Deliverable report

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Introduction

The main objective of LignoCOST is to jointly establish a network in which relevant information packages are produced with a focus on sustainable lignin production and valorisation at industrial level (https://LignoCOST.eu/). The LignoCOST action has been structured in 5 working groups (WG) of which WG4 is dedicated to promising value chains. WG4 has been organized into 4 tasks, where Thermoplastics (Polyblends) is one.

Summary

WG4 is dedicated to the development of value chains for lignin and lignin-derived products. It will cover:

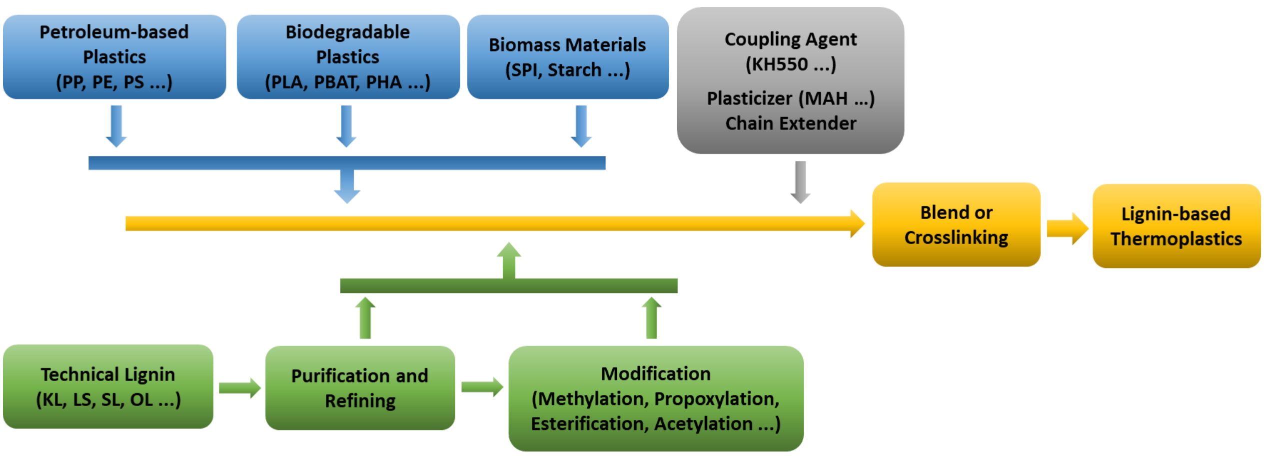
- Carbon materials
- Thermoplastics (polyblends)
- Phenol formaldehyde resin
- Bitumen for asphalt applications

In this task, with the aim of evaluating the commercialization potential of lignin-based thermoplastics, current state of the art from market and technical points of view and value chains with required processing steps and stakeholders were overviewed and summarized.

Current state of the art – market overview

Plastic is in practically every part of everyday life, simply because it is inexpensive, versatile in use, and light-weighted and resistant. It also has a critical role in the protection and preservation of goods and reducing transportation-related emissions. When being used in an automobile, electronics or packaging, plastic helps meet consumer's demands for convenience.

Lignin is naturally one of the most promising bio-based polymers and thus an excellent replacement for petroleum-based plastics. Lignin can be modified and pelletized, compounded and extruded using the same equipment and a similar process used for producing petroleum-based plastics. This makes it the ideal polymer to substitute for plastics in a broad range of existing consumer products.



R. A. Meyers (ed.), *Encyclopedia of Sustainability Science and Technology*, © Springer Science+Business Media, LLC, part of Springer Nature 2018, https://doi.org/10.1007/978-1-4939-2493-6_1015-1

The global plastic market size is huge. About 335 millions tons of plastics are produced annually (**Figure 1**). Currently, less than 1% is biobased. It was projected that its market volume would increase from 2.11 million tons in 2018 to 2.62 million tons by 2023.

