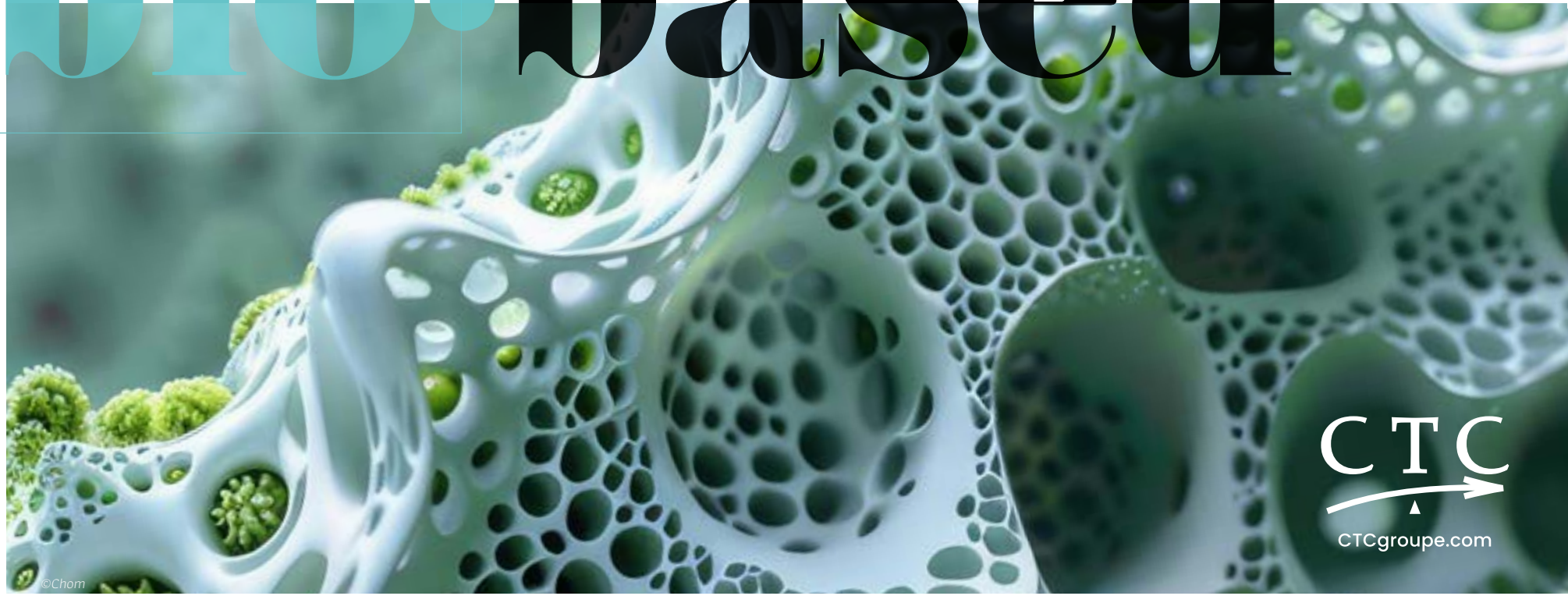
bio-based CONTENT OF MATERIALS

White paper on bio-based materials



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1 Bio-Circular economy

The bio-circular economy blends two powerful concepts:

Bioeconomy, which uses renewable biological resources (like plants, algae, animals and waste biomass) to produce food, energy, and materials, and circular economy proposing keeping resources in use for as long as possible through reuse, recycling, and regeneration. Both concepts together create a system that minimises waste, reduces dependence on fossil fuels, and enhances ecosystem health.

In this context, **the concept of Bio-based materials is generating growing interest in the construction, design, packaging and fashion due to their contribution to the circular economy**. They are considered sectors indispensable for resource-saving and environmentally sound recycling management.

A bio-based product refers to a product **totally or partially derived from biomass**, and the percentage of the bio-based components in materials is therefore **an indicator of the rate of components of biological origin**, excluding materials embedded in geological and/or fossil formations.

