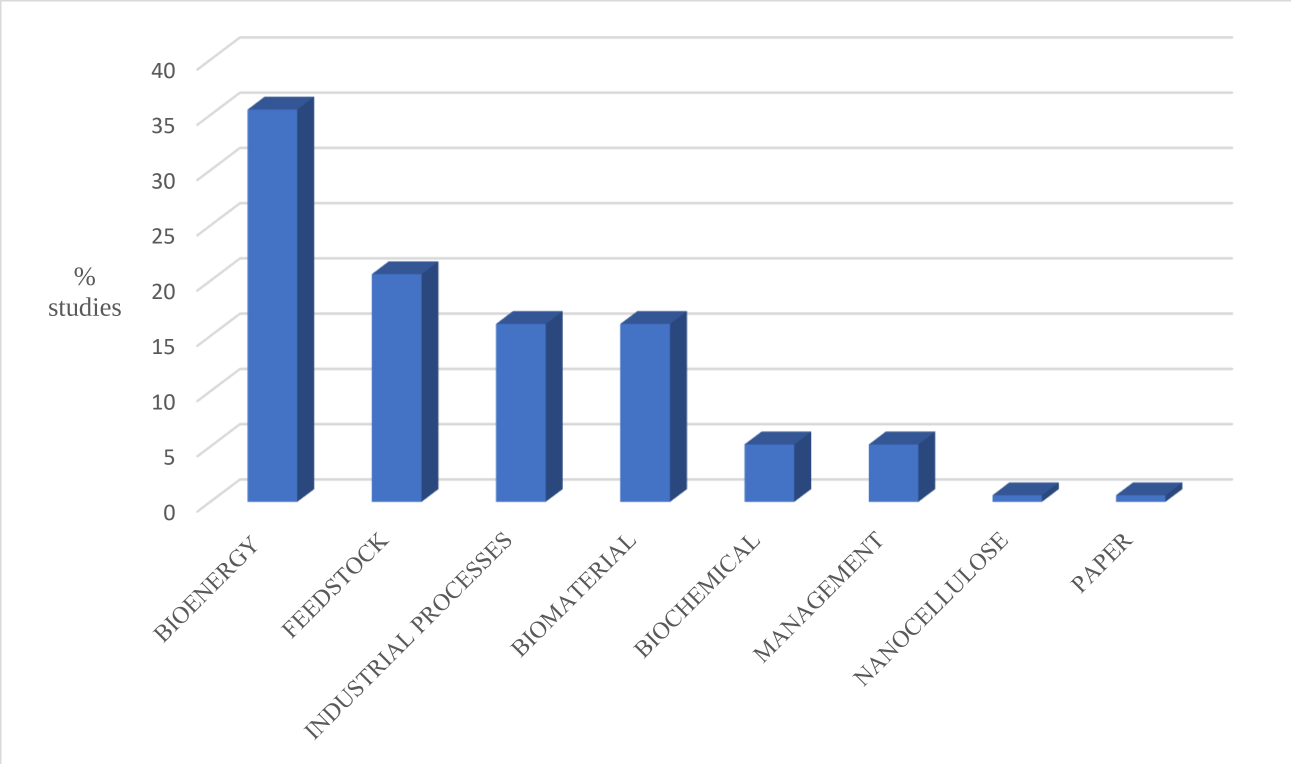

Figure 13: Representation of the different products assessed in the collected articles.

Bioenergy is included in 55 studies and represent 35.5 % of the total products. This group includes power and/or heat generation (29 articles) and second generation biofuel (26 articles) (as detailed in Table A.2. in the Appendix). About power generation, 21 articles were found and the various authors focused on its generation using woody residue (waste wood), biomass (perennial crops or other) or biochar to generate electricity through direct combustion or cofiring with coal and wood pellets. In addition, they focused also on its supply chain and water demand for its production. For heat generation, 5 articles were found focusing on heat generation using willow short rotation crops or forest crop and solid biofuel as chips or pellets in different countries to be distributed in buildings. Only 3 articles focused on both heat and power generation. About second generation biofuel, seven articles focused on supply chain and production of bioethanol and three articles included both bioethanol with biomethane and bioethanol with biobutanol. Other four articles focused-on bio-oil production using thermochemical conversion, fast pyrolysis or other technologies, four focused on biodiesel and gasoline production, one focused on bio iso-parafinic kerosene (jet fuel), one focused on biofuel production for torrefied wood not specifying the bio product and the last on biofuel focused on syngas from lignocellulosic feedstock used then for energy production.

Feedstock includes feedstock harvest or used for bioenergy (14), biomass (14), industrial processes (3) and management (1) and account for 32 articles. In particular, this category includes production, harvesting, transportation and processing of wood material. For example, six articles focused on the pellet or chip production for energy use, nine on the wood plantation for energy, construction material or biomass (raw material). Seven articles focused on single forest operation such as harvesting, logging and transportation and their related problems such as loss of biodiversity. One article referred to transport operation for forest biomass and residues. Five articles focused on the complete supply chain of wood. Finally, three articles focused on the selection of biomass to use in industrial processes such as torrefaction and one focused on the forest biomass production under different forest management.

Industrial processes include 25 articles where different processes and technological improvement within the context of bioeconomy are explained. Compared with the other categories they focused mainly on the process itself such as pre-treatment of biomass, its refining, torrefaction, pyrolysis, gasification and hydrothermal liquefaction processes. Other studies (9) focused on enzyme and catalyst production as well as application of bioproducts and wood waste in industries, treatment of wood and optimisation in coupled heat and power plant. Finally, one focused on the supply chain and biorefinery processes that are in act for biofuel production.

Biomaterial includes construction material, composites, bioplastic, treatment application and management. A total of 25 articles were found for this category. Construction material include 12 studies about utilisation of agglomerate, expanded and granules cork for building isolation, wood for building, roof, panels and particle boards, woody waste material used in cement industry and also consideration of future scenarios in using bio-based material in construction. Three studies regarded composites (such as woody-plastic composites, wood-based furniture, and polylactic composite with bio-based fillers). Five studies regarded bioplastic (such as bio-based polyethylene terephthalate (PET) bottles, formaldehyde-free pine tannin foams from bark, bio-based polyethylene and polypropylene, phenolic resin). Two articles focused on treatment application (where biochar or activated carbon derived from biomass are used for tertiary wastewater treatment), two on management (management of wood waste for future application, end-of-life treatments of wood flour reinforced with different bio-based products) and finally one included both bioplastic and second generation biofuel (referring to renewable rubber and Jet fuel from biomass).

Biochemical investigated in the studies were biobutanol, isobutanol, hydrogen, oxymethylene ether, acetonitrile, adipic acid, lignin, aromatic-rich hydrocarbons (addressed in eight studies in total).

Management processes included in the studies (eight articles) were wood products chain, cascading use of woody biomass in the wood sector; the introduction of woody biomass processing in rural areas; bioenergy policies and its implication on biodiversity loss; the management of the different end-use of biomass such as recycle, bury, or burn wood waste stating what is the best solution; production of climate and energy plan in municipalities. Finally two articles focused on industrial symbiosis: one article studied the environmental sustainability of industrial symbiosis (wood and chemical industries) for producing high-value-added biobased products, the other one evaluated two strategies for an industry cluster in Sweden (firsts strategy was the substitution of the fossil feedstock used in the industry cluster with forest-based feedstock, the other was to improve energy efficiency through thermal energy integration).

As far as the applied approaches are concerned, results show (Figure 13) that out of 155 studies, the large majority performed LCA (86%), while 10% used a mix of methods, including LCA, cash flow analysis, economic assessment, techno economic analysis, material and energy flow analysis, LCC, sustainability impact assessment, social LCA, geoprocessing coupled with geographic information systems, or ecosystem modelling. Other studies employed only LCC (2%), LCCO2, 0.6%, LCSA, 0.6%), life cycle water footprint assessment (LCWFA, 0.6%) and hotspot analysis, which is also following the four steps of a typical LCA, (0.6%).

