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Regulatory review: Upcoming regulation affecting biocomposite use and recycling in Finland

Ella Kärkkäinen[1], Anna Zaikova[2], Anu Kurvinen[3], Alexander Matrosov[3], Kirsi Immonen[1]

[1]VTT Technical Research Centre of Finland, [2]LUT Lappeenranta-Lahti University of Technology, [3]LAB University of Applied Sciences

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The big picture

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Regulatory framework

- The European Green Deal is the guiding European strategy, aiming to reach climate neutrality by 2050 [1]
- The Circular Economy Action (CEAP) plan makes sustainable products as the norm
- EU regulation highlights circularity and resource efficiency, non-toxicity and reduction of waste [1,2]

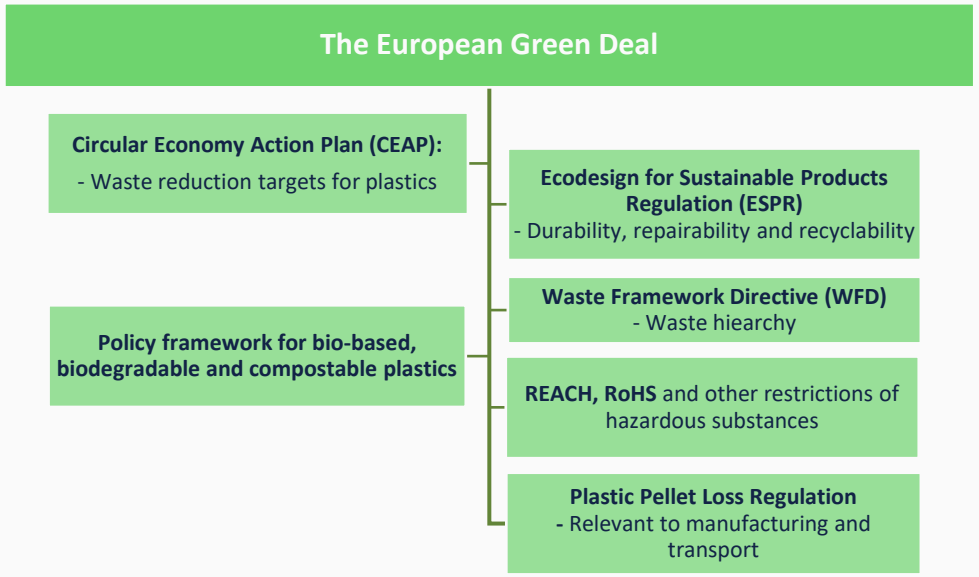

Figure 1: Examples of legislation and policies under the European Green Deal, relevant to biocomposites

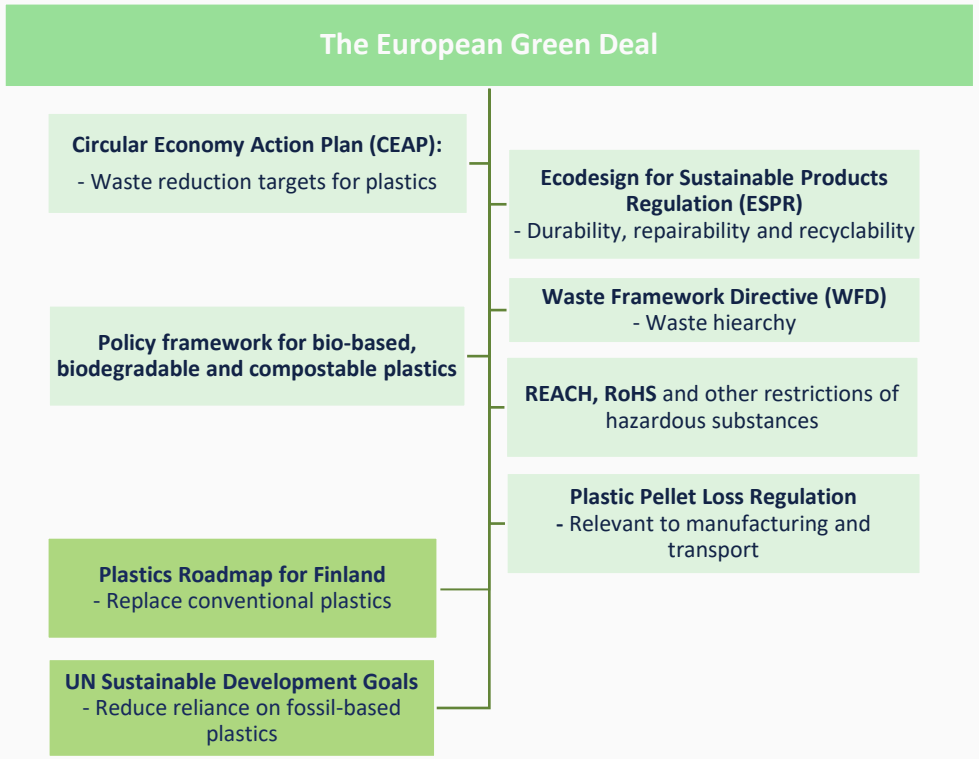

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Figure 2: Examples of other incentives closely related to the goals of the European Green Deal and biocomposites.

Regulatory framework

- In Finland, the Plastics Roadmap highlights bio-based plastics as a replacement for fossil-based plastics [3]
- Bio-based materials are mentioned potential especially in long lifecycle products and if recycling solutions are available
- Biocomposites reduce reliance on fossil-based plastics and can offer material innovation and industrial transformation

Figure 3: Examples of the UN Sustainable Development Goals that biocomposites can contribute to. [4]

The EU climate law

- Net-zero Europe by 2050 [2,5]
- Greenhouse gas emissions down by at least 55% by 2030 compared to 1990 levels
- Net-zero emissions are achieved through greenhouse gas removals (GGRs) → GGR-centred industry is required
- Carbon removals are allowed as part of achieving climate neutrality [5]
- Proposed amendment to the Climate Law [6] introduced international carbon credits to cover up 3% of the net emissions reduction [6,7,8]
- International carbon credits increase the need for domestic decarbonization between 2040-2050 but there are uncertainties regarding the availability and the cost of these credits [8]

EU Bioeconomy

2018
- The EU Bioeconomy provides a holistic approach to sustainability, focusing on 5 key objectives: ensure food security, manage natural resources, reduce dependence on non-renewable resources, mitigate climate change, strengthen European competitiveness. [9]

2020
- **European Green Deal** adopted as a comprehensive policy framework for the European climate actions. [1]

2022
- Bioeconomy Progress aligned with the European Green Deal targets, such as climate goals, biodiversity and zero pollution. [10]
- Up-scaling of sustainable bioeconomy more important in view of the food and energy prices.

2025
- Updated Bioeconomy strategy replaces the 2018 strategy with 4 key objectives: scale up innovation and investments, build lead markets for bio-based materials and technologies, ensure sustainable biomass supply for the value chains, harness global opportunities. [11]

Figure 4: The timeline of the EU Bioeconomy strategy.

- First bioeconomy strategy was published in 2012, updates in 2018 and 2025
- The recent update to Bioeconomy strategy allows for speeding up the permit processing for bio-based innovations [12]

EU Plastics Strategy

2018

- **Circular Economy Action Plan** sets a product-lifecycle approach for key value chains, including plastics. [13]
- It signals mandatory requirements for recycled content and waste reduction and calls for a policy framework on bio-based, biodegradable and compostable plastics.

2020

- Plastic and Packaging Waste Directive (PPWD) moves from a directive to **Packaging and Packaging Waste Regulation (PPWR) proposal**. [14]
- Bioplastics Policy Framework sets conditions for when biobased, biodegradable or compostable plastics provide environmental benefits. [15]

2025

- New **PPWR** was adopted, it sets recycled content targets for plastics in packaging and requires all packaging to be designed-for recycling by 2030. It will start applying in August of 2026. [16]
- Phasing in of restrictions of intentionally added microplastics started. [17]
- EU Plastic Pellet Loss Prevention Regulation focuses on preventing microplastics unintentionally released during production. [18]

Figure 5: The timeline of the EU Plastics strategy.