It is found and also well understood that several driving forces are taking the green alternatives in general to the markets. For example,

- Very large market is existing and will keep growing
- Sustainable bio-based alternative to petroleum and fossil based resources will bring up
    - Reduced demand of fossil based polymers
    - Significantly reduced carbon footprint
- Legislation: there are bans on single-use plastic products, such as grocery bags, straws and water bottles etc.

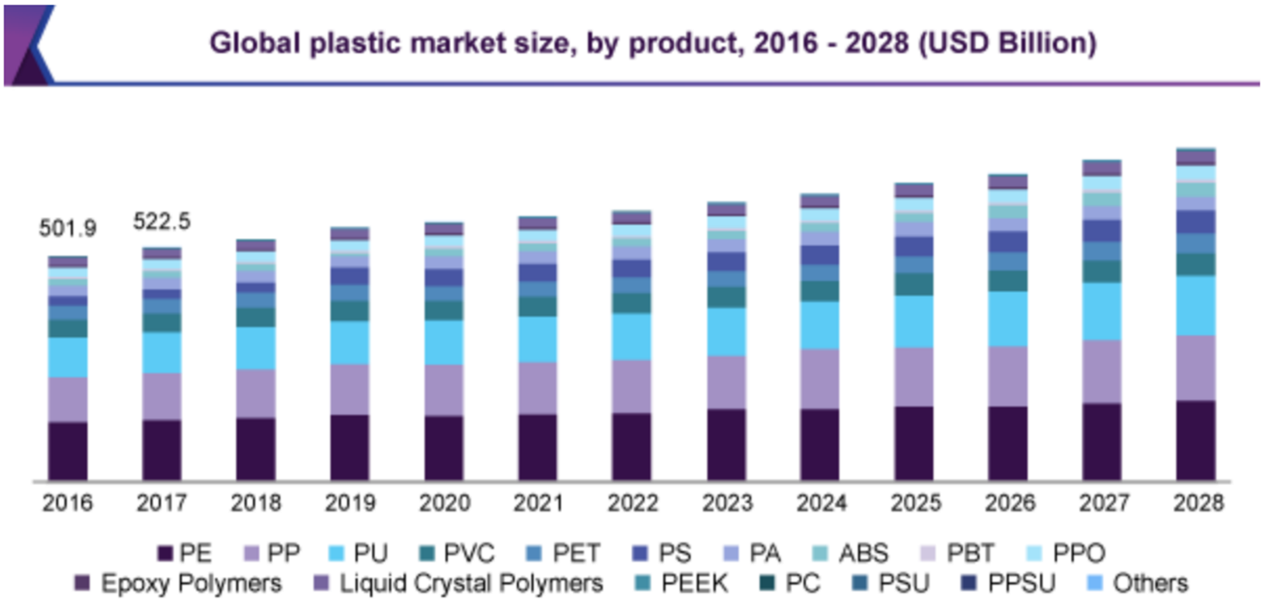


Figure 1. Global pastic market size, by product, 2016-2018. (Source: www.grandviewresearch.com)

Current state of the art – technical perspective

Thermoplastics can be classified in accordance with thermal and mechanical performances to:

- commodity plastics
- engineering plastics (EPs)
- super engineering plastics (SEPs)

In fact, lignin can fit in all the mentioned categories. Lignin-based thermoplastics is a new material and must be considered as such.

There are attempts to develop bioplastics. They are often divided into two groups:

- Degradable
    - Polylactic acid (PLA)
    - Polyhydroxyalkanoates (PHA)
    - Polybutylene adipate terephthalate (PBAT)
    - Starch
- Non-degradable
    - Polyethylene terephthalate (PET)
    - Polyamide (PA)
    - Polyethylene (PE)
    - Polypropylene (PP)
    - Acrylonitrile butadiene styrene (ABS)

The global production capabilities of bioplastics are illustrated in Figure 2.