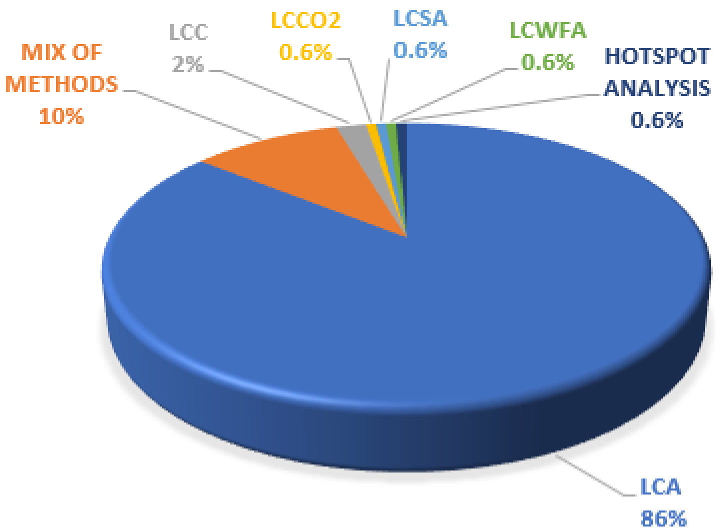

Figure 13: Types of LCA approaches used in the reviewed studies on forest bio-products.

Various system boundaries were considered in the reviewed studies. Cradle to gate was used in 74 articles, cradle to grave in 53 articles, gate to gate in 13. Three articles used a well to wheel system boundary; one used both cradle to cradle and cradle to gate; one focused from waste treatment facility to different type of disposal and recycling; one used both cradle to gate and cradle to grave; and one focused on a grave to grave approach, in which the authors used the wasted wood as a material for new applications (Faraca et al., 2019). In seven studies, no system boundary was defined.

Describing the functional units (FU) used in the reviewed documents is not an easy process, because almost every single work used a different one. For bioenergy products, heat and power FU were mainly described as energetic unit values such as (Tera, Giga, Mega, Kilo) Joule or watt. Biofuels and bioenergy were described either in terms of: energy released, litre or Kilos of biofuel produced or Km travelled per vehicle. Feedstocks were generally described as Kilo, Ton or m^3 of wood and its derivates (pallet, pellet, chips) fresh or dry; another study used hectare of forest land. For biomaterials, depending on the type of product, different FU are used. For example, bioplastic is mainly described as Kilo or Ton of product; composites as Kilo or piece of product; construction material as m^2 or m^3 of material; paper as well as the other biomaterials as Kilo of product. FU of industrial processes change from study to study depending on the process in use, sometimes using energy delivered/produced or Kilo of product. Also, biochemicals are described in term of Kilo of product or, in two specific studies, as MJ of hydrogen and MJ of heat produced. Management categories include very heterogeneous FU, which are difficult to summarize: examples include “the total production of the industry cluster”, “an annual production volume of 430,000 Tonnes per annum (T/a)” or “ Km^2 ”.

Various impact assessment methods are used in the reviewed studies (for an overview of existing methods see Section 2.2.2). These methods range from midpoint to endpoint methods although midpoint methods are more commonly applied (figure 14).

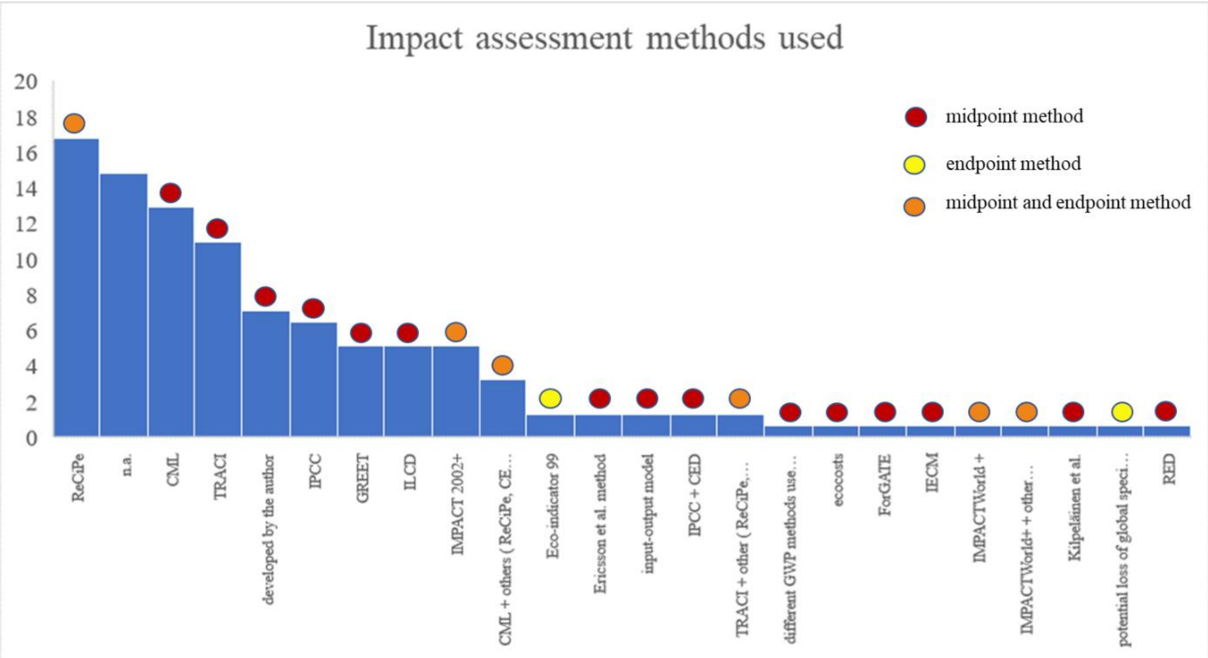

Figure 14: Impact assessment methods used in LCA approaches applied to forest bio-based products.

About 17% used ReCiPe which allows to calculate both midpoints and endpoints (usually only eight midpoints out of eighteen possible are used). CML was used on 13% of the studies, usually including six midpoints out of eleven. Traci was frequently used (in about 10% of the studies). In 7% of the studies impact assessment methods were specifically developed by the authors, while in 15% of them, the adopted method was not specified. Within this 15%, most are LCA studies and deal with GHG emission, while the rest use different approaches such as LCWFA, LCC, LCSA, LCCO2A for which no specific methods are available. The remaining studies (about 40%) used other LCA midpoint or endpoint methods, or a mix of them.

4.2 Midpoints and Endpoints used to assess impacts

As anticipated in the previous paragraph, each of the analysed articles selected a different list of midpoints and/or endpoints, for which results were estimated and discussed.

As shown in table A.3 in appendix, the midpoints and endpoints calculated in the reviewed literature, were grouped, on the basis of their similarity, in the following macro-categories: climate change, radiation, energy, particulate matter, acidification, eutrophication, ozone, smog, material, waste, resources depletion, environmental toxicity, human toxicity, human health, land, ecosystem. The macro-category "climate change" includes midpoints related to greenhouse gas emissions usually expressed as CO_2 equivalent. The category "radiation" includes cumulative radiating forcing and ionising radiation midpoints; "energy" includes renewable/non-renewable energy consumption midpoints; "particulate matter" includes both emission and formation of $PM_{2.5}$ and PM_{10} and human health impacted by them. "Acidification" includes terrestrial, aquatic and air compartments, usually using SO_2 equivalent as unit measure; "eutrophication" includes terrestrial, aquatic (fresh water or marine) and aerial compartments and the main unit of measures were phosphorous or nitrogen equivalent in their different chemical oxidation states as (N, NO_2, NO_3, P, PO_2, PO_4). The "ozone" macro-category includes both ozone depletion and photochemical ozone formation midpoints. In particular, ozone depletion was measured as CFC_{11} equivalent and as trichlorofluoromethane (R_{11}) equivalent while photochemical ozone formation was measured as VOC, ethylene and NOx equivalent. "Smog" includes a single midpoint expressed as O_3 equivalent. The "material" category includes kilograms of both renewable and non-renewable material consumed, and water utilisation in litre. Similarly, "waste" includes the quantity of waste generated in kilograms. The "resource depletion" macro-category includes both abiotic and biotic resources, represented by mineral (antimony equivalent, Sb eq.), metal (Iron equivalent, Fe eq.), and water (m^3 equivalent) depletion and by fossil fuel (MJ and Kg Oil eq.), respectively; in this macro-category economic indicators are also included such as capital cost, operating cost, maintenance cost, feedstock cost, salvage value and by-product credit, as well as the cost of extracting mineral and fossil fuel .