- Packaging makes up the greatest share of total plastic production [12,19]
  - PPWR [16] sets recycled content and recycling for all plastic packaging, including
    - All packaging must be recyclable by 2030
    - Plastic recycled content 10-35% depending on application by 2030
    - Plastic recycled content 25-65% depending on application by 2040
- The Microplastics regulation and the Plastic Pellet Loss Prevention Regulation regulate how plastic pellets should be manufactured, handled and documented.

→ Regulation has entered into force late 2025: a 2-year period before it is mandatory

Plastics production and segments

- Total, global plastics production is estimated at 430.9 Mt/year (2024) [20]
  - Fossil-based plastics 89.8%
  - Mechanically recycled (post-consumer) plastics 9.5%
  - Bio-based plastics 0.6%
  - Chemically recycled plastics 0.1%
  - Carbon-captured plastics <0.1%
- Global production of biobased plastics 1.673 Mt (2025) with market pull for packaging [21]
  - Total global plastics production is on steady increase, while European plastics production is steadily declining
- Production capacity of biobased packaging solutions is expected to expand.

Global production capacities of biobased plastics 2025 and forecast for 2030 (% of total) [20].

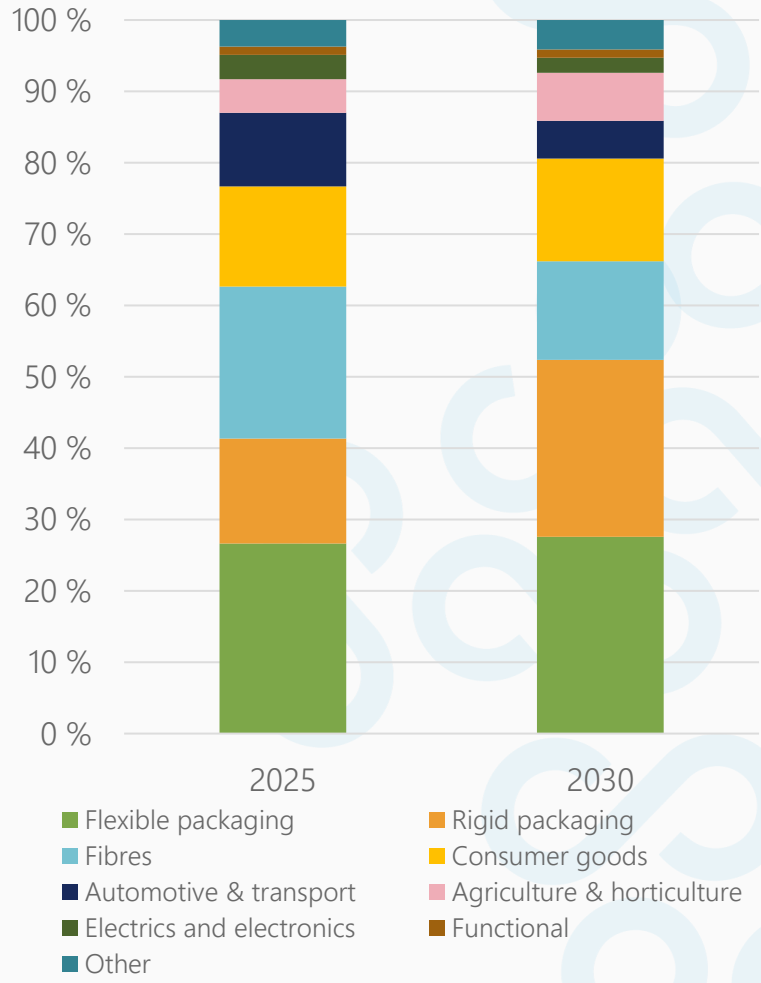

Figure 6: Global production capacities of biobased plastics 2025 and forecast for 2030.

Realised and forecasted bio-based plastic production volumes

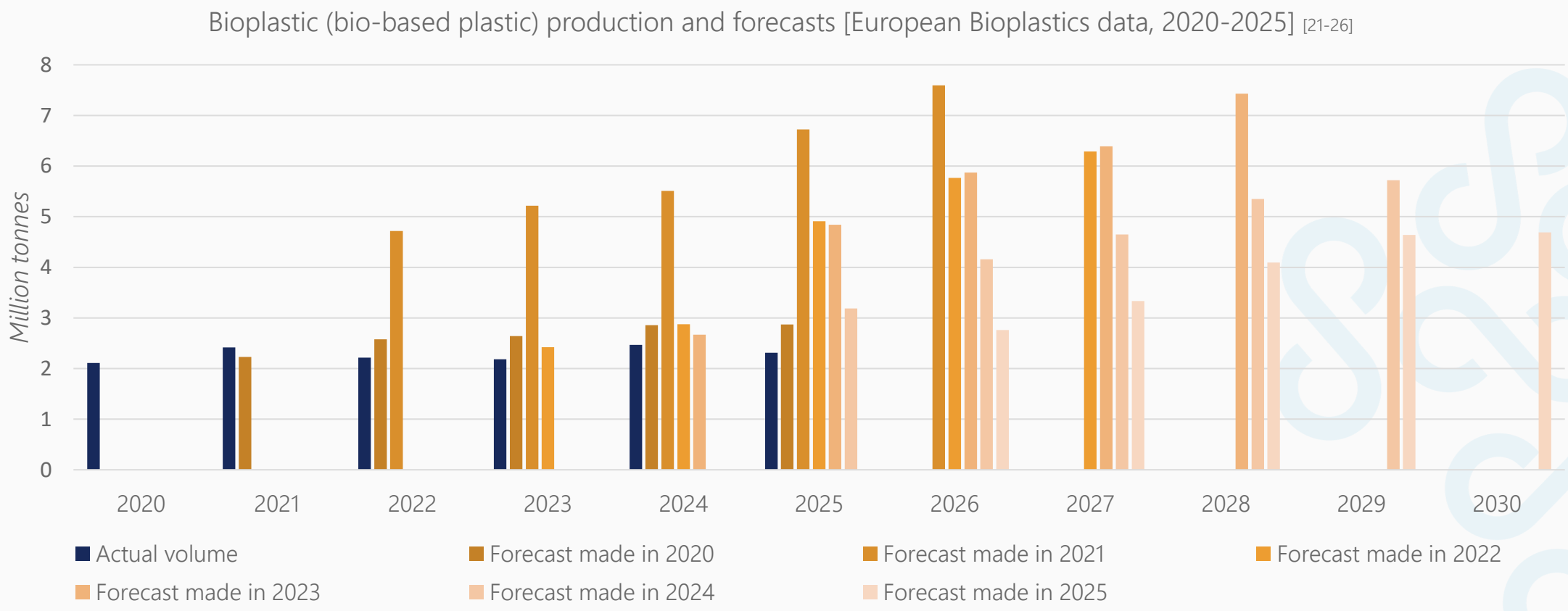

Figure 7: Bioplastic (bio-based plastic) production and forecasts.