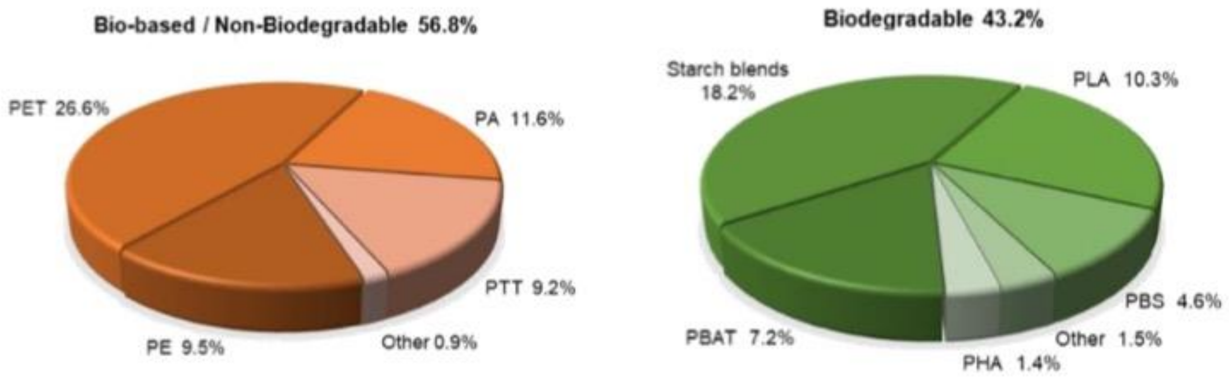


Figure 2. Global production capabilities of bioplastics. (Source: European Bioplastics 2019)

While there is a lot of information related to plastics, information about lignin-based plastics is scarce. The main bioplastics are cellulose-based, starch-based, glucose-based and synthetic and others.

With growing concern for carbon pollution and the inherently open-loop cycle of the petroleum industry, lignin and other sources of biomass have become prime candidate feedstocks for the production of low-carbon and carbon-neutral chemicals and material[1]. One key area of research has been the development of bio-based polymers and composite materials, and rigid bio-based plastics and composites have seen increased industry adoption in recent years due to growing demand for materials with a low carbon footprint. As a low-cost by-product with a strong aromatic component, lignin is a promising feedstock for bio-based polymers. To date, lignin has primarily been treated as a filler material in other polymers. In attempts to treat lignin as a discrete copolymer phase, recent research efforts have focused on chemical modification of lignin feedstocks prior to combining with other polymers, which require energy intensive chemical separations using solvent-based organic chemistries. Of all these efforts, few have made it to commercial scale. Development of a method for incorporating unmodified technical lignins in quantities above 30% would represent a significant advancement for this field and open new opportunities for the commercial potential of lignin-based thermoplastics and thermoplastic composite materials.

Aspects related to value chains

To evaluate the value-chain, evaluation criteria were for commercialization potential as follows:

- Market potential:
  - Drivers for lignin use
  - Current commercial production and actors
  - Market volumes & product segments
  - Estimated polymer & product/end use prices
- Technical requirements & potential challenges for commercialisation
  - Lignin requirements – Applicability of different lignin types
  - Technical product requirements / specifications
  - Technical challenges for commercialisation
  - Upgrading technologies to improve lignin quality for this specific application (TRL levels, production costs, actors)
- Barriers for commercialisation
- Value chains: processing steps, key actors & potential gaps
- Final conclusions: SWOT for commercialisation potential

Driving forces for green alternatives in general

The identified driving forces for green alternatives in general are listed as below:

- Sustainable bio-based alternative to petroleum and fossil-based resources:
  - Cost competiveness
  - Reduced demand of fossil-based polymers
  - Significantly reduced carbon footprint
  - Very large market and growing
- Enhanced profitability of forest industry
  - Higher value than current use (combustion)
- Legislation
  - Bans on single-use plastic products, such as grocery bags, straws and water bottles etc.

Driving forces for specifically use lignin

The identified driving forces for specially used are listed as below:

- Renewable material that can be obtained in large amounts
- Lignin is a renewable feedstock composed of aromatic units and is scalable
- Lignin structural composition: phenolic-OH, aliphatic-OH
- Lignin properties as UV resistance, anti-microbial, and fire retardant

Market status

Current actors with commercial production of lignin-based thermoplastics are Tecnaro, RenFuel, BASF, Covestro, and lignin Industries.