Two main types of toxicity were assessed in the studies: human and environmental. "Human toxicity" includes cancerogenic (in kilograms of toluene, benzene, 1,4-dichlorobenzene and vinyl chloride equivalent), non-cancerogenic (in comparative toxic unit (CTU), Kg toluene, Kg C2H3Cl eq), respiratory effect (in comparative toxic unit (CTU)) and ionizing radiation (in kBq U235 equivalent) midpoints. "Environmental toxicity" macro-category includes midpoints and endpoints focusing on three main environmental compartments such as freshwater, marine and terrestrial using mainly 1,4-dichlorobenzene equivalent as unit measure. "Human Health" macro-category includes only the endpoint human health. "Land" includes (agricultural and urban) land occupation and transformation expressed as square meter used per year or as Kg of carbon deficit. Finally, "ecosystem" includes ecosystem quality, biodiversity damage and global species lost equivalent per year (gSL eq.). To complete the scheme, only two articles focused on social impacts together with other environmental and/or economic indicators. Social indicators included five different stakeholder such as worker, consumer, land community, society, value chain actors not including consumers. Social indicator referred to the worker were: freedom of association and collective bargaining, child labour, fair salary, working hours, forced labour, equal opportunities/discrimination, healthy and safety, social benefits/social security, employment potential, employment wages and benefit. Social indicator referred to consumer was health & safety. Social indicators used for land community stakeholder were: access to material resources, delocalization and migration, safe & healthy living conditions, respect of indigenous rights, and local employment. Society indicators include: Public commitments to sustainability issues and Corruption. Finally, social indicator used for value chain actors not including consumers were fair competition and promoting social responsibility. Social indicators were not grouped in one macro-category due to their very limited presence in studies. Therefore, they were also not linked to ecosystem services.

Figure 15 shows the frequency of each macro-category in the reviewed studies.

"Climate change" occurred in 93.5% of the studies, and the main midpoints calculated were global warming potential (Kg CO_2 eq.) and greenhouse gas emission (Kg CO_2 eq.). This macro-category is followed by "ozone", calculated in 60.6% of the studies and mainly expressed as ozone depletion using Kg CFC_{11}eq. and photochemical oxidant formation using Kg VOC. "Eutrophication" follows, being calculated in 53.55% of the studies with the following midpoints (in order of occurrence): freshwater eutrophication (Kg P eq.), eutrophication (general meaning, Kg N-eq.), marine eutrophication (Kg N-eq), and, in only one article, air eutrophication (Kg N-eq).

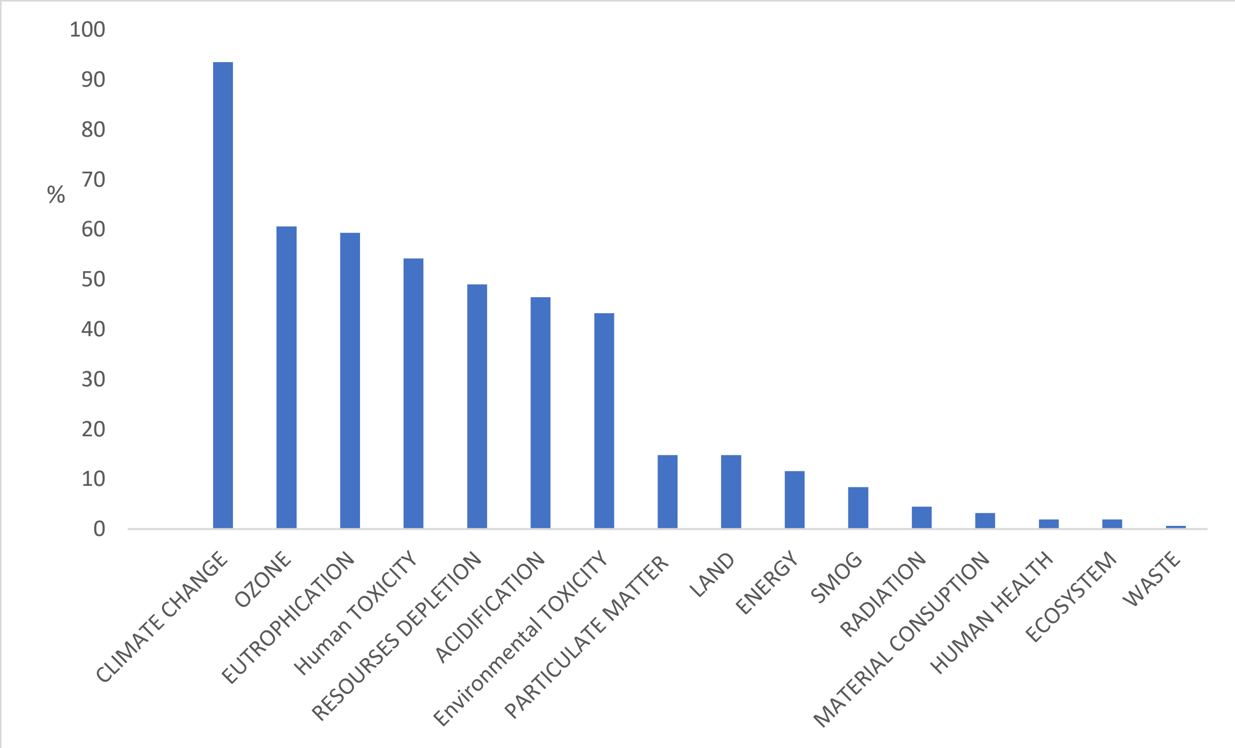

Figure 15: frequency of each macro-category in the reviewed studies.

"Human toxicity" was included in 54.2% of the studies and the main midpoints considered were human toxicity (Kg 1,4-dichlorobenzene eq.) and respiratory effect (Kg PM2.5 eq). "Resource depletion" was calculated in 49% of the studies mainly as fossil depletion (Kg Oil-eq.), depletion on fossil resources (MJ) and water depletion (m^3). "Acidification" was present in 46.5% of the studies mainly as acidification (general meaning) in Kg SO_2 eq., followed by terrestrial acidification (Kg SO_2 eq.).

"Environmental toxicity" was included in 43.23% of the studies, with the main focus being on Freshwater aquatic ecotoxicity (kg 1,4-dichlorobenzene eq.) followed by marine aquatic ecotoxicity (kg 1,4-dichlorobenzene eq.) and terrestrial ecotoxicity potential (Kg DCB eq). All the other categories were present in less than 20% of the studies; specifically: "particulate matter" (14.84%) focusing more on particulate matter formation (Kg PM10 eq.), "land" (14.84%) focusing on both agricultural and urban land as m^2*years, "energy" (11.64%) as primary energy consumption-not renewable (MJ), "smog" (8.39%) as smog midpoint (kg O3-eq), "radiation" (4.52%), "material consumption" (3.23%), "human health" (1.94%) , waste (0.65%). Similar frequencies of macro-categories and midpoints/endpoints occurred when analysing the individual product categories.

4.3 Relation between impact macro-categories-and ecosystem services

Once described which kind of midpoints/endpoints are considered in the LCA approaches on forest bio-based products, their relation to ecosystem services were identified (Figure 16, see also table A.4. in appendix). These connections were possible thanks to the identification of individual ecosystem services present within the CICES classification. In particular, starting from the long CICES list, different types of ecosystem services have been selected, such as provisioning, regulating and maintenance, which refer to both biotic and abiotic components. It was not possible to identify cultural ecosystem services as they focus more on physical-perceptive aspects than on strictly environmental aspects. Before going on to the description of the individual connections, a clarification must be made. Impact macro-categories "material consumption” and “resources depletion" were mixed together in “material and resources” because despite being different, the object of study are materials and resources. Furthermore, following the same logic, the macro categories of "Human toxicity", "Environmental toxicity" and "Human Health" were grouped into the "toxicity and human health" macro-category. These groupings were not made in the previous sub-chapter in order to clearly illustrate the types of impacts considered in the literature. Starting from these considerations, links with ES were defined to understand which services are affected by the bioeconomy sector. However, it is also important to keep in mind that other ES might be affected, but impacts related to those ES may not be assessed in LCA approaches.