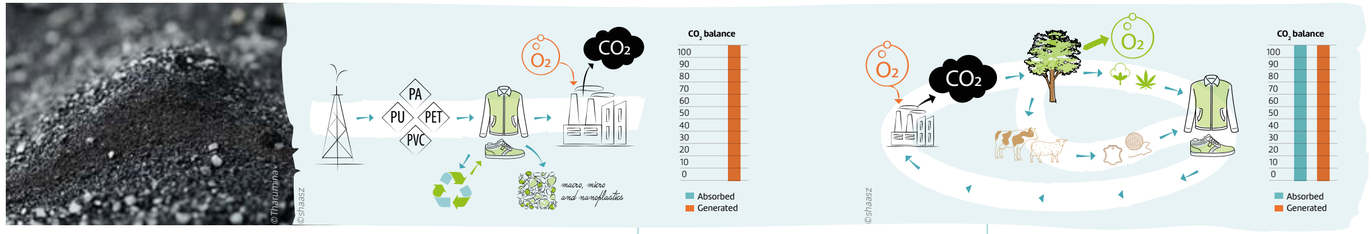
With a growing demand for greater transparency from consumers and following European and French regulations , there is an absolute need to inform consumers on the characteristics, quality and environmental impact of consumer goods & their component materials. As a result, CTC Ars Tinctoria developed a testing method to assess and classify materials according to their **bio-based carbon content**. representing the recent biological origin carbon, excluding the geological and fossil content.

2 A better understanding of bio-based materials

The concept of linear and circular economy models

The circular economy is a sustainable model of production and consumption that aims to close the loop of the life cycle of products. Instead of the traditional “take-make-dispose” linear approach, it promotes reducing the depletion of fossil resources, reducing waste by a virtuous end-of-life management, reusing, repairing, refurbishing, and recycling materials and products, and eco-designing products to be more durable and resource-efficient, defining not only the assembly but also the disassembly.

Figure 1 – Linear 100% fossil materials environmental fate compared to a circular biomass supply chain-based material



Analysing the environmental fate of linear modelled organic chemistry-based materials (Figure 1 left) the carbon source is petrol or coal, which, transformed by petrochemical industry become monomers that after polymerization can be transformed in plastic materials (fibres, nonwovens, coatings, structured plastics, synthetic gums, among others). Materials like PET (Polyethylene Terephthalate), Pu (Polyurethane), PVC (Polyvinyl Chloride), Acrylic, Polycarbonate, can be used alone or combined with natural fibres to develop consumers goods.

These goods can be eventually recycled, **but most of them will release micro and nanoplastics in the environment during their lifetime.** In rare cases few of these materials may be biodegraded to their minimum forms i.e. CO_2, NO_2, CH_4, NH_3, H_2O to be metabolized by nature in a new biomass circle, otherwise they persist as POPs (Persistent Organic Pollutants).

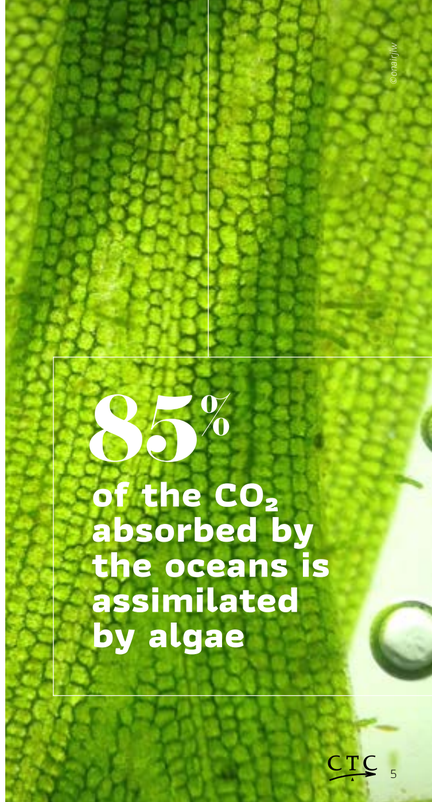
The most appropriate end-of-life option for synthetic materials is incineration (with eventual energy recovery), in which case it will share the environmental fate of fossil fuels, with stoichiometric conversion of Carbon into CO_2, and proportional consumption of atmospheric Oxygen (O_2).

In linear supply chain models carbon is originated from follil resources such as petrol or coal. Upon incineration **the CO_2 is emitted into the atmosphere, O_2 consumed, and no CO_2 is absorbed, increasing the abundance of GHGs (Greenhouse Gasses),** implicated in the current global warming issues.

In a circular biomass supply chain, the raw material is environmental CO_2, which model is metabolised by plants and algae into biomass, releasing O_2 into the atmosphere. **As vegetable biomass it can be used for food, heat, and as natural apparel materials** such as cotton, wool, hemp, sisal, or serve **to feed animals** which may be farmed for food and wool and leather production.