The plastics packaging materials and unlaminated film and sheet manufacturing industry are reported to have market volumes of $257 billion. The European market is $7.3 billion in 2019.

Table 1. The market volume and product segments of thermoplastic resins and plastics materials, polyesters. (Source: 2019 Global Manufacturing & Markets by C. Barnes & Co.)

INDUSTRY TITLE	2019 Sales ($000)	2018-2019 % Charge
Food and beverage manufacturing	6,120,403,923	7%
Chemical manufacturing	4,519,140,853	5%
Fabricated metal product manufacturing	1,508,970,710	2%
Machinery manufacturing	2,199,031,195	2%
Computer and electronic product manufacturing	1,877,962,082	4%
Electrical equip., appliance manufacturing	803,497,523	6%
Transportation equipment manufacturing	6,463,263,704	5%
Miscellaneous manufacturing	1,010,621,289	6%

There are many initiatives for technical lignin production. It is summarized and listed in Table 2.

Table 2. Selections of the global production of technical lignins.

Lignin	Recovery technology	Main producer	Production capacity (Kt/year)
Kraft (Indulin)		Ingevity[a]	65
SW Kraft	LignoBoost	RISE/Bäckhammar, Sweden	6-10
SW* Kraft	LignoBoost	Domtar, Plymouth, NC	25-27
SW Kraft	LignoBoost	Stora Enso, Sunila, Finland	50

SW/HW* Kraft	LignoBoost	Klabin, Brazil	1?
SW Kraft	LignoBoost	Mercer, Germany	1?
SW kraft	LignoForce	West Fraser, Canada	10
HW kraft	Suzano own method	Suzano	20
HW (Protobind 1000)	Soda	GreenValue, Granit, Switzerland	5-10**
CIMV	Organosolv[b]	CIMV, DECHEMA/Fraunhofer, Dedini	3
Lignosulfonates	Sulfite	Borregaard	1,000
Lignosulfonates	Sulfonated HW	Rayonier, USA, France, Canada	150
Lignosulfonates	Sulfonated HW/SW	Domsjo Fabriker, Sweden	120
	Sulfonated HW/SW	Saica, Spain	~100
	Sulfonated SW	Cartier Burgo, Italy	38
	Sulfonted HW/SW	Nippon Paper, Japan	100

[a] Formerly part of WestRock, (Mead)Westvaco [b] Acetic acid: formic acid: water (50:30:20)

*SW=Softwood & HW=Hardwood

**Not clear if they still produce at this site in India

Lignin requirements - Applicability of different lignin types

Lignin is a complicated polymer due to several factors, including, sources (softwood, hardwood, and annual plants) and processes (kraft, soda, organosolv, lignosulfphonate). Several structural features are critical and they need to meet the requirements. Such technical product requirements and specifications include but are not limited to:

- molar mass (Mw),
- glass transition temperature (Tg), lignin has a relatively high Tg compared to synthetic thermoplastic polymers.
- melting temperature (Tm),
- purity,
- thermal degradation,
- reactivity (hydroxyl content),

- condensation degree, At high temperature lignin undergoes radical –induced self condensation which limits its thermal processability.
- solvent-specific solubility, and
- smell.

A thermoplastic containing lignin is expected to benefit from the relatively superior thermal properties of lignin.

However, several technical challenges have limited the use of lignin such as:

- Odour
- Volatiles
- Colour in certain application
- Condensation or low reactivity depending on the process
- Compatibility with other components
- Lignin is not thermoplastics, its thermoplasticity needs to be increased
- Chemical stability, storage over time
- Quality control (reproducibility) of produce lignin
- Lignin-based materials (higher lignin content than 40% in the materials) are usually brittle and exhibit poor mechanical properties.

Different upgrading technologies are developed to improve lignin quality. Figure 3 shows one example.