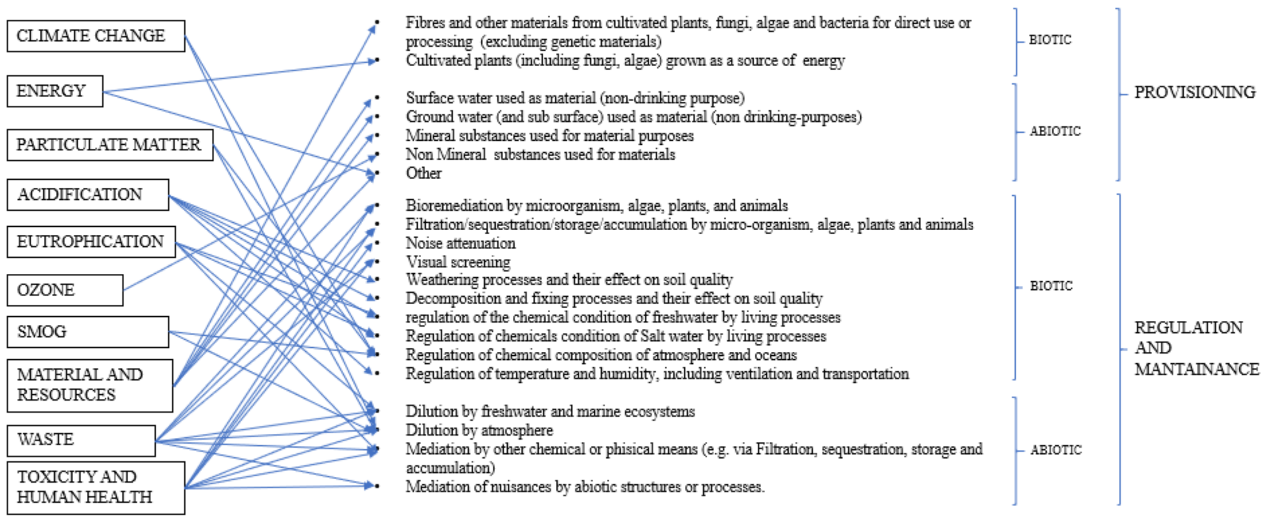

Figure 16: Representation of wood-based LCA impact categories and their relations with ecosystem services.

The “climate change” category can be linked to two main ecosystem services: “regulation of chemical composition of atmosphere and ocean” and “dilution by atmosphere”. In fact, several reviewed articles stated that utilising biomass instead of fossil fuel to produce energy as power, heat and biofuel leads to a net decrease in greenhouse gases.

“Energy” is related to the ecosystem service “cultivated plant (including fungi, algae) grown as a source of energy”. It can also be related with “other mineral or non-mineral substances or ecosystem properties used for nutrition, material or energy” because in the reviewed articles energy needed for all processes (from harvesting to industrial processes) was derived both from renewable and non-renewable feedstock (from biomass to fossil fuel or other form of energy).

“Particulate matter”, similarly to “climate change” can be related with “dilution by atmosphere” and with “regulation of chemical composition of atmosphere and ocean” due to its release in the atmosphere, especially after the biomass combustion.

“Acidification” is linked to “decomposition and fixing processes and their effect on soil quality”; “regulation of the chemical condition of freshwater by living processes”; “regulation of chemicals condition of Salt water by living processes” and with “Regulation of temperature and humidity including ventilation and transportation”. Such links are plausible because acidification is mainly derived from combustion processes, so the releasing of acidifying chemicals directly act on these ecosystem services. For example, it influences the normal decomposition of biological matter consequently influencing the normal composition of the soil and its typical characteristic necessary for the human use. Acidification could also influence the presence of plants that in turn mediate atmospheric conditions, for example by creating a microclimate, thus increasing the living conditions of the population.

“Eutrophication”, which is mainly due to the utilisation of fertilizer for improving biomass yield, can be linked to biotic regulating services such as “regulation of the chemical condition of freshwater by living processes” and “regulation of chemicals condition of Salt water by living processes”. This may be possible because it affects the nutrient load present, thus changing the normal ability of plants or other organisms to remove nutrients due to the fact that the concentration is very high. This consequently leads to influence the maintenance of the chemical condition of the water which can then be used for human uses. It can also be related with abiotic regulating and maintenance services such as “dilution by freshwater and marine ecosystems” and “mediation by other chemical or physical means (e.g. via filtration, sequestration, storage and accumulation)”. For example, the increase in nutrients leads to an increase in the concentration of these substances in water, decreasing the dilution capacity of the water present, which helps mitigate damaging effects such as eutrophication itself .On the other hand, the uncontrolled growth of aquatic plants due to eutrophication, then decreases the space that could have been used for the seizure of toxic chemical components (for example in marine sediments) which consequently protected people from the presence of these toxic components.

On the other hand, “smog” impact macro-category is linked to “Regulation of chemical composition of the atmosphere and ocean” and with the “dilution by ocean”; linkages are possible due to the exposure and deposition of ozone on the atmosphere and water.

“Material and resource” macro-category is linked to both biotic and abiotic provisioning ecosystems. Biotic material and resources include “fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)”. However, the majority of material and resources are abiotic ones such as “Surface water used as material (non-drinking purpose)”, “Ground water (and sub surface) used as material (non drinking-purposes)”, mainly due to the need of water for industrial processes such as gasification, combustion as well as feedstock production; “Mineral substances used for material purposes” is linked to this macro-category due to the mineral extraction from a mine for mineral acid production such as chloride acid (HCl) and sulphuric acid (H2SO4) and used for industrial processes such as pre-treatment of lignocellulosic feedstock.

“Waste” macro-category can be related only to regulating and maintenance ecosystem services. They include “Bioremediation by microorganism, algae, plants, and animals” and “filtration/sequestration/storage/accumulation by micro-organism, algae, plants and animals” going to influence the ability that plants (and other living organisms) have to transform/fix and storage organic and inorganic substances thus mitigating their harmful effect and at the same time reducing the cost of disposal; on the other hand also “visual screening” can be linked with “waste”. This connection is due to the fact that, despite the attempt to avoid generating waste in bioeconomy, the presence of solid waste, if in large quantities, can generate a visual impact. Finally, waste was related with “Dilution by freshwater and marine ecosystems”; “Dilution by atmosphere”; “Mediation by other chemical or physical means (e.g. via Filtration, sequestration, storage and accumulation)”; due to the fact that the presence of waste can influence the normal ability of atmosphere and water to dilute waste pollutants and thus to have air and water more pure as well as to reduce the normal ability to remove waste substance helping to protect people from waste exposure.

The last impact macro-category referred to “toxicity and human health”. Also this category was related only to both biotic and abiotic provisioning & maintenance ecosystem services. In particular, considering the biotic ecosystem services, “Bioremediation by microorganism, algae, plants, and animals”; filtration/sequestration/storage/accumulation by micro-organism, algae, plants and animals” were selected due to the fact that the environment has the ability to reduce the amount of toxic pollutants through these processes; “Noise attenuation” and “Visual screening” were selected due to the fact that toxic component in the environment can reduce or totally eliminate the presence of woody land or other crops that act as a source of noise reduction or reduction of visual impacts as in the case of shelterbelts around industrial structures. Considering the abiotic ecosystem services, links are proposed to “Dilution by freshwater and marine ecosystem”; “Dilution by atmosphere”; “Mediation by other chemical or physical means (e.g. via Filtration, sequestration, storage and accumulation)” considering the fact that these environmental processes are useful to protect humans and the ecosystems from the exposure to toxic substances. In addition, by greatly increasing the concentration of toxic components, the capacity of the environment to remove them is reduced.

Finally, it was not possible to link “radiation” because it has no direct connections with ecosystem services, as well as “ecosystem” and “land” due to the fact that they are too general to link them to a specific ecosystem service.

5. Discussion

The emerging bioeconomy and the forest sector have a central role to move our global economy from fossil to biomass-based. In this contest LCA approaches can be used to assess the environmental, economic and social impacts of production and consumption processes.

This thesis proposed a review of the studies applying LCA approaches to bioeconomy products and processes. A total of 155 scientific articles were analysed, which is a consistent number considering that the scope of the review was restricted to forest and/or wood-based raw materials only (while other types of feedstock are also largely used in bioeconomy) and to empirical studies published from 2016 to 2019.

The results showed a constant number of studies published during each year in the above-mentioned time period. LCA approaches are largely used in this field underlining the fact that scientific community and policymaking are paying attention to monitoring the environmental performance of these bioproducts. As an example, in 2016 about 50 scientific articles used LCA approaches. This is a rather high number, considering that in the previous year the whole literature on bioeconomy counted more or less 100 article (D'Amato et al., 2017).

A large part of the study regarded North America and Europe, but several other countries were also involved in this type of research, confirming that despite the bioeconomy sector is quite new, the interest on the topic is diffuse. Comparing the bioeconomy strategies worldwide (figure 2) with the distribution of the reviewed studies (figure 12), it appears that often, where strategies at national level occur, techniques to monitor their environmental performance are used. It is possible that LCA approaches help to give weight, relevance and strength to the global political strategies despite LCA approaches are voluntary (European Commission, 2019).