Understanding composite products

- Composites are often used in construction industry, automotive industry, biomedical field, aerospace industry, marine industry, sports equipment, packaging and furniture [27,28]
- Material choices are driven by the product requirements, e.g. their lightweight, durability, sustainability and aesthetics, but also business drivers such as cost reduction and external factors, e.g. CO_2 regulations and other regulatory drivers
- Biocomposites largest market segments include the automotive sector, construction, consumer goods, packaging and biomedical applications [27,29]
- Biocomposites are often described weaker in long-durability than conventional composites, but their performance can be enhanced with use of fillers and other modification [30]

The legislation on automotive, construction and electronics sectors

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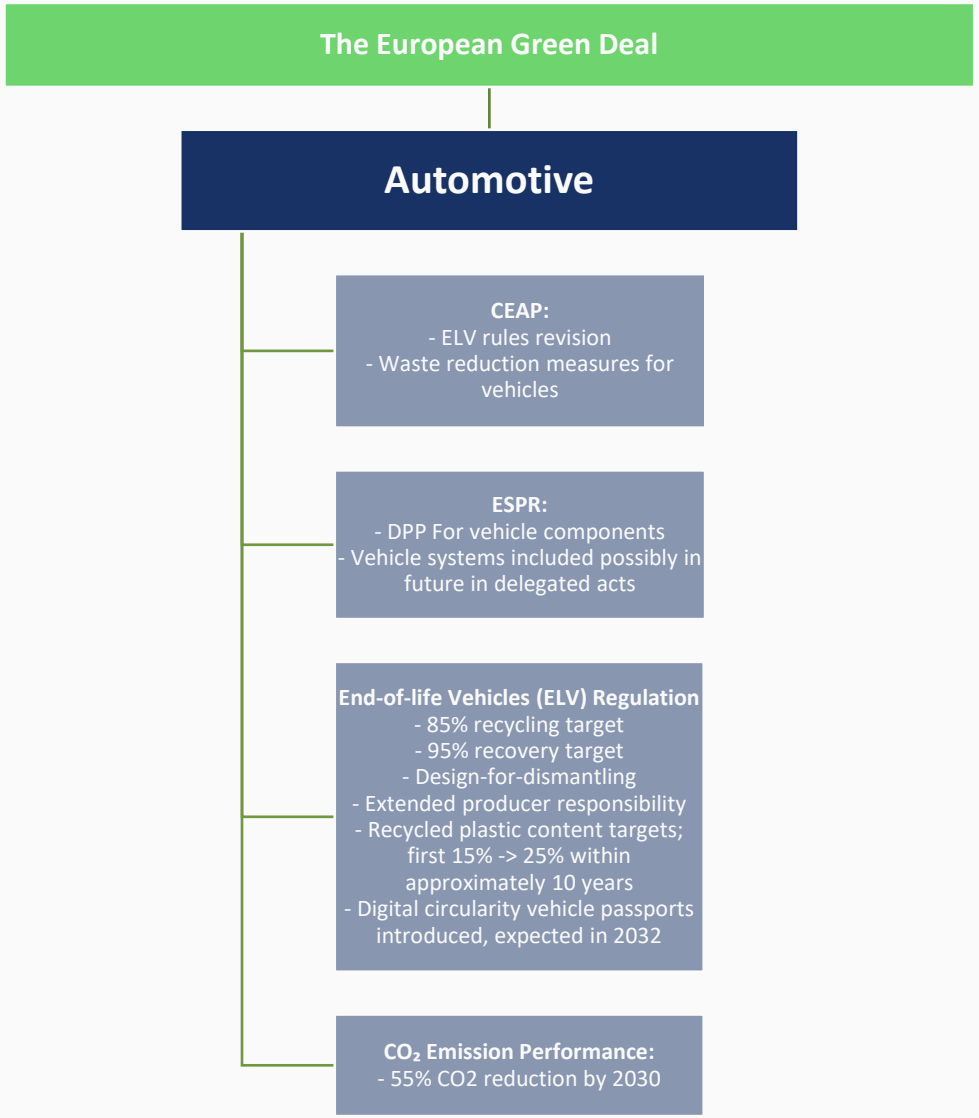

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Figure 8: The Automotive legislation that was considered in ABiCo.

- The size of the ELV sector is not clear, but on average 4-6 million ELVs are reported in the EU yearly
  - In 2023, it was estimated this generated **5.0 million tonnes of waste** [31]
  - In 2023, 88.3% of generated ELV waste was reused or recycled and 93.7% was recovered
- The main circular regulation for the automotive sector is the End-of-life Vehicles (ELV) Regulation [32]
  - The Regulation was adopted in 2026, replacing the previous ELV Directive framework
  - Since 2015, the ELV Directive has set an 85% recycling target and 95% recovery target with design-for-dismantling incentive
  - The regulation sets mandatory post-consumer recycled plastic targets, 15% for 2032 and 25% for 2036
    - **As of now, bio-based plastics do not qualify toward fulfilling these thresholds**
- The lifecycle of the product is becoming increasingly relevant with the current EU trends in waste reduction measures and design for circularity [33,34]
  - **It is not enough for plastics to be bio-based**
- Vehicle-level DPPs will likely be introduced under the ESPR in delegated acts
- For vehicles, European Green Deal sets mandates for emission decrease
  - **The lightweight biocomposite components have the potential to reduce emissions through weight reduction**

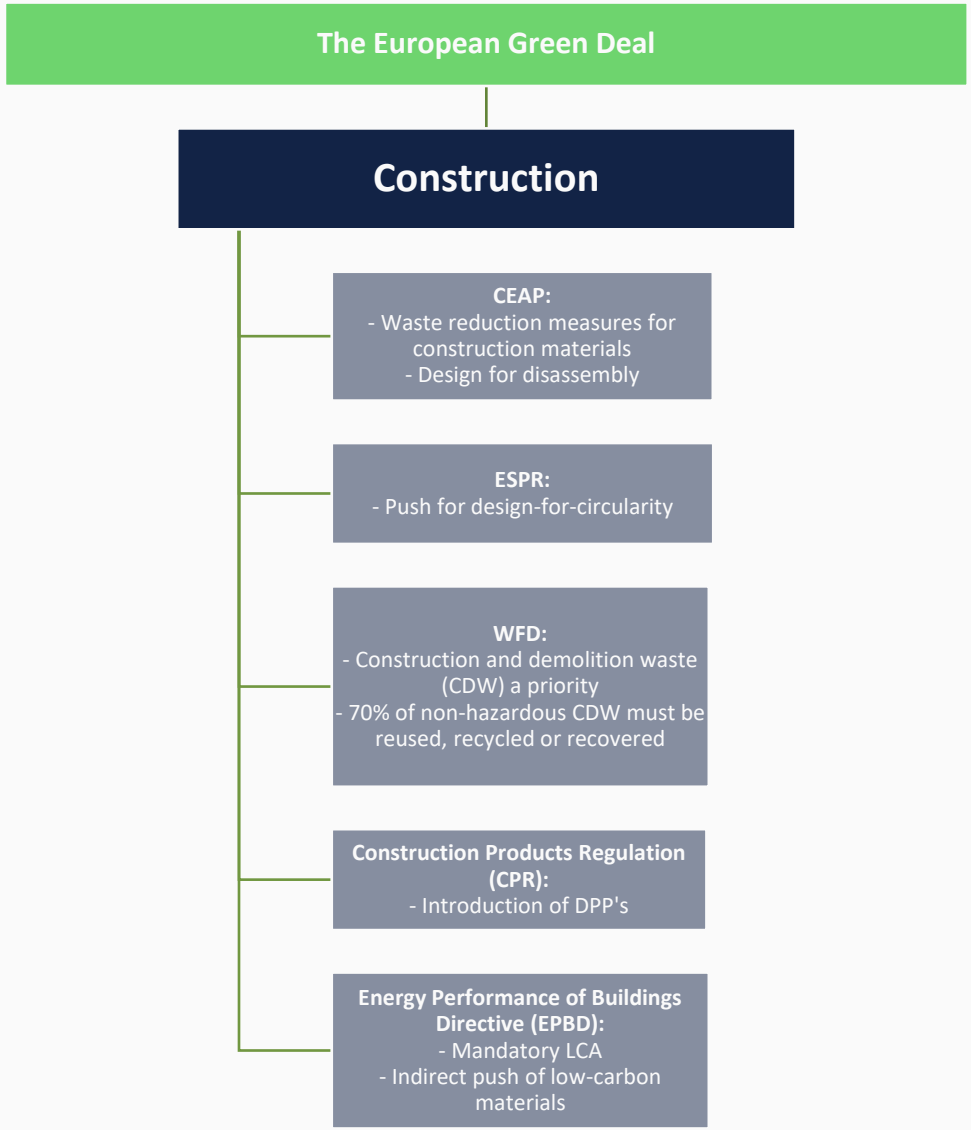

Figure 9: The Construction legislation that was considered in ABiCo.