Considering the worst possible end of life option (incineration) for circular supply chain materials with stoichiometric conversion of Carbon into CO_2, and proportional consumption of atmospheric O_2 in an equivalent proportion to the release upon biomass generation. This is a so-called Carbon-Neutral concept if we consider the intrinsic contribution of the material excluding processing and supply chain energy.

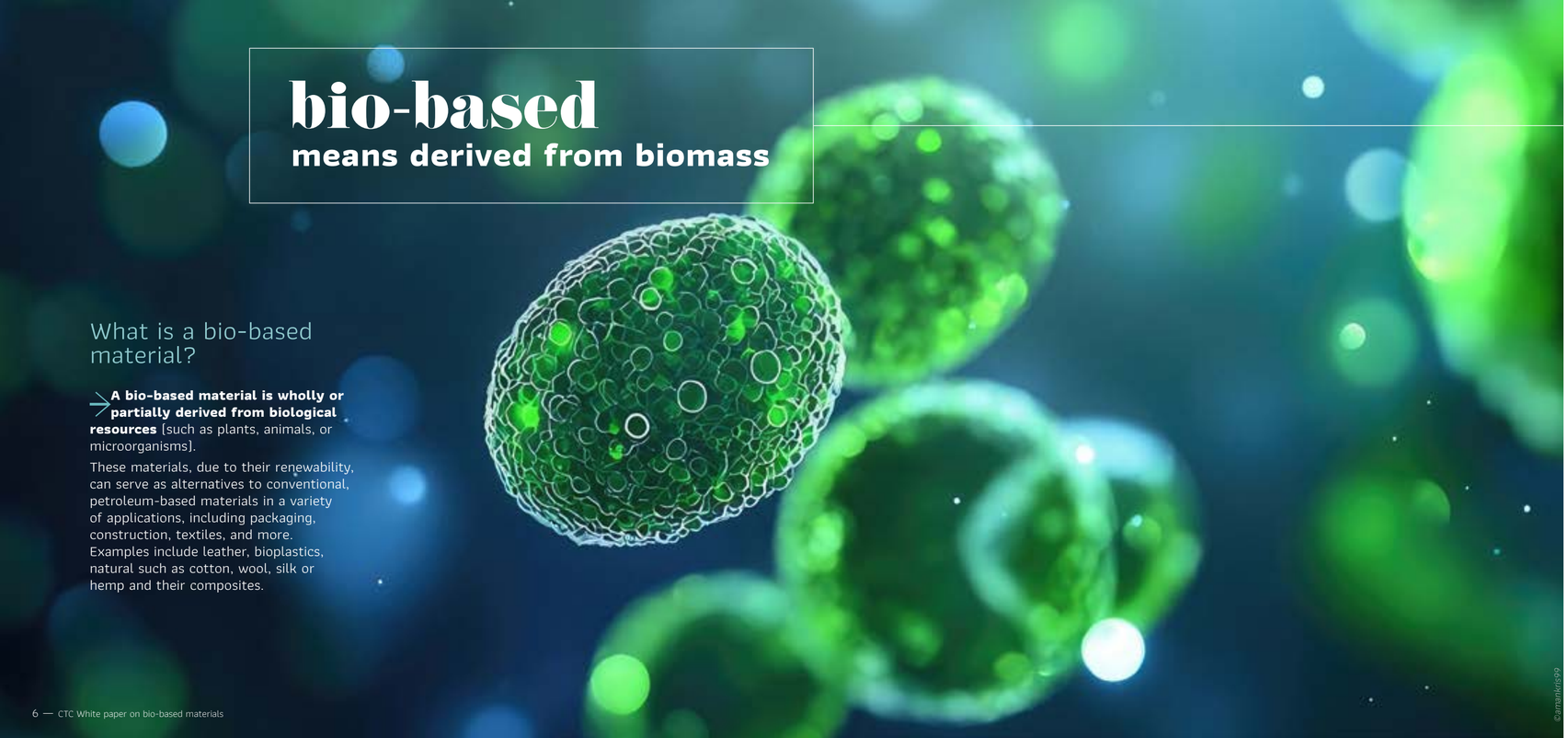
A sustainable material is the result a series of sustainable events. To have a better understanding of it, it is of utmost importance to deeply analyse the intrinsic features of the material itself, and the supply chain (sustainable energy resources, sustainable transport, water consumption, atmospheric emissions, wastewater treatment and its emissions, etc.). Acting on each event it is possible to ensure the best results in terms of sustainability, after which we may consider compensations, when no other viable solutions to reduce environmental impact are available.