Considering the bioproducts and processes analysed by the reviewed studies, the majority of the articles focused on low value products while high value products were less considered. Particularly, bioenergy category (power/heat/second generation biofuel) resulted as the most studied type of bioeconomy activity. This makes sense considering that the production of bioenergy from biomass is seen as the most promising way to reduce the GHG emissions in order to reach the reduction by 40% by 2030 (EU, 2018). The second most represented category in the literature was feedstock, including production, harvesting, processes and transportation of biomass for both bioenergy and other wood-based products. It is fundamental that these pre-product processes are sustainable in order to ensure a greener supply chain (being it an important part of the cost and environmental stressor of the final product). For example in forest operations, i.e. transportation and comminution process within the forest biomass supply chain, high amount of fuel is consumed, so switching on a high energy efficiency is important (de la Fuente et al., 2017). Summarizing, feedstock category was well studied because it positively influence environmental, economic and social performance if exploited in a proper way (Yue et al., 2014).

Industrial processes were also highly considered due to the fact that conversion technology in biorefineries is at an embryonal stage, and it is necessary to find the most cost-efficient one with low environmental impacts. Consistent improvements are needed in this field, especially in the pre-treatment processes and enzyme production were high amount of energy is used, both causing the highest environmental issue (Bello et al., 2018).

Biomaterials were considered in a consistent share of the articles. This can be related to their market value and to an increasing demand in using these kinds of products instead of fossil-based one (Lundmark et al., 2014). For example, LCA approaches were also used in construction sector with the intent to shift towards a major utilisation of timber material and composites instead of other materials. It was shown that increasing use of wood in construction might help to achieve climate protection target (Hafner and Rueter, 2019).

On the other hand, the smaller number of studies on bioplastics can be related to the fact that the market of these products is not very large.

Biochemicals and management are found to be assessed only by a small number of articles. Biochemicals were less considered in LCA studies due to the fact that it is a recent theme and that technological innovation for this type of product is still premature. The utilisation on LCA approaches in management can help also policymaker to understand the strength of bioeconomy. For example, one study focused on the implications of the introduction of woody biomass processing in a rural area, showing improvements in environmental and economic benefits (Jackson et al., 2018). Another key use of these approaches was their utilisation in identifying environmental sustainability on industrial symbiosis. It can be stated that also in bioeconomy as well as in other sectors, LCA is useful for policymaking (Serenella et al., 2015).

Nanocellulose, despite its higher value in the bioeconomy pyramid, is considered only in one study, in Japan. It is interesting the fact that only in this country Nanocellulose is accounted in LCA approaches. Japan wants to use biomass feedstock not only for bioenergy production but also as material (Moon et al., 2017). It wants to substitute heavy plastic resin used in vehicle with soft nanocellulose fibre. The production of nanocellulose showed greater impact on GHG emission and cost compared with the plastic material production used in vehicle. However, it was stated that these environmental and economic risks could be broken down improving energy efficiency and social risk could be reduce improving safe and healthy condition in the communities (Moon et al., 2017).

Another unexpected result was that only one publication on pulp and paper production using LCA was present. I expected more studies on these industries because of the high impact in term of energy and water demand, as well as chemical released (Avşar and Demirer, 2008; Conti et al., 2016).
This work was done in a pulp and paper industry in Finland and the general result showed high impact in energy and water consumption during industrial processes but also high impact in eutrophication (Corcelli et al., 2018).

Considering the overall results, almost the totality of the studies used environmental LCA, rather than other LCA approaches such as LCC and SLCA. This result was expected, and it was in line with other sectors. This might mean that, in the wood based bioeconomy sector, environmental issues are more relevant/necessary than social and cost analysis. On the other hand, it might also mean that these approaches are less commonly used due to technical reason such as less available data and methods. However, it would be important to study and let stakeholder know the social impact that this sector can have. For example, in this review only two articles focused on SLCA, mixed with the classic LCA. This approach can help to understand the employment potential and employee wages on population that forest based bioeconomy can give (Mahbub et al., 2019), so utilisation of this approach was suggested. LCC was also considered less than LCA, usually in combination with it. For example, in the bioethanol production, despite the global price seems to decrease in the following years, the most relevant aspects are feedstock and operating costs. Therefore, having this information stakeholders can think to develop or use different technologies helping to reduce both costs and environmental issues. In fact, mixing LCA with LCC and other economic tools can have multiple advantages, helping to understand which process is better to utilise in term of environmental improvement and optimisation of cost (Lu and El Hanandeh, 2017). Despite its importance in this field, the consumption of water has not been considered in a proper way. Indeed, only on article focused on this topic, and considering that biomass conversion, as well as other procedures require huge amount of water (Wong et al., 2016a) the utilisation of this specific LCA approach should be more intensively applied. LCCO2 was also used rarely in the reviewed literature.

Considering system boundary, about fifty percent of the articles reviewed focused their studies on a cradle to gate approach. Within this amount all bioproducts were considered, from biomaterial to bioenergy, feedstock, industrial processes, biochemical and management. This result showed that in the last few years the authors put a lot of effort to reach out the impact on the production of these products, starting from the supply chain of feedstock to the conversion process until the final products such as power or biofuel generation, pellet, construction material, biochemical and other. Second most used system boundary was cradle to grave, showing that the interest on this problem is increasing. However, this approach is mostly considered in the bioenergy sector, mainly focusing on power and/or heat but also in second generation biofuel. Few other products were considered in this approach, so additional efforts are needed. On the other hand, only thirteen per cent of the literature reviewed used gate to gate approach, meaning that the authors preferred to have an overview of the products instead of focusing only on a particular process such as harvesting and transportation of feedstock or on one industrial step such as thermochemical conversion or production of enzyme.

Functional units are also not homogeneous. Indeed, a lot of different functional units was found, also within the same product category. This makes difficult any comparison and indicates that for future studies functional units should be standardized in order to make such comparison possible.

Methods used clearly showed that in this field there is a preference on utilising midpoint methods compare to endpoint ones. This is a positive result, considering that midpoint methods have more scientific robustness than endpoint ones. However, the results they provide are more difficult to explain to non-expert people.

About midpoints and endpoints considered in the studies, results clearly showed that almost the totality of LCA studies include the analysis of impacts on climate change. This was expected, considering that this is a problem of societal relevance at global level (Steffen and Rockström, 2015). For instance, the EU aims at a 40% reduction of GHG emission by 2030. In addition, the main goal of the bioeconomy is explicitly to address climate change through the substitution of fossil fuels (McCormick and Kautto, 2013; Ramcilovic-Suominen and Pülzl, 2018). In this context it makes sense to assess the emissions of the various types of biomass utilisation in order to determine if the bioeconomy can contribute to decreasing greenhouse gas emissions (and almost all the studies reviewed showed such reduction). Ozone was also assessed in most of the reviewed studies. This is not surprising, considering that all the bioeconomy processes need energy, either from fossil or other resources, and it was shown that the impact related with the ozone depletion is mainly due to the utilisation of fossil derived-diesel combustion during the collection and transportation of wood or forest activity in general (Laschi et al., 2016). Eutrophication impact was also highly considered in this field, accounted in 59,35% of the studies. It also has sense considering that feedstock for the production of bioproducts came from woody biomass. If such feedstocks are non-food crops (non-food terrestrial biomass, see 2.1.2) common production and utilisation of fertilizer occurs, thus contributing to eutrophication. In general, it is the use of fertilizers that markedly increases the value of the impact indicators of this category. Other impact macro-categories commonly used in this sector are human toxicity, resource depletion, acidification and environmental toxicity and, although in some cases they achieved a significant impact, the authors gave more importance to other impacts such as climate change. For example, biobased PET bottles, perform better in terms of climate change impact than those that are completely fossil fuel-based. However they perform worse in terms of environmental toxicity due to the production of pesticides and due to the processing of wood to generate a biochemical precursor (para-xylene) for the production of bio plastic (Chen et al., 2016). Another impact macro-category not considered in a proper way is particulate matter. Its use in this field should be expanded, considering that one of the major impacts in bioeconomy is the emission of particulate matter in the atmosphere due to biomass combustion and ash formation in industrial processes. Other impact macro-categories almost not considered in this field include land, ecosystem and waste. Unfortunately, this result was expected whereas it is a known problem. First because many studies used "cradle to gate" approach and consequently the "waste" is not considered. Second, because some authors state that there is a lack use of land and ecosystem impact indicators since these problems are of global relevance and are especially relevant for bio-based products (Martin et al., 2018), thus the use of such midpoints in this field should be expanded.