- Construction sector is the most waste-intensive sector in EU: **0.84 billion tonnes of the total 2.2 billion tonnes waste generated**. [35] At the same time, the products must fill strict quality, safety and environmental requirements.
- There's a strong push for design-for-disassembly and design-for-circularity
- WFD revision in 2008 set a 70% target for preparing for re-use, recycling and other material recovery of non-hazardous construction and demolition waste
  - National total target, by mass
  - The end-of-waste criteria might imply that products retained at construction site do not qualify as waste (does not need to be recorded according to WFD)
- EU has well established CDW management systems and the 70% target has been met almost everywhere
- The revised CPR introduces DPPs for construction products [36]
  - Usually DPPs are under the ESPR framework
  - EU DPP Registry opens in July 2026, January 2028 is the target date for full mandatory compliance
  - The scope covers any construction product "placed on the market for incorporation in a permanent manner in construction works"
  - A planned harmonization for release of VOCs from construction products has been planned, some countries have set their own limits [37]
- Energy performance of buildings makes LCA mandatory
  - **While low-carbon materials are indirectly pushed forward, the biocomposite long-term durability and regulatory acceptance in for example fire safety are still uncertain**

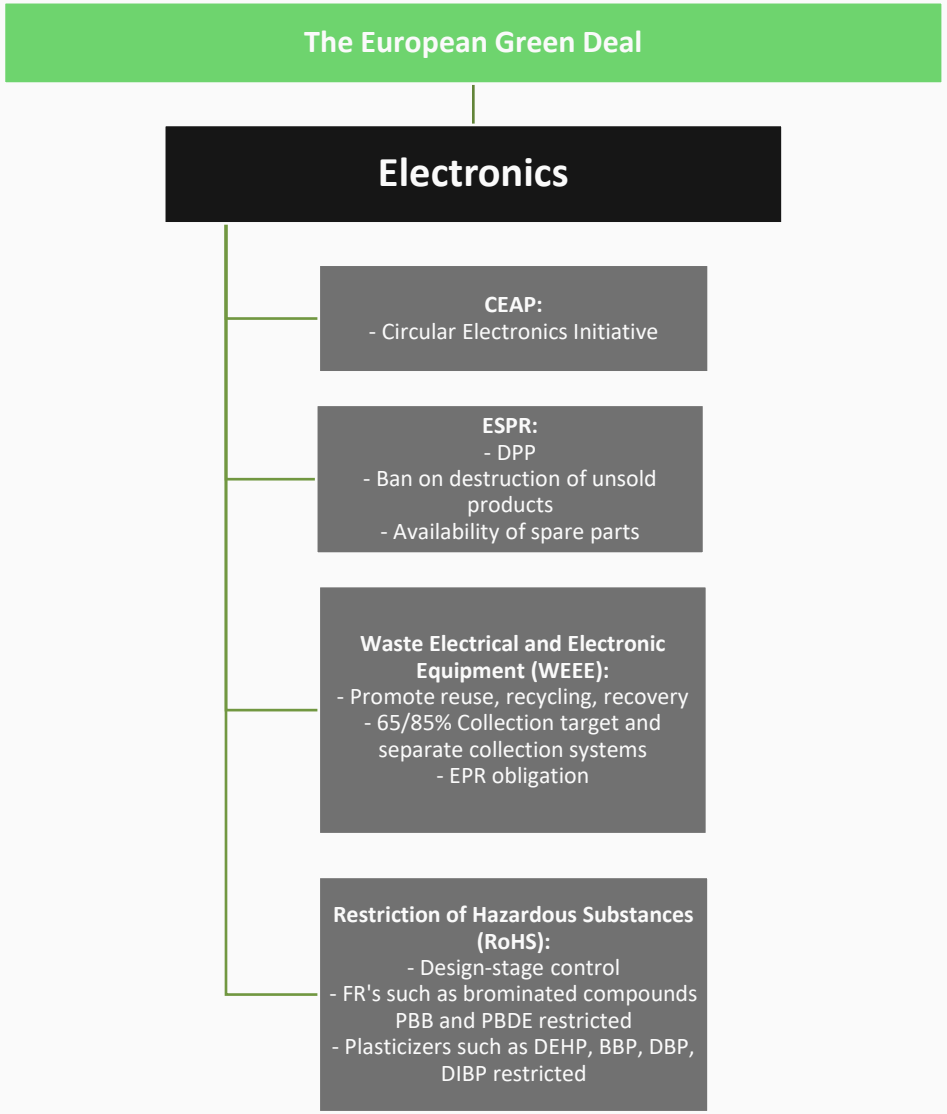

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Figure 10: The Electronics legislation that was considered in ABiCo.

- 5.2 million tonnes of WEEE were separately collected in 2023 in the EU, approximately 11.6 kg per inhabitant [38]
- Circular Electronics Initative introduced durability requirements, right to repair and improved collection, reuse and recycling systems
- The main circular regulation for the electronics sector is the WEEE Directive, complemented by RoHS
  - WEEE sets collection, recycling and recovery obligations [39]
    - 65% of the average weight of EEE placed on the market during the preceding three years OR 85% of WEEE generated
  - RoHS restricts hazardous substances [40]
- Strong focus on end-of-life management and extended producer responsibility (EPR)
  - Producers are responsible for collection and treatment of e-waste
  - The target of 65% collection rate is currently not achieved, and in 2022 the rate was 40.6%
- Increasing push for design-for-circularity
  - Design for dismantling, reuse and recyclability is becoming more important
- The ESPR introduces broader lifecycle requirements
  - Covers durability, repairability, recyclability and material efficiency
  - Electronics are a priority product group
- ESPR will introduce DPPs for electronics

Recycling of biocomposites

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Future paths

- Enabling sustainable and circular ecosystems requires
  - Solving systemic challenges
  - Focusing on resource efficiency
  - Supporting economic growth
  - Advancing climate-neutral and climate-positive solutions
  - Strengthening knowledge and innovation
  - Creating societal impact
  - Improving integration and scalability [41]

What should be clarified to enable bioplastics & biocomposites recycling?

***Figure 11**: The main actions and activities needed to happen to make biocomposites and bioplastics recyclable.*

EU Waste Framework Directive (WFD)

- The EU WFD (2008/98/EC) defines the legal framework for management of waste [42,43]
- End-of-waste criteria (Article 6) defines which waste ceases to be waste after recovery or recycling, but the assessment is done on a case-by-case basis according to specific criteria [42, 44]
- Article 6(5) introduced in 2018 requires natural or legal persons placing materials that have ceased to be waste on the market for the first time to ensure the material complies with relevant chemical and product regulation [43]
    - REACH exludes waste (Article 2(2)) [45] but if a material ceases to be waste, it is affected by REACH
- Article 8 of WFD establishes the foundation for Extended Producer responsibility (EPR), meaning the producers must cover the cost and/or operations of waste management. This is usually done through PROs [46]

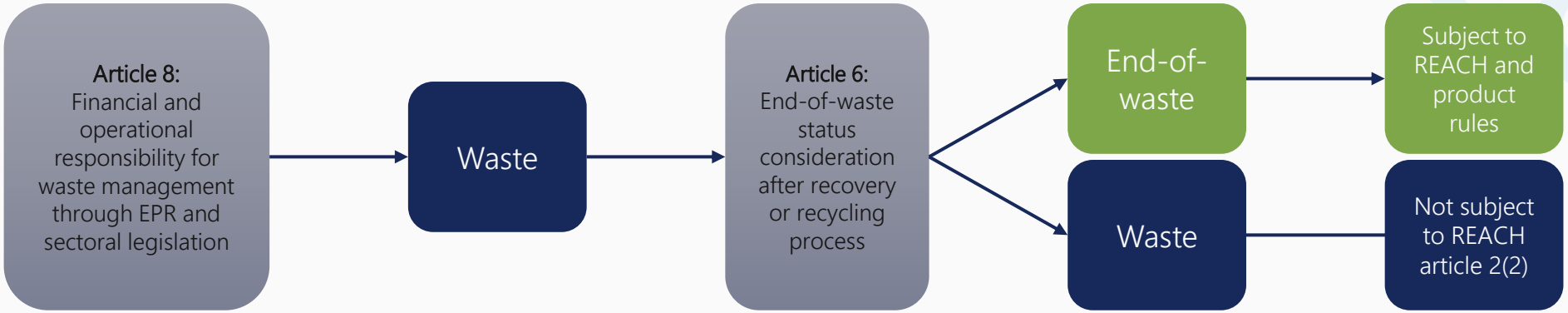

Figure 12: A schematic illustration of WFD and its main impact on waste.