85%

of the CO_2 absorbed by the oceans is assimilated by algae

bio-based
means derived from biomass



What is a bio-based material?

A bio-based material is wholly or partially derived from biological resources (such as plants, animals, or microorganisms).

These materials, due to their renewability, can serve as alternatives to conventional, petroleum-based materials in a variety of applications, including packaging, construction, textiles, and more. Examples include leather, bioplastics, natural such as cotton, wool, silk or hemp and their composites.

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Despite their renewability, bio-based materials are not inherently sustainable, as their environmental impact depends on multiple factors. To fully assess their sustainability, we must also consider energy consumption and its origin, transportation emissions, land and water usage, waste management practices, and end-of-life disposal options, among other key parameters.

In 2014, the CEN/TC 411 "Technical Committee for Bio-Based Products" published the standard EN 16575 "Bio-based products – Vocabulary" and defined the following terms:

bio-based

means
[derived from biomass]

biomass

[material of biological origin, excluding materials embedded in geological and/or fossil formations]

bio-based product

[a product wholly or partly derived from biomass]
In the case of a partially bio-based product, the standard recommends providing a quantification of the bio-based content of the product.

Carbon, the backbone of life and a modern challenge

Carbon along with other biogenic elements (nitrogen, oxygen, and hydrogen), gave birth to life, creating important reservoirs of fossil carbon during the Earth's evolution.

Fossil carbon belongs to a past biosphere's natural equilibrium. Fossil carbon, such as coal, gas, and petrol has been used throughout human history for heat, transportation, material manufacturing, and lightning.

However, the massive use of fossil carbon as an energy source since the Industrial Revolution has accelerated the depletion of fossil resources, with a proportional increment of carbon dioxide emissions in the atmosphere. Additionally, modern petroleum extraction techniques, such as horizontal drilling, are further contributing to methane emissions, exacerbating this issue. **Both carbon dioxide and methane are the most abundant greenhouse gases, and the unbalanced increment abundance in the atmosphere has been demonstrated to be one of the main causes of global warming.**

Materials evolution: from natural resources to synthetic polymers

For centuries, human societies relied on natural and renewable bio-based materials for clothing, footwear, and accessories. Leather and furs were the first materials that humans used, learning how to preserve them from putrefaction while keeping their unique protective properties. The rise of agriculture saw the evolution of natural fibres, such as cotton, wool, hemp, silk, etc.

These natural textiles, originally manufactured using artisanal methods, became central to mass production with the Industrial Revolution. However, this shift also contributed to an increasing environmental footprint, as industrial-scale processing and transportation further amplified carbon emissions.

The petrochemical industry evolved strongly during the last two centuries.

The invention of Bakelite in 1907 marked the dawn of the synthetic polymer era, followed by the development of widely used plastics, such as polyethylene, nylon, polyurethane, and polyester.

These materials fuelled innovation in countless industries, enabling the mass production of packaging, disposable tools and devices, fashion materials, and all sorts of cheap consumable goods.

However, the rise of synthetic polymers also brought new environmental threats: the persistency of synthetic polymers has evolved in certain forms of the so-called "forever chemicals" or products with limited biodegradation, and a degradation pattern of slow polymeric chain shortening, evolving from macro to micro and finally nano plastics forms.

Even if it is possible to recycle plastic waste, the reality is that less than 9% of produced polymers worldwide are recycled. **The challenge is how to treat plastic waste**.
If recycled, it is impossible to avoid generating persistent plastic forms. If incinerated, it will increase the abundance of carbon dioxide in the atmosphere. Some governments have taken action to challenge this environmental emergency by reducing the usage of fossil-based materials with initiatives such as the EU Green Deal policy or the UN Sustainable Development Goals.

Leather and material circularity

Leather has long been a cornerstone of the fashion industry, valued for its durability, versatility, and timeless appeal. As industry shifts towards sustainability, **leather remains a crucial bio-based material, offering a natural alternative to synthetic, petroleum-derived fabrics**. Unlike plastic-based alternatives, which often contribute to microplastic pollution and waste, responsibly sourced leather can be one of the most sustainable choices when produced with ethical and eco-friendly practices.