What was observed is that the midpoints and endpoints considered in bioeconomy (here grouped in macro-categories) can be conceptually linked to ES. On the other hand, it is equally true that while the list of ES is wide, only few of them are reflected in the LCA midpoints and endpoints. For example, the “climate change” macro-category can be related only with two ecosystem services: “regulation of chemical composition of atmosphere and ocean” and “dilution by atmosphere”. Several of the articles reviewed stated that utilising biomass instead of fossil fuel to produce energy as power, heat and biofuel leads to a net decrease in greenhouse gases. This linkage is plausible because the emission of GHG in the atmosphere increase their concentrations; the environment cannot adsorb and chemically modify more than a certain amount of gasses, therefore climate change category directly influences the natural capacity of adsorbing and processing such gasses.

In general, the impact macro-categories were linked to supply and regulation & maintenance ES, both biotic and abiotic, as well as to provision of ES and supportive ES. However, while for provisioning ES it was quite easy to identify the links, for supportive ones more efforts were needed as such ES are more general and conceptual than LCA midpoints and endpoints.

To conclude, this type of approach allows to highlight more clearly the links between the impacts caused by the bioeconomy sector and the benefits that the environment provides us. Moreover, although LCA approaches consider a limited number of ES, there is a broader discussion that is brought to light from this perspective that can contribute to give a wider view.

6. Conclusion

The aim of this thesis was to perform a comprehensive review of the empirical scientific literature assessing the sustainability performance of bio-based products from wood through LCA approaches. More specifically, the aim was not to investigate the sustainability performance of bio-based products against traditional alternatives, rather to provide grounds for discussion on the challenges and opportunities for LCA in the context of bioeconomy activities. In particular, research questions included what is the state of the art of the literature, including the temporal distribution of the literature, the products and geographic areas at study, and the methods used; which impacts, and related midpoints are considered by the reviewed studies and how do midpoints relate to ecosystem services.

To answer these questions, I searched for relevant scientific literature from 2016 to January 2019 using Scopus. After a screening process to identify suitable documents, 155 scientific articles were included in the sample and used as source of data. The results showed that the number of articles was evenly distributed between 2016 and 2018 and a smaller number of articles was found in 2019 (in line with the fact that the study started on January 2019). Within these articles, the geographical distribution identified has global coverage, including all continents, but more articles were found in North America and Europe. Investigated products were bioenergy (heat and/or power, second generation biofuel), feedstock, biomaterials, bioeconomy related industrial processes, biochemical, pulp and paper, nanocellulose and management of different products. Results showed that bioenergy products were the most commonly studied. Mostly used LCA approaches were the classic LCA approach followed by a mix of methods and a small number of LCC, SLCA and others.

Cradle to gate system boundary was commonly used and considering that bioeconomy is an emerging sector it is a good starting point, however more efforts are needed to include also the end of life impacts of the products. Multiple types of functional units are used for each midpoint thus not allowing comparison of different studies. Midpoints are more often used than endpoints, and in general only few midpoints are considered. More specifically, almost the totality of LCA studies includes climate change, followed by ozone depletion and formation, eutrophication, human toxicity, resource depletion, acidification and environmental ecotoxicity. Only a small number of articles considered midpoints as particulate matter, energy consumption, smog, radiation, material, health, ecosystem and waste.

Estimated midpoints and endpoints can be conceptually linked with ecosystem services, which can provide a more comprehensive understanding of ecological issues to be considered in LCA and bioeconomy literature in the future. Moreover, although LCA approaches consider a limited number of ES, there is a broader discussion that is brought to light from this perspective that can contribute to give a wider view.

The implications of this study are of use for the LCA scientific community to understand which ecosystem services are included or missing in its studies, and to further develop LCA approaches in this regard; and to the bioeconomy community to understand the state of the art of LCA studies on forest/wood-based products and processes. Following these results, a review of the literature comparing bio-based and non-biobased products would be of interest.

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Appendix

Table A.1: Distribution of studies worldwide.

COUNTRY	# STUDIES	BIOENERGY	FEEDSTOCK	BIOMATERIAL	INDUSTRIAL PROCESSES	BIOCHEMICAL	MANAGEMENT
USA	33	14	8	5	3	1	2
Canada	18	10	1	-	4	3	-
Italy	11	6	4	-	-	1	-
Sweden	11	3	4	2	-	1	1
Germany	9	2	2	3	1	-	1
Finland	8	3	3	2 *	-	-	-
China	5	-	1	1	3	-	-
Spain	5	1	1	1	2	-	-
Japan	4	2	-	2 *	-	-	-
Norway	4	1	-	1	1	-	1
UK	4	4	-	-	-	-	-
Australia	3	3	-	-	-	-	-
Portugal	3	1	-	3	-	-	-
Poland	3	1	2	-	-	-	-
France	3	2	-	1	-	-	-
North Amer.	2	-	-	1	1	-	-
Brazil	2	1	1	-	-	-	-
Denmark	2	-	1	1	-	-	-
European un.	2	-	-	-	-	-	2
Austria	1	-	-	-	-	-	1
CA-S	1	-	1	-	-	-	-
China (uni)	1	-	-	1	-	-	-
Colombia	1	-	-	-	-	1	-
Nordic count.	1	1	-	-	-	-	-
Neths/Ge	1	1	-	-	-	-	-
n.a.	1	-	-	-	-	1	-
n.a.	1	-	-	1	-	-	-
n.a.	1	1	-	-	-	-	-
NW- Europe	1	-	-	-	1	-	-
Norway(data from Zambia, Indonesia and Nepal)	1	-	-	-	1	-	-
Pakinstan	1	-	-	1	-	-	-
Philippine	1	1	-	-	-	-	-
Mozambique	1	-	1	-	-	-	-
Mali	1	1	-	-	-	-	-
South Africa	1	-	-	1	-	-	-
Malaysia	1	1	-	-	-	-	-
Ireland	1	1	-	-	-	-	-
Sweden-Brazil	1	-	-	1	-	-	-
Switzerland	1	1	-	-	-	-	-
The Netherlands	1	1	-	-	-	-	-
Guadeloupe island	1	-	1	-	-	-	-
Chile	1	1	-	-	-	-	-

* Paper was added in biomaterial category in Finland only in this table; **Nanocellulose was added in biomaterial category in Finland only in this table. These additions were done in order to safe space in the table due to the fact that only one article account Paper and only one account Nanocellulose

Tab A.2.: Classification of the reviewed studies according to the type of product or process under investigation and the adopted LCA approach.

CATEGORIES	type of product or process	AUTHOR	LCA APPROACH
BIOENERGY	Power	(Boschiero et al., 2016)	LCA
	Power	(Giuntoli et al., 2016)	LCA
	Power	(Laganière et al., 2017)	LCA
	Power	(Paolotti et al., 2017)	LCA+ EA
	Power	(Morrison and Golden, 2017)	LCA
	Power	(Ali and Kumar, 2017)	LCA
	Power	(Weldu and Assefa, 2017)	LCA + LCC
	Power	(Weldu et al., 2017)	LCA
	Power	(Homagain et al., 2016)	LCCA
	Power	(Leino et al., 2016)	LCA
	Power	(Weldu, 2017)	LCA
	Power	(Almeida et al., 2016)	LCA
	Power	(Qun et al.,2018)	LCA
	Power	(Röder and Thornley, 2018)	LCA
	Power	(da Costa et al., 2018)	LCA
	Power	(W. Liu et al., 2017)	LCA
	Power	(Martinez and Lopez, 2017)	LCA
	Power	(González-García and Bacenetti, 2019)	LCA
	Power	(Omura et al., 2018)	LCCO2A
	Power	(Vadenbo et al., 2018)	LCA
	Power	(Cavalett et al., 2018)	LCA
	Heat	(Pelletier et al., 2019)	LCA
	Heat	(Dias et al., 2017)	LCA
	Heat	(Fitzpatrick, 2016)	LCA
	Heat	(Wolf et al., 2016a)	LCA
	Heat	(Wolf et al., 2016b)	LCA
	Heat and power	(Kanematsu et al., 2017)	LCA
	Heat and power	(Oreggioni et al., 2017)	LCA
	Heat and power	(Havukainen et al., 2018)	LCA
BIOENERGY	Second generation biofuels	(Miret et al., 2016)	LCA
	Second generation biofuels	(Yue et al., 2016)	LCA
	Second generation biofuels	(Cambero et al., 2016)	LCA
	Second generation biofuels	(Handler et al., 2016)	LCA
	Second generation biofuels	(Malik et al., 2016)	LCA
	Second generation biofuels	(Meyer et al., 2016)	LCA+TEA
	Second generation biofuels	(Janssen et al., 2016)	LCA
	Second generation biofuels	(Zaimes et al., 2017)	LCA
	Second generation biofuels	(Wong et al., 2016a)	LC(water foot - printing)A
	Second generation biofuels	(Fan et al., 2016)	LCA
	Second generation biofuels	(Sundaram et al., 2017)	LCA
	Second generation biofuels	(Karvonen et al., 2018)	LCA +ToSIA