Plastics recycling and EPR

- Plastics recycling is heavily focused on packaging due to established **Extended Producer Responsibility (EPR) rules for packaging manufacturers** and the wide use of plastics in packaging
- There are currently EPRs for packaging, electronics, batteries, end-of-life vehicles and used oils [47]
    - Textiles, tyres, furniture, waste oils and construction products are expected to be included in the legislation in the future
- Companies may organise take-backs and reuse and recycling opportunities for any products they wish without EPR mandates

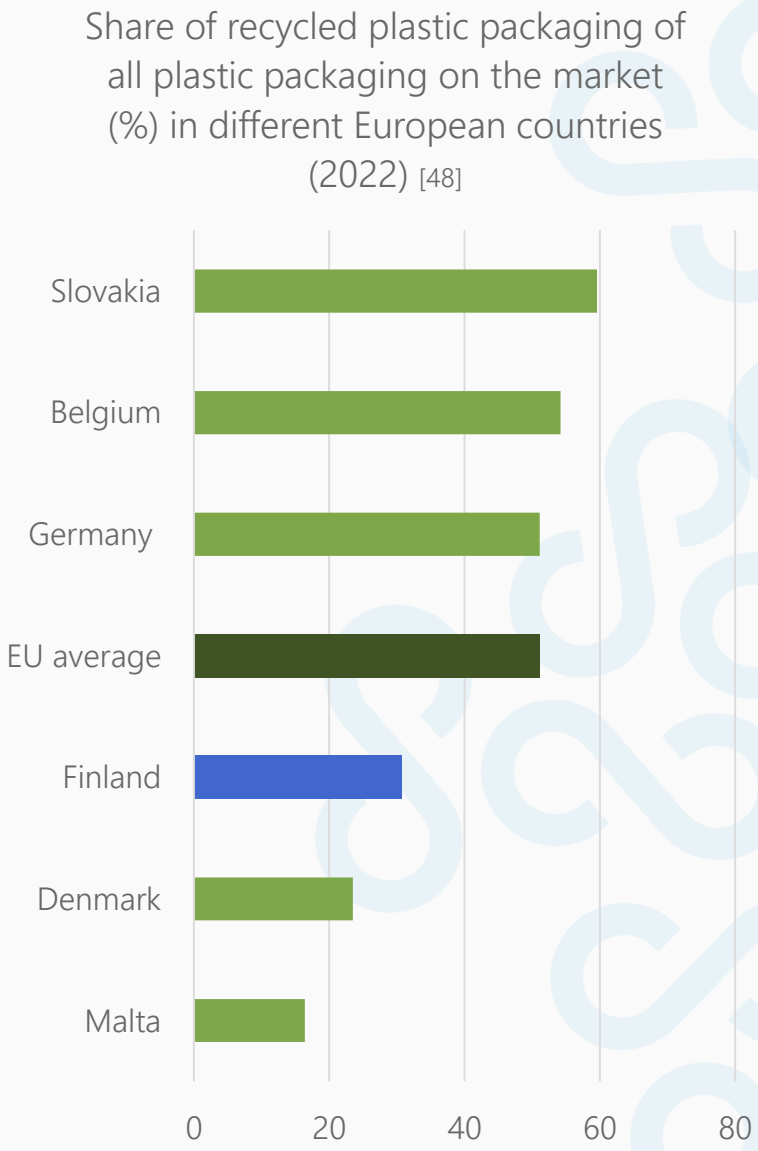

Figure 13: Share of recycled plastic packaging of all plastic packaging on the market in different European countries in 2022.

Plastic and biocomposite recycling barriers

Different plastics require different recycling methods. Biocomposites often contain plastics in the matrix, but the bio-ingredient often requires another method.
Plastic products are complex and include multi-materials, additives, inks, etc. Biocomposites bring more complexity to the mix. Identification of materials is needed, but it is difficult to separate the different parts of the products.
Additives and degradation products can accumulate weakening the output or the process efficiency. The chemical heterogeneity complicates recycling in general.
Differences in contents and impurities in collected streams (e.g. food residue in plastic packaging) can decrease the quality of recyclates. Polymer properties often degrade in recycling processes.
Apart from plastic packaging and other plastics that are under the EPR or sector specific mandates and recycling targets, there is not a regulatory or economic push to develop suitable recycling methods or to collect and sort plastics.
The chemical composition defines partly if the substance is under product/material or waste regulations.
The TRLs for composite products are in general higher than for biocomposites, for example, the mechanical recycling of composites is at TRL 8, and the mechanical recycling of biosomposites is at TRL 4. There is currently no better options for biocomposites.
Recycling costs, and especially inefficient recycling or lack of markets for recyclates make the cost unattractive.
If there is no suitable or accessible recycling method, incineration is often chosen.

Compiled from [49,50,51,52]

Content certifications

- The material of packaging has an identification system derived from the PPWD mandate and was established already in 1997 [53,54]
- There are many voluntary content certifications available, e.g. for bio-based content or other product declarations
- The aim of these labels is to identify material and/or communicate about the product
    - Plastic identifiers, the Resin Identification Codes (RIC) are not a guarantee of recyclability

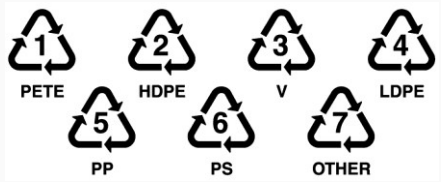

Figure 14: The plastic material identifiers, or Resin Identification Codes (RIC) used in Europe.

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Environmental labelling
ISO 14024:2018 *Environmental labels and declarations — Type I environmental labelling — Principles and procedures*

Bio-based content
EN 16785-1:2015 *Bio-based products. Bio-based content. Part 1: Determination of the bio-based content using the radiocarbon analysis and elemental analysis*

Biodegradable packaging
EN 13432:2001 *Packaging. Requirements for packaging recoverable through composting and biodegradation. Test scheme and evaluation criteria for the final acceptance of packaging*

Self-Declared Environmental Claims
ISO 14021:2016 *Environmental labels and declarations — Self-declared environmental claims (Type II environmental labelling)*

Environmental Product Declarations
ISO 14025:2006 *Environmental labels and declarations — Type III environmental declarations — Principles and procedures*

Figure 15: The environmental labels, including examples of content and product claims.

Future opportunities for biocomposites

CSR (European business network for Corporate Sustainability and Responsibility) reports [55] the circular opportunities for composites according to their impact and complexity:

- Recyclable materials and closed systems for recycling; design-for circularity, material passports, recycled class labelling, secondary marketplaces, new markets; carbon tax, standardisation and harmonization of policies for efficient reverse logistics are of the higher priority when enabling circular opportunities
- Particularly **design-for-circularity, material passports and material recyclability** (i.e. design-for-recycling) would have a high impact for the circular future
- Creating secondary marketplaces is not considered too complex, but would help create demand for recyclable materials, and to increase other activities
- Bio-based materials are secondary in priority, and their implementation is rather complex
- Material passports, classifications and harmonization of different systems would create the necessary field for efficient recycling operations

Figure 13:

Prioritisation of opportunities according to impact and complexity.