The rise of bio-based materials has introduced new alternatives derived from renewable sources such as plants, fungi, and agricultural waste. While these materials promise sustainable solutions to the environmental impact of traditional textiles and leather, many still incorporate fossil-based polymers, chemicals or resource-intensive processes.

In this context, **carbon origin plays an important role in circularity**, due to its detrimental influence on the environment when abused or mismanaged. Quantifying the proportion of fossil and bio-sourced carbon in materials is therefore essential for ensuring transparency in sustainability claims.

Thus, according to the EN 16575 standard, a material is considered bio-based if at least part of its raw materials is of biological origin (excluding geological origin). It can be 100% or only a fraction bio-based. As the standard recommends specifying the quantification of bio-based content, the analyses and verification of the supply chain can supplement this information. Hence, the bio-based content of any material is an indication of its renewability. A measurement campaign highlighted varying bio-based contents from 23% to 100% for various materials such as Desserto (cactus), AppleSkin (apple peels and cores), among others. Further measurements on various leather samples indicated values ranging from 50% to 100%, depending on the type of leather. (Carcione, Defeo, Bartalini et al, 2023).

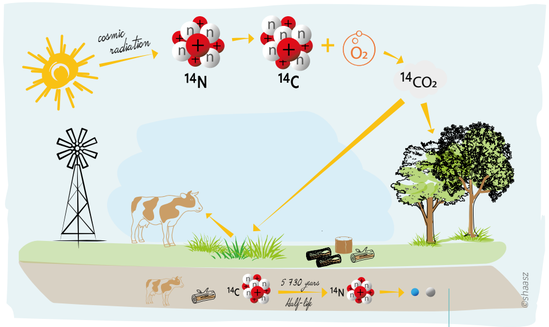
Is it possible to differentiate fossil from biogenic carbon?

Understanding the abundance and fate of carbon isotopes is the clue to this question: **Carbon has 15 different isotopes**, two of which are stable: ^{12}C (carbon 12) which is the most abundant and ^{13}C (carbon-13). The others, considered unstable and therefore radioactive, are called radioisotopes.

The most stable among the carbon radioisotopes is carbon-14 (^{14}C) with a half-life of 5,730 years. It is the only naturally occurring carbon radioisotope because the second most stable radioisotope has a half-life of 20 minutes, and the rest have half-life of less than 20 seconds.

^{14}C is a cosmogenic isotope which is generated in the upper atmosphere by cosmic rays' bombardment on nitrogen (^{14}N) which is the most abundant gas in the atmosphere. It then reacts with atmospheric oxygen producing $^{14}CO_2$, being uniformly distributed. Plants incorporate this $^{14}CO_2$ through photosynthesis, metabolizing it and transferring it to living organisms through the food chain. This way ^{14}C keeps a relatively stable proportion in animals and plants at the same concentration as in the atmosphere (1 atom of ^{14}C per 1 trillion of ^{12}C and ^{13}C atoms, or 10-12). Since fossil carbon emissions are far higher than what the biosphere is able to metabolise, the ^{14}C proportion is reduced every year, obliging the tunning officially defined by NIST referred to the radiocarbon standard.

Figure 2 - The lifecycle of cosmogenic radiocarbon and its transfer to biomass



Petrochemical products, derived from fossil resources dating back millions of years, have completely lost their original ^{14}C content, therefore **the ^{14}C proportion in any material or product containing carbon, indicates its bio-based or renewable carbon content.**

Based on this principle, the method for analysing the bio-based content of a sample relies on quantifying the ^{14}C presence.

Does the bio-based content indicate the carbon impact of a product?

Bio-based content accounts for the intrinsic renewable carbon contained in a product or raw material. It does not account for:

- **Greenhouse gas** (GHG) emissions related to the cultivation of a plant (cotton, hemp, etc.) or livestock (wool, leather, etc.)
- **CO_2 emissions** from boilers for heat production
- **Emissions related to electricity production** (coal, etc.)
- **Transport emissions** (freight, etc.)
- **The energy** needed to manufacture chemicals
- **Chemicals auxiliaries** which are removed or washed out during the process (solvents, detergents, etc.)

Inorganic compounds

Depending on the method applied, the analysis of the bio-based material may be expressed relative to the total carbon content or to the just organic.

Renewable Bio-based Materials

[Bamboo, hemp, and corn-based bioplastics *are renewable because they come from rapidly growing plants that can be replanted and replenished.*]

Non renewable biosources

Bio-based materials are generally considered renewable and sustainable because they are derived from biological sources that can regenerate over time, such as plants, algae, animal or microorganisms.