BIOENERGY	Second generation biofuels	(Pierobon et al., 2018)	LCA
	Second generation biofuels	(Morales et al., 2017)	LCA
	Second generation biofuels	(Deswarte et al., 2007)	LCA
	Second generation biofuels	(Wong et al., 2016b)	LCA
	Second generation biofuels	(Daystar et al., 2017)	LCA
	Second generation biofuels	(Gu and Bergman, 2017)	LCA
	Second generation biofuels	(Winjobi et al., 2016)	LCA
	Second generation biofuels	(B. Liu et al., 2017)	LCEA
	Second generation biofuels	(Tsalidis et al., 2017)	LCA
	Second generation biofuels	(Hanif et al., 2016)	LCC
	Second generation biofuels	(Lu and El Hanandeh, 2019)	LCA+LCC
	Second generation biofuels	(Tasca et al., 2019)	LCA
	Second generation biofuels	(Sorunmu et al., 2018)	LCA
	Second generation biofuel	(Liang et al., 2017)	LCA
FEEDSTOCK	For bioenergy	(Ortiz et al., 2016)	LCA
	For biomass	(Kilpeläinen et al., 2016)	LCA
	For biomass	(Klein et al., 2016)	LCA
	For bioenergy	(Hossain et al., 2016)	LCA
	For bioenergy	(Proto et al., 2017)	LCA
	For biomass	(Zhang et al., 2016)	LCA
	For bioenergy	(Schweier et al., 2016)	LCA
	For bioenergy	(Bacenetti et al., 2016)	LCA
	For biomass	(Zhang et al., 2016)	LCA
	For biomass	(Laschi et al., 2016)	LCA
	For bioenergy	(Buchholz et al., 2017)	LCA
	For bioenergy	(Hossain and Poon, 2018)	LCA
	For biomass	(García-Durañona et al., 2016)	LCA
	For bioenergy	(Porsö et al., 2016)	LCA
	For biomass	(Ault et al., 2016)	LCA
	For biomass	(Abbas and Handler, 2018)	LCA
	For bioenergy	(Snäll et al., 2017)	LCA
	For biomass	(de la Fuente et al., 2017)	LCA
	For industrial processes	(Chen et al., 2017)	LCA
	For bioenergy	(Chary et al., 2018)	LCA
	For bioenergy	(Padilla-Rivera et al., 2017)	LCA
	For bioenergy	(Saez de Bikuña et al., 2017)	LCA
	For bioenergy	(Alam et al., 2017)	LCA
	For biomass	(Milota and Puettmann, 2017)	LCA
	For biomass	(Zhang et al., 2016)	LCA
	For biomass	(Krzyżaniak et al., 2019)	LCA
	For bioenergy	(Pereira et al., 2018)	LCA
	For industrial process	(de la Fuente et al., 2018)	LCA

FEEDSTOCK	For management	(Baul et al., 2017)	LCA + SIMA
	For industrial process	(Bałazińska, 2017)	LCA
	For biomass	(Pergola et al., 2018)	LCA + LCC
	For biomass	(Żelazna et al., 2019)	LCA
BIOMATERIAL	Construction material	(Sierra-Pérez et al., 2016)	LCA
	Construction material	(Hossain et al., 2017)	LCA
	Construction material	(Peñaloza et al., 2016)	LCA
	Construction material	(Skullestad et al., 2016)	LCA
	Construction material	(Demertzi et al., 2017)	LCA
	Construction material	(Peñaloza et al., 2018)	LCA
	Construction material	(Ferreira et al., 2016)	LCA
	Construction material	(Bergman et al., 2016)	LCA
	Construction material	(Hu et al., 2018)	LCA
	Construction material	(Hussain et al., 2018)	LCA
	Construction material	(Hafner and Rueter, 2019)	LCA
BIOMATERIAL	Construction material	(Crafford et al., 2017)	LCA
	composites	(Sommerhuber et al., 2017)	LCA
	composites	(Linkosalmi et al., 2016)	LCA
	composites	(Haylock and Rosentrater, 2018)	LCA + TEA
	bioplastics	(Chen et al., 2016)	LCA
	bioplastics	(González-García et al., 2016b)	LCA
	bioplastics	(Kikuchi et al., 2018)	LCA
	bioplastics	(Liptow et al., 2018)	LCA
	bioplastics	(Hildebrandt et al., 2019)	LCA
	Treatment application	(Thompson et al., 2016)	LCA
	Treatment application	(Gu et al., 2018)	LCA
	Management	(Faraca et al., 2019)	LCA
	Management	(Beigbeder et al., 2019)	LCA
BIOMATERIAL	bioplastic and second generation biofuel	(Riazi et al., 2018)	LCA
PAPER	paper	(Corcelli et al., 2018)	LCA
NANOCELLULOSE	nanocellulose	(Moon et al., 2017)	LCA + SLCA (PSILCA)
INDUSTRIAL PROCESSES	torrefaction	(Mcnamee et al., 2016)	LCA
	Torrefaction	(Porsö et al., 2018)	LCA
	biorefinery	(González-García et al., 2016a)	LCA
	biorefinery	(Budzinski and Nitzsche, 2016)	LCA + cash flow analysis
	pyrolysis	(Li et al., 2017)	LCA
	Biochar production	(Smebye et al., 2017)	LCA

	Cellulase production	(Gilpin and Andrae, 2017)	LCA
	catalyst	(Benavides et al., 2017)	LCA
	Cement industry	(Zhang and Mabee, 2016)	LCA
	pyrolysis	(Ayer and Dias, 2018)	LCA
	Construction activity	(Hossain and Poon, 2018)	LCA
	Heat and power plant	(Karlsson et al., 2018)	LCA
	Upcycling wood waste	(Hossain et al., 2018)	LCA
	Hydrothermal liquefaction	(Nie and Bi, 2018)	LCA
	Post combustion	(Schakel et al., 2018)	LCA
	pre-treatment	(Nwaneshiudu et al., 2016)	LCA
	gasification	(Li et al., 2018)	LCA
	biorefinery	(Bello et al., 2018)	LCA
INDUSTRIAL PROCESSES	Softwood treatment	(Essoua et al., 2017)	LCA
	Bioenergy plant	(Lu and El Hanandeh, 2017)	LCA+LCC
	Thermochemical Conversion system	(Gu and Bergman, 2016)	LCA
	CHP plant	(Tagliaferri et al., 2018)	LCA
	Bioenergy plant	(Krč et al., 2016)	LCA
	Bioenergy chain	(Ruiz et al., 2018)	LCA
	biorefinery	(Bello et al., 2018)	LCA
	Biomass co-firing	(Schakel et al., 2014)	LCA
BIOCHEMICAL	Butanol	(Levasseur et al., 2017)	LCA + TEA
	hydrogen	(García et al., 2017)	LCA
	oxymethylene ether	(Mahbub et al., 2017)	LCA
	Acetonitrile	(Tripodi et al., 2018)	LCA
	adipic acid	(Aryapratama and Janssen, 2017)	LCA
	oxymethylene ether	(Mahbub et al., 2019)	LCSA
	Lignin for phenols	(Lettner et al., 2018)	Hotspot Analysis (Including 4 steps of LCA)
	Isobutanol and Aromatic-Rich Hydrocarbons	(Cai et al., 2018)	LCA+ TEA
MANAGMENT	Forest to wood products	(Braun et al., 2016)	LCA
	Wood product cascading	(Bais-Moleman et al., 2018)	LCA + MEFA
	Woody biomass processing	(Jackson et al., 2018)	LCA
	Wood using	(Morris, 2017)	LCA
	Municipal planning	(Valente et al., 2018)	LCA + GEOSKOG+ GIS
	Industrial symbiosis	(Hildebrandt et al., 2018)	LCA
	Bioenergy policies	(Di Fulvio et al., 2019)	LCA
	Industry cluster	(Røyne et al., 2018)	LCA