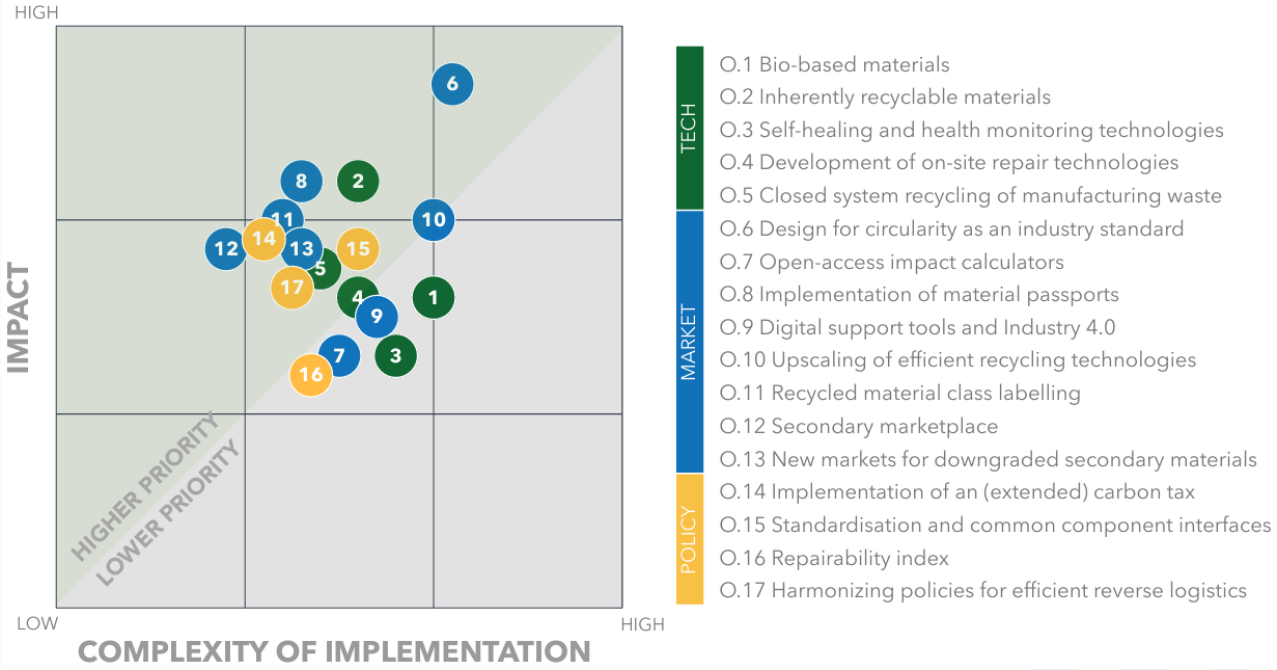

Figure 16: The priorisation of opportunities for composite materials. Source: CSR Europe (2022), Composite Materials: A Hidden Opportunity for the Circular Economy, Figure 13. Reproduced under CC BY-NC-ND 4.0. No modifications made. [55]

Bioeconomy business support

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Bioplastic and biocomposite markets

Examples of policies and regulatory frameworks supporting the bioeconomy include:

- The sector specific recycling targets, such as ELV directive, WEEE Directive, PPWR [56]
- Product content certificates, product declarations and LCAs that show the product compliance and true sustainability or the environmental benefit
- The Ecodesign for Sustainable Products Regulation (ESPR) [57,58]
    - Furniture (a possible application area for biocomposites), is expected to be covered by a delegated act ~2027–2028, making a Digital Product Passport (DPP) for furniture mandatory on the EU market
    - The DPP shall include at minimum "*information relevant for disassembly, preparation for reuse, reuse, recycling and the environmentally sound management of the product at end-of-life*" (article 7) and may be required to specify recycled content.
- Green Public Procurement (GPP) [59,60]
    - Public authorities shall source goods and services that have lower environmental impact thus dricing markets towards sustainable consumption
    - With LCA or other scientific-backed methods of proving environmental benefit, the
    - EU Ecolabel is one of the primary tools for executing GPP owing to its inclusion of specifications, verifiability and linkage to legal framework (ISO 14024)

***Figure 17**: Enablers of the bioplastic and biocomposite markets.*

Boundary conditions shaping the future of businesses of advanced biocomposites (PESTE analysis)

P

”The Commission will work to create a coherent and simplified regulatory framework that rewards circular and sustainable business models, while safeguarding EU safety standards.“*

“The Commission will boost demand for bio-based content in products, for example by setting targets in relevant legislation.”*

E

“The EU Bioeconomy Strategy aims to unlock the potential by scaling up innovation and investments, developing lead markets for bio-based materials and technologies, ensuring a sustainable supply of biomass, and harnessing global opportunities.”*

S

Eco-friendly products enjoy positive interest by the markets. EU Commission identified innovative markets for bio-based materials and technologies. These include e.g. bio-based plastics, and fibres, construction materials, and permanent storage of biogenic carbon.

T

Technological advancements enhance the performance and applications of biocomposites in different sectors.

Regulatory operation environment is a driver of technological development.

E

Regulatory operation environment is a driver of sustainability actions.

Use of resources can be enhanced by use of biocomposites.

Raw materials from industrial side streams, recycled raw materials.

*The direct quotes are from European Comission’s new Bioeconomy Strategy 11/2025 [11]

TEA from regulatory perspective

The interviews* with industrial stakeholders suggest that regulation is not yet a uniformly strong direct adoption driver, but it is an important background condition shaping market readiness. The clearest regulatory concerns are around recyclability, circularity, end-of-life handling, closed-loop models, additive compliance such as REACH, fire/safety requirements, traceability, and documentation of raw materials.

Companies expect clearer guidance on how biocomposites fit future regulatory and recycling requirements, especially where customers ask how the material can be collected, reused, certified, or justified against existing materials.

Overall, regulation should be treated as an enabling and risk-reducing factor rather than the main commercial argument: the project should monitor regulatory changes, include CO_2/recyclability evidence, and prepare scenario models for possible regulation-driven demand shifts.

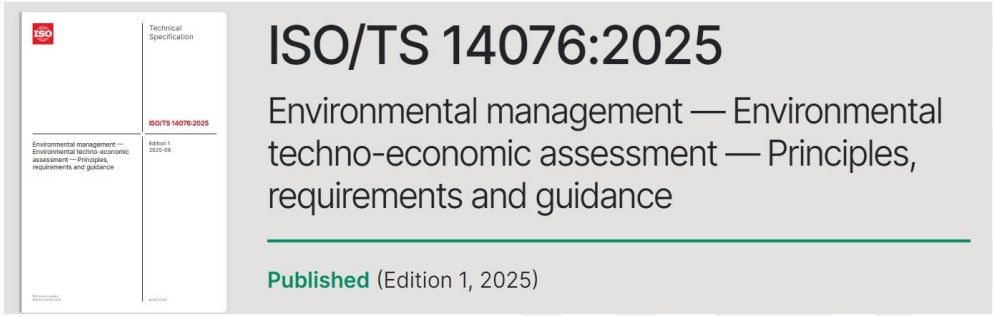

Figure 18: *The Environmental Techno-Economic Assessment standard practice, published in 2025.*

Companies could use an eTEA-based framework to compare biocomposites against existing materials through technical, economic and environmental indicators. This would help structure decisions around performance, cost, process changes, CO_2 impact, recyclability, regulation and assumptions behind future business cases.