Non-Renewable Bio-based Materials

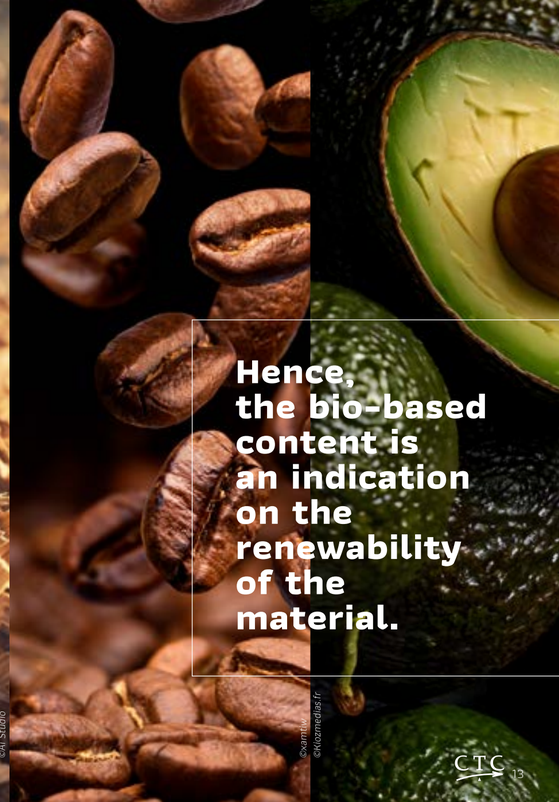
[Peat, a bio-based material formed from decomposed plant matter, *is considered non-renewable because it takes thousands of years to regenerate. Similarly, certain old-growth forest products may be bio-based but are non-renewable if harvested unsustainably.*]

However, in some cases, bio-based materials can also be non-renewable, depending on factors like resource depletion, slow regeneration rates, or unsustainable harvesting practices. For example:

Persistent Bio-based Materials

[*It is possible to produce bioplastics which are not biodegradable or may release micro and nanoplastics during their lifetime.*]

Thus, while most bio-based materials are renewable, their renewability depends on how they are sourced and managed. Other aspects of bio-based products sustainability are considered in the various CEN TC 411 standards, covering not only bio-based content, but also sustainability criteria, LCA calculations, and communication which will be enumerated in the following point.
In summary, according to the standard, the concept of bio-based refers to the origin of the raw materials, which must be biological, excluding materials of geological origin (petroleum, coal, gas which is non-renewable).



Hence, the bio-based content is an indication on the renewability of the material.

3 Standards and regulations for bio-based products

. EN 16848 - Requirements for Business to Business communication of characteristics using a Data Sheet

European standards

CEN/TC 411, the European technical committee responsible for standardization in the field of bio-based products, aims to develop standards that ensure transparency, reliability, and consistency in production, labelling, and certification of materials derived from renewable biological resources. These standards play a crucial role in fostering the transition from fossil-based to bio-based economies by providing clear criteria for sustainability, bio-content determination, and performance evaluation. This technical committee was created in May 2011 in response to mandates from the European Commission with the scope to support the development of a sustainable bioeconomy.

The scope of CEN/TC 411 covers key aspects such as terminology, testing methods, sustainability assessment, and certification schemes for bio-based products. By establishing harmonized standards across Europe, CEN/TC 411 is helping industries, policymakers, and consumers to make informed choices, promoting innovation, and ensuring environmental and economic benefits.

Key Standards Developed by CEN/TC 411

The following standards define critical aspects of bio-based materials:

- EN 16575 - Bio-based products — Vocabulary
- **EN 16640 – Bio-based products** — Determination of the bio-based carbon content of products using the radiocarbon method
- EN 16785 standards were developed to calculate Bio-based content as biomass in its two parts:

  - EN 16785-1, Bio-based products — Bio-based content — Part 1: Determination of the bio-based content using the radiocarbon analysis and elemental analysis

  and

  - EN 16785-2, Bio-based products — Bio-based content — Part 2: Determination of the bio-based content using the material balance method
- EN 16751, Bio-based products — sustainability criteria (This standard sets horizontal sustainability basis applicable to all bio-based products excluding food. It considers environmental, social and economic criteria for bio-based products)
- **EN 16848** – Requirements for Business to Business communication of characteristics using a Data Sheet
- **EN 16935 – Requirements for Business to Consumer communication and claims**

Both EN 16935 and EN 16848 rules the way to communicate bio-based content on materials and commercial products transparently to avoid greenwashing.