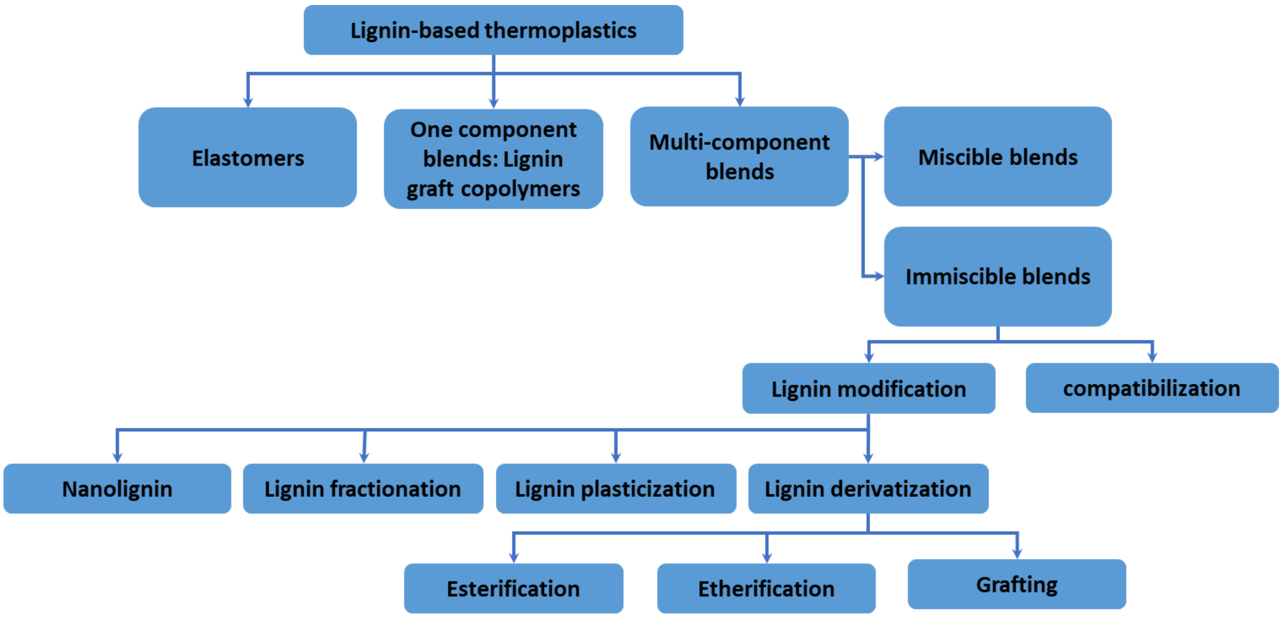


Figure 3. Technical routes for upgrading lignin.

Environmental impacts

Lignin-based thermoplastics offer various benefits such as biodegradability, cost-effectiveness, and sustainability, which will drive product demand.

Barriers for commercialization

Barriers for commercialization could be:

- Challenges associated with lignin are relatively lower molecular weight, higher polydispersity, uncertain reactivity, degree of cross-linking, the amount of residual carbohydrates, etc.
- Poor dispersion in the polymer matrix – lignin self-interactions give rise to a brittle material.
- Heterogeneous lignin structure:
  - Lignin structure and properties are dependent on species, the process to produce lignin and the isolation process.

Lignin producers

Identified producers for lignins are listed in Figure 4.

Figure 4. Lignin producers for different type of lignins.

Conclusions and perspectives

This task has overviewed current status of market related to thermoplastics and lignin-based thermoplastics. Challenges and impacts of those lignin-based thermoplastics are also discussed.

References

[1] Saito, T.; Brown, R. H.; Hunt, M. A.; Pickel, D. L.; Pickel, J. M.; Messman, J. M.; Baker, F. S.; Keller, M.; Naskar, A. K., Turning renewable resources into value-added polymer: development of lignin-based thermoplastic. Green Chemistry 2012, 14 (12), 3295-3303.