*As a part of ABiCo, techno-economic assessment consisting of literature review, laboratory material development, market benchmarking, and semi-structured interviews with industrial stakeholders representing different stages of the biocomposite value chain were synthesised into a conference paper. [61]

Regulation concerning the additives in ABiCo

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Regulatory compliance

- Novel components in biocomposites have carbon-negative material potential
- The compliance of chemical components should be checked in for example **VOC limits, PAH limits and other sector-specific and national restrictions**
- **REACH** [62] sets out chemical and product requirements that include registration and information sharing of materials
  - The REACH Authorisation List focuses on substances of very high concern (SVHC)
  - The REACH Restriction List sets total bans or partial restrictions
  - Substances that are well-defined and have a main component are called single substance
  - Substances defined by their source and process, that cannot be defined by single molecular formula are called UVCBs (=Unknown or Variable Composition, Complex reaction products or Biological materials)
- **RoHS** [63] restricts 10 harmful substances, including heavy metals (Pb, Hg, Cd, Cr6+) flame retardants (PBB, PBDE) and plasticizers (phthalates DEHP, BBP, DBP, DIBP)
  - RoHS restrictions apply to electronics

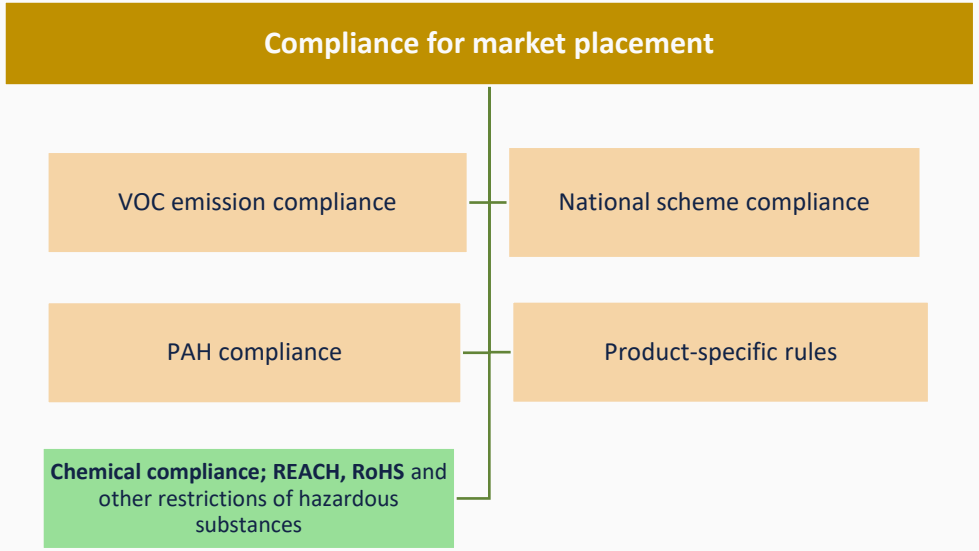

Figure 19: The Automotive legislation that was considered in ABiCo.

REACH

- REACH Sets out chemical and product requirements that include registration and information sharing of materials
  - Annex XIV: The Authorisation List → Focus on substances of very high concern (SVHC)
  - Annex XVII: The Restriction List → Total bans or partial restrictions
- If a product contains >0.1 % of a substance identified on the Candidate list, certain measures must be taken by the supplier of those products: customers must be informed about the presence of and the name of the SVHC in question, and further sufficient information must be given to allow safe use. [64]
- To ease recycling, exemption criteria and verification (for example through WFD article 6(5)) can be used
  - A recovery operator does not have to re-register the material if the substance that results in recovery process is the same as the substance that has been registered according to REACH earlier (article 2(7)(d)), i.e. matching a registered dossier
  - Verification through EoW criteria cannot be given if the recovered material leads to any environmental or human health impacts (WFD article 6(1)(d))
- Substances that are well-defined and have a main component are called single substance
- Substances defined by their source and process, that cannot be defined by single molecular formula are called UVCBs (=Unknown or Variable Composition, Complex reaction products or Biological materials)

ABiCo recipe ingredients

Flame retardants
- DEPAL
- APP
- Melamine phosphate

Additives
- Phenols/phenolic fractions in plasticizers
  - Catechol
  - Syringols
  - Methoxycatechol
- Maleic anhydride in compatibilizer
- Polydimethylsiloxane (PDMS)

Bio-based components
- Biochar
- Wood distillates
- Wood chips
- Tar acids, tar oils

Ceramic materials
- Fibre clays
- Calcium carbonate

Thermoplastic components
- PVA
- PLA
- PP
- PE
- r-PP
- r-PE

ABiCo ingredients REACH compliance

Substance	EC No.	CAS No.	REACH compliance	Other compliance	Health and environmental hazards
Charcoal (biochar)	240-383-3	16291-96-6	Subject to REACH registration if manufactured/imported ≥1 t/year (treated as UVCB substance)	Must be treated as UVCB	
Carbon (biochar)	231-153-3	7440-44-0	Not on Authorisation or Restriction list		H335, H319
Distillates (petroleum), steam-cracked, polymd.	614-301-5	68131-77-1	Not on Authorisation or Restriction list	Must be treated as UVCB	H317, H412
Pyroligneous acids	232-450-0	8030-97-5	Not on Authorisation or Restriction list	Must be treated as UVCB	H302, H315, H319, H335
4-ethyl-2,6-dimethoxyphenol (4-ethylsyringol)	639-043-0	14059-92-8	Not on Authorisation or Restriction list		Not harmonised – classification varies
2,6-dimethoxy-p-cresol (4-methylsyringol)	229-641-6	6638-05-7	Not on Authorisation or Restriction list		H302, H335, H315, H319
2,6-dimethoxyphenol (syringol)	202-041-1	91-10-1	Not on Authorisation or Restriction list		H302, H335, H315, H319, H317
4-methylpyrocatechol (4-methylcatechol)	207-214-5	452-86-8	Not on Authorisation or Restriction list		H302 (possible), H335, H315, H319
3-methoxycatechol	213-276-4	934-00-9	Not on Authorisation or Restriction list		H302, H335, H315, H319
Ammonium polyphosphate (APP)	269-789-9	68333-79-9	Not on Authorisation or Restriction list	UVCB-like behaviour	
Diethyl phosphite (DEPAL)	210-031-7	762-04-9	Not on Authorisation or Restriction list		H302, H315, H319, H335
Melamine phosphate (MP)	[reaction product]	41583-09-9	Not on Authorisation or Restriction list	Often treated as UVCB/complex salt	

CLP hazard	Code
Carc. 1B	H350
Muta. 2	H341
Acute Tox. 3 (Dermal)	H311
Acute Tox. 3 (Oral)	H301
Acute Tox. 4 (Oral)	H302
STOT SE 3	H335
Skin Irrit. 2	H315
Eye Irrit. 2	H319
Skin Sens. 1	H317
Aquatic Chronic 3	H412

UVCB = *Unknown or Variable composition, Complex reaction products or Biological materials*

Compliance needs to be checked in PAH limits, VOC limits and sector-specific concerns.

UVCBs require composition description. If a UVCB contains SVHCs over thresholds, they must be reported in the DPP.