The term 'bio-based' means 'derived from biomass'

The role of EN 16640 and EN 16785-1 in bio-based carbon assessment

Within these standards, **EN 16640 allows the quantification of the bio-based carbon content of any material towards radiocarbon quantification**. As stated in this standard, "it is important to understand what the term 'bio-based product' covers and how it is being used. The term 'bio-based' means 'derived from biomass'. **Bio-based products are those which are wholly or partly derived from biomass**. It is essential to characterize the amount of biomass contained in the product by, for instance, its bio-based content or bio-based carbon content. The bio-based content of a product does not provide information on its environmental impact or sustainability, which may be assessed through LCA and sustainability criteria. In addition, transparent and unambiguous communication within bio-based value chains is facilitated by a harmonized framework for certification and declaration"[2].

Regarding EN 16785-1, the method allows to calculate the bio-based content in relation to the organic components following radiocarbon and elemental analysis. Both methods are requested in EN 16848 and EN 16935 data sheets for sustainability characteristics communication and claims.

Other standards

While CEN TC 411 standards are intended transversal, to be able to analyse either chemicals, fuels, single materials and composites for any sector, other bio-based quantification standards are limited to specific materials or for a limited application.

One case is that of ISO 16620-2:2019 - Plastics — Bio-based content — Part 2: Determination of bio-based carbon content. This document specifies a calculation method for the determination of the bio-based carbon content in monomers, polymers, and plastic materials and products, based on the ^{14}C content measurement, and limited to plastic products and plastic materials (e.g. plasticisers or modifiers), polymer resins, monomers, or additives, which are made from bio-based or fossil-based constituents.

Also, the American standard ASTM D 6866-12[3], serves for the calculation of the bio-based carbon content, but as fraction of the organic carbon. This way, any inorganic carbon present in the product, (such as carbonates or calcite) fossil of bio-based is not considered in the determination calculation.

4 How is bio-based content measured?

Instruments for reliable ^{14}C quantification

Currently three instruments are available to assess the bio-based content:

- **AMS - Accelerator Mass Spectrometry**
- **LSC - Liquid Scintillation Counting**
- **SCAR - Saturated-Absorption Cavity Ring-Down Spectrometry**

The ^{14}C quantification using these three instruments gives the result in ^{14}C units, which must be converted thru calculation to pMC (percent modern carbon). The reference used as standard is oxalic acid (NIST SRM 4990C), which must be measured at the highest precision to achieve a good accuracy in the results.

Due to the so-called Suess effect, the pMC value of a 100% biogenic sample is drifting yearly towards lower values currently at a rate of about –0.5 pMC/year. This is due to the unbalanced emission of fossil carbon. Once the carbon neutrality will be reached, this value will increase till finding a new equilibrium. As a reference in 2021 100% biogenic samples reached the value of 100 pMC[5]. Practically, we can assume that the pMC value measured for nowadays materials nearly corresponds to their biogenic fraction in %.

Chemicals and materials samples preparation

Both chemicals and materials to be analysed, should be prepared ensuring that the fraction extracted corresponds to the average fossil / bio-based proportions of it.

In the case of chemicals' analysis if solvent based, they should be analysed without any preventive drying, while in case of liquid aqueous solutions or dispersions it is recommended to dry it at low temperature (45ºC maximum) and under strong vacuum.

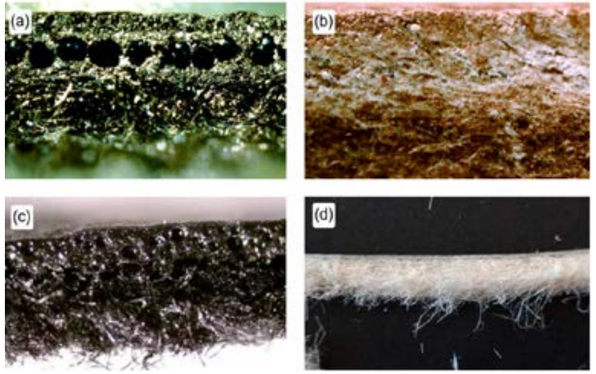
For materials it is advisable to verify different vertical cuts under the microscope to ensure that the eventual coating keeps a proportion corresponding to the whole. Avoid milling. The percentage of bio-based carbon (bio-based C) corresponds to the amount of bio-based carbon relative to the total amount of carbon, including both bio-based and fossil carbon.