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Table A.3: midpoints/endpoints considered in wood-based LCA approaches from 2016 to 2019:

MACRO-CATEGORIES	MIDPOINTs/ENDPOINTs
CLIMATE CHANGE	GHG emission (kg CO2-eq ∗ m−3); GHG emission (g CO2 eq)/ MJ of electricity delivered; GHG emission (kg CO2 eq/KWh; CO2 emission (kg CO2/MWh); GHG emission (kg CO2 eq); climate change (kg CO2 eq); GWP100 (CO2-eq./per gigajoules (GJ) fuel); Global warming potential 100 (Kg CO2 eq); Global warming potential (GWP, g CO2 eq/Mj); global warming potential (Kg CO2 eq); climate change (endpoint); CO2 emission (Ton CO2), net climate impact (ton CO2); GHG emission (ton)
RADIATION	cumulative radiative forcing (CRF, W/m2); Ionizing radiation (IR) Bq C-14 eq; radiation
ENERGY	primary energy consumption-not renewable (MJ); primary energy consumption-renewable (MJ); Cumulative energy demand (CED, MJ); Energy (J); Cumulative Energy Demand of fossil energy (CED, MJ-eq)
PARTICULATE MATTER	particulate matter (ppm); particulate matter (PM, kg PM2.5-eq); particulate matter formation (kg PM10 eq); Human Health Particulate (Kg PM 2.5 eq); PM2.5 Emissions (g); emissions of particulate matter
ACIDIFICATION	Acidification (kgSO2-eq); Aquatic acidification (AAci) kg SO2 eq ; Acidification moles of H+-Eq; air acidification (AA, Kg SO2 eq); acidification; terrestrial acidification (Kg SO2 eq);
EUTROPHICATION	Eutrophication (kg N-eq); Eutrophication (kg PO2-eq); Eutrophication (kg (PO4)3 -eq; marine eutrophication Kg N-eq); Eutrophication Potential (EP, kg PO4-eq); Terrestrial eutrophication (mole N eq); Eutrophication potential (EP,Kg Nox eq); eutrophication Nox; Aquatic eutrophication (AEu) kg PO4 P-lim ; water eutrophication (WE, Kg N-eq); Freshwater Eutrophication (Feu, CTUe); Fresh water eutrophication (kg P eq); Eutrophication; air eutrophication (AE, Kg N-eq).
OZONE	Ozone depletion (kg CFC-11-eq); ozone depletion (10-10 kg CFC-11 eq); Ozone depletion kg R11 eq.; Ozone layer; formation potential of tropospheric ozone photochemical oxidants (Kg Ethene-eq); Photochemical oxidation (kg ethylene eq.); Photochemical oxidation kg NOx-Eq; Nox emission (g); Photochemical oxidant formation (Kg NMVOC); photochemical ozone formation potential (POFP, kg O3 eq).
SMOG	Smog (kg O3-eq)
MATERIAL CONSUMPTION	Material resources consumption (nonfuel) non- renewable materials (Kg); Material resources consumption (nonfuel) Renewable materials (kg);); Material resources consumption (nonfuel) Fresh water (L)
WASTE	Waste generated Solid waste (Kg)
RESOURSES DEPLETION	Depletion of abiotic resources – elements, ultimate (kg antimony eq.; kg Sb eq); Depletion of biotic resources – fossil fuels (MJ); Fossil depletion (kg oil eq); Fossil fuel; Water depletion (m3); water source depletion (m3 water eq); Water depletion (L H2O); Water use (L H2O) ; Water scarcity (WD), [1/AMD]; Resources; Mineral extraction (MEx) MJ surplus; mineral consumption; Metal depletion (Kg Fe eq); Mineral, fossil and renewable resource depletion (mg Sb-eq); Fossil Resource Depletion (MFRD, kg Sb eq); capital cost, operating cost, maintenance cost, feedstock cost, salvage value and by product credit, overall cost ; cost of extraction of minerals and fossil fuels;
Human TOXICITY	Carcinogenics (comparative toxic units, CTU); Carcinogenic kg benzene-Eq; HumanToxicity Cancer Effects (HTC. CTUh); Carcinogens (CG) kg C2H3Cl eq, ;), Human Toxicity Non-cancer Effects (HTNC,CTUh); Non-carcinogenic kg toluene-Eq,; Non-carcinogens (N-CG) kg C2H3Cl eq; non carcinogenics (CTU); Human toxicity (kg 1,4-Dbeq); Human toxicity (Kg C2H3Cl eq); Respiratory organics (ROg) kg C2H4 eq,; Respiratory inorganics (RIn) kg PM2.5 eq,; Respiratory organics; Respiratory inorganics; respiratory effects (kg PM2.5 equiv); Respiratory effects (kg PM10 eq),; ionizing radiation kBq U235 eq
Environmental TOXICITY	Freshwater aquatic ecotoxicity (kg 1,4-dichlorobenzene eq.); , Freshwater aquatic ecotoxicity potential (FAETP, Kg DCB-eq),; Aquatic ecotoxicity (AEco) kg TEG water; Marine aquatic ecotoxicity (kg 1,4-dichlorobenzene eq.); Marine aquatic ecotoxicuty (MAETP, Kg DCB eq),; Terrestrial ecotoxicity (kg 1,4-dichlorobenzene eq.); Terrestrial ecotoxicity (kg 1.4-DB eq); terrestrial ecotoxicity potential (TETP, Kg DCB eq),; Terrestrial ecotoxicity (TEco) kg TEG soil; ecotoxicity (CTU); Ecotoxicity kg 2,4-D-Eq;
HUMAN HEALTH	Human health
LAND	Agricultural land occupation (m2year); Land occupation (LOc) m2org.arabl,; Natural land transformation m2; land use (measured in m2year); Land-use-related impacts on biodiversity loss (LU); Land use (Kg C deficit); Land use; Urban land occupation m2year
ECOSYSTEM	Ecosystem quality; biodiversity damage, global species-lost-eq.·year (gSLeq.)]

Table A.4.: midpoint/endpoint related with relevant ecosystem services following the CICES classification

Macro-category	Relevant ecosystem service	CICES code (v.5)
CLIMATE CHANGE	Regulation of chemical composition of atmosphere and oceans; Dilution by atmosphere	2.2.6.1; 5.1.1.2
RADIATION	na	na
ENERGY	Cultivated plants (including fungi, algae) grown as a source of energy; Other mineral or non-mineral substances or ecosystem properties used for nutrition, materials or energy	1.1.1.3; 4.3.2.6
PARTICULATE MATTER	Regulation of chemical composition of atmosphere and oceans; Dilution by atmosphere	2.2.6.1; 5.1.1.2
ACIDIFICATION (aquatic, terrestrial, atmospheric)	Regulation of physical, chemical, biological conditions in the soil, water and atmosphere; Dilution and mediation of waste, toxics and other nuisances by non-living processes in the soil, water and atmosphere	2.2.4.1; 2.2.4.2; 2.2.5.1; 2.2.5.2; 2.2.6.1; 2.2.6.2; 5.1.1.1; 5.1.1.2; 5.1.1.3
EUTROPHICATION	Regulation of the chemical condition of fresh and salt waters by living processes; Dilution and mediation of waste, toxics and other nuisances by non-living processes in the water	2.2.5.1; 2.2.5.2; 5.1.1.1; 5.1.1.3
OZONE	na	na
SMOG	Regulation of chemical composition of atmosphere and oceans; Dilution by atmosphere	2.2.6.1; 5.1.1.2
MATERIAL and RESOURCES	Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing and as a source of energy; Surface and ground water used as a material (non-drinking purposes); Mineral substances used for material purposes; Other mineral or non-mineral substances or ecosystem properties used for nutrition, materials or energy	1.1.1.2; 1.1.1.3; 4.2.1.2; 4.2.2.2; 4.3.1.2; 4.3.2.6
WASTE	Mediation of wastes or toxic substances of anthropogenic origin by living and non-living processes	2.1.1.1; 2.1.1.2; 2.1.2.2; 2.1.2.3; 5.1.1.1; 5.1.1.2; 5.1.1.3;
TOXICITY and HUMAN HEALTH	Mediation of wastes or toxic substances of anthropogenic origin by living and non-living processes	2.1.1.1; 2.1.1.2; 2.1.2.2; 2.1.2.3; 5.1.1.1; 5.1.1.2; 5.1.1.3;
LAND	na	na
ECOSYSTEM	na	na