Biochar

- Can serve as reinforcement in biocomposites [65]
    - Thermal stability, electrical properties
    - Limited compatibility without surface modification
- Biochar longevity of carbon storage and persistence [66] make it a desirable component for carbon reductions.
- Assessment of safety in application of biochar is needed [67]
- Biomass feedstock poses the greatest challenge, as it may include harmful components such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), perfluorochemicals (PFCs), etc. [67]
    - The pollutants are mainly affected by the choice of feedstock
    - Biochar is often produced from residues [66]
- **The main risk is related to PAHs,** which are harmful to human health and the environment [68,69]
    - REACH Restriction List has maximum concentrations for eight PAH in plastic or rubber components of consumer products that come into contact with human body → cannot be sold in EU if components contain more than 1mg/kg of any of thei eight PAH, with even lower limits for toys and childcare articles
    - **PAH can form and accumulate in plastic recycling processes**, but their presence before recycling is a key factor to their content [70]
- European Biochar Certificate (EBC) as a voluntary industry standard in Europe [71]
- International Biochar Initiative (IBI) created World Biochar Certificate (WBC) to answer to the safety and sustainability criteria from the biochar users [72]
    - It was developed based on the EBC but does not include the requirements from European Legislation Biochar is registered under REACH within the charcoal dossier (EC No. 240-383-3) [73]

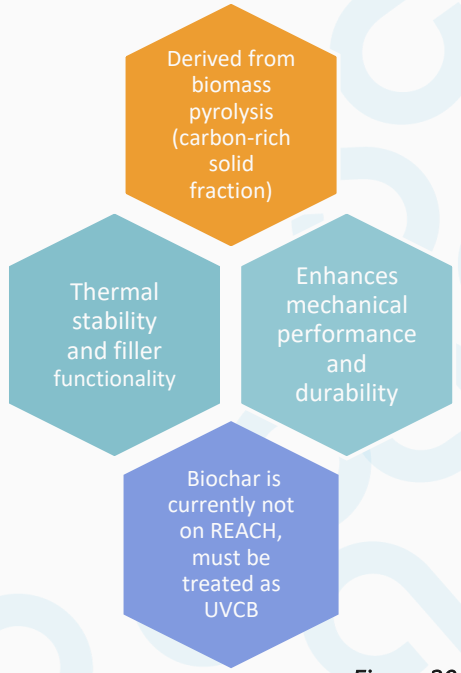

Figure 20: Biochar summary.

* (EC No. 240-383-3)

APP & DEPAL & MPP

ammonium polyphosphate & aluminium diethylphosphinate & melamine polyphosphate

- These phosphorus-based additives are substitutes for conventional flame retardants, offering more stability and safety
  - Many of the conventional, brominated flame retardants have negative environmental impact [74]
  - Many halogenated flame retardants that include bromine, chlorine or phosphorus are considered hazardous to health [75]
  - Generally, halogen-free flame retardants are considered safer than conventional ones, although there are growing concerns related to health risks and environmental aspects [76]
  - APP has low volatility and low toxicity, generally good regulatory acceptance
  - DEPAL has low viscosity and is easy to process
  - MPP has low volatility and low toxicity.
  - Free melamine is in the list of Substances of very high concern and in MPP free melamine limit is <0.1%
- Generally compatible with polymer matrices
  - APP is moisture sensitive and not compatible with hydrophobic polymers, compatibilization for better mechanical properties needed
  - DEPAL has low thermal stability
  - MPP has low solubility
- Fire performance of phosphorus-based flame retardants is generally retained after repeated recycling cycles [77]
- Due to the complexity of these substances and their many components, it is advisable to follow up on REACH and RoHS to ensure compliance.

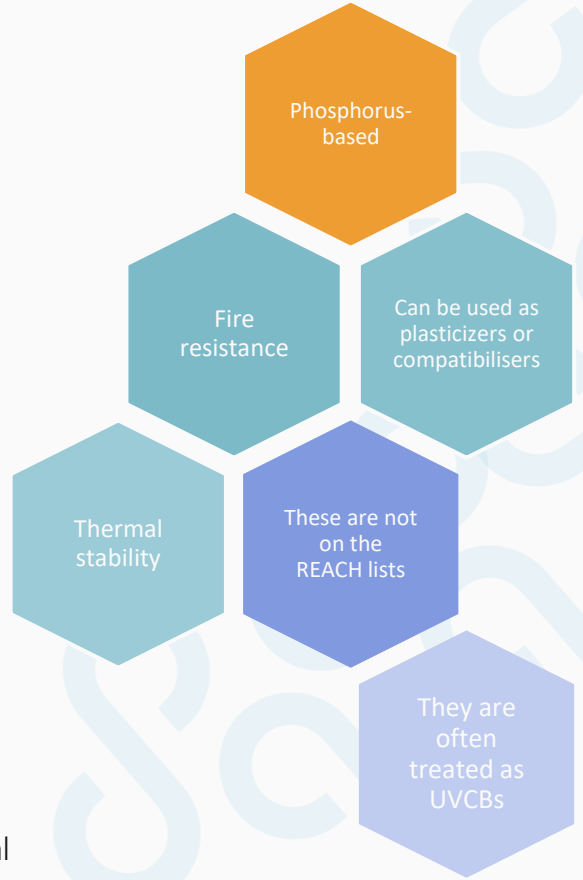

Figure 21: APP, DEPAL, MPP summary.

Phenols and phenolic fractions

- Can potentially replace fossil plasticizers
  - Many benefits in stability and compatibility increase
  - Valorize lignin streams
- Wood distillates, phenolic compounds from wood pyrolysis, are additives with potential antimicrobial and stabilizing effects
- While opportunities arise from performance variability, challenges are related to variability in composition (uncertainties), thermal instability, volatility and poor plastization efficiency
- Phenolic compounds (especially low molecular weight) can be semi-volatile, leading to emissions and odor issues during processing and use [78,79]
  - These **volatile organic compounds (VOCs)** are regulated in certain product categories, such as aerosols, paints and certain adhesives with different limits for different categories
  - VOCs are not yet uniformly regulated, but for example for construction, there are some national thresholds in Belgium, Germany, France, and Italy [80]
- **VOCs are emitted in plastic recycling processes but there are ways to limit them** [81,82]
- Some phenols are toxic, and their health and environmental hazards are harmonised under Classification, Labeling and Packaging of chemicals (CLP). Some toxic phenolics can be found on the REACH Authorisation list and should be avoided accordingly.

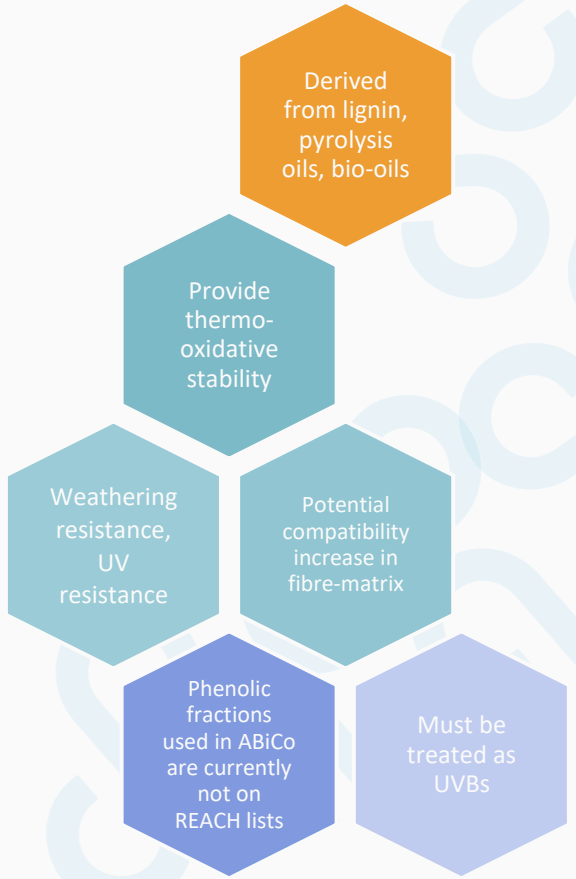

Figure 22: Phenols and phenolic fractions summary.

Conclusions

Conclusions

Regulatory direction
Green Deal, CEAP and Climate Law make circularity and resource efficiency the baseline.
Plastics Roadmap and Communication from the EU support bio-based materials when recycling routes are credible and they are truly a better option.

Sector pressure points
Automotive: ELV revision may require recycled plastic content and vehicle-level DPPs.
Construction and electronics: DPPs, repairability, recyclability and safety requirements are strengthening.

Recycling & market enablers
EPR is established in packaging, electronics, batteries, ELVs and oils, with possible expansion.
Labels, material passports, secondary markets and harmonised classifications are needed to create pull.

ABiCo additive watch-outs
Biochar: carbon-storage potential, but PAH/feedstock safety must be controlled.
APP/DEPAL/MPP and phenolics: useful performance roles, but require ongoing REACH, RoHS, VOC and SVHC review.

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