^{14}C results interpretation regarding standards

All three methods for bio-based content are transversal giving results from different viewpoints which can be compared (even in the case of different matrices) within the same method. The differences are the following:

- EU Bio-based carbon content (EN 16640): The amount of bio-based carbon is calculated as a fraction of the total amount of carbon in the sample (organic + inorganic).
- EU Bio-based content (EN 16785-1): The amount of bio-based C, H, N, O, S expressed as a fraction of the total mass of sample.
- US Bio-based content (ASTM D6866-12): The amount of bio-based organic carbon expressed as fraction of the total amount of organic carbon in sample.

Figure 3 - Section uniformity verification under the microscope: (a) Desserto®, (b) chestnut traditional tanning, (c) Vegea®, (d) Piñatex performance®



Al three approaches are based on the same underlying principle: the ^{14}C content may be considered as a tracer of recently produced bio-based products. However, the methods differ in how they use the amount of ^{14}C to express bio-based content, as each standard applies distinct definitions and assumptions.

Therefore, when information about bio-based (carbon) content is exchanged between businesses, or from business to consumer, it is crucial to be aware of these differences and to clearly state the underlying standards on which these statements are based.

The validation of SCAR spectrometry on materials analysis

During 2019, Ars Tinctoria's (currently CTC Ars Tinctoria) research team was looking for affordable alternatives, coming across the publications of the research from CNR-INO (Istituto Nazionale di Ottica) and LENS (European Laboratory for Non-linear Spectroscopy), and thus getting in touch with Professor Saverio Bartalini and his team.

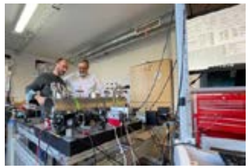
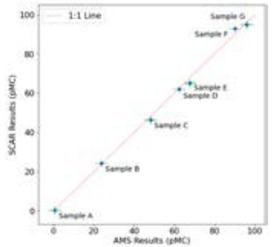


Figure 4 – February 2022, Prof. Saverio Bartalini showing Gustavo Defeo the evolution of the construction of CTC Ars Tinctoria's SCAR spectrometer

CTC-ARS Tinctoria currently counts among their analytical instruments with one of the first ^{14}C SCAR analysers currently operating worldwide. SCAR technology is based on (Saturated-Absorption Cavity Ring-Down) Spectrometry, developed by CNR-INO Florence (National Institute of Optics). This is an instrument for trace-gas detection by laser spectroscopy, which exploits the technique of cavity ring-down (CRD) in a saturated absorption regime (SCAR).

SCAR ^{14}C analyser can detect the radiocarbon in a gaseous carbon dioxide sample with a precision approaching accelerator mass spectrometry (AMS). The achievable precision level in 30 minutes of averaged measurements can be close to 1% of the modern carbon content (1 pMC) and the dynamic range is higher than 5 orders of magnitude (highly enriched samples can be measured, too). The preparation of each sample takes about 30 minutes. The CRD technique relies on coupling the laser radiation to a high-finesse cavity; once a predetermined filling level has been reached, the laser is rapidly switched off, and the radiation coming out of the cavity is detected while decaying exponentially. The time constant of the decay is related to the losses in the cavity. With the empty cavity, the losses are only due to the mirrors; if there is an absorbing gas in the cavity, the decay time is shorter; from the difference in the decay.

Figure 5 – The results obtained by SCAR spectroscopy are compared with those obtained by AMS for each sample. The red line represents the 1:1 proportionality and allows the agreement between the two sets of results to be visualised. The error bars (3 pMC for AMS and 2 pMC for SCAR) include statistical and systematic uncertainty.



From this partnership the early analysis of Bio-based content on Leather and alternative materials, were developed and the validation against AMS (Accelerator Mass Spectrometry) was published as peer reviewed paper on MDPI Coatings Magazine[6].

This paper can be freely downloaded from the following link: https://www.mdpi.com/2079-6412/13/5/892

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5 CTC Ars Tinctoria's testing solutions

State-of-the-art equipment for bio-based material analysis

CTC-ARS Tinctoria currently assesses the bio-based carbon content of materials (leather, textiles, plastics, alternative fashion materials, chemicals, etc.) used for any application including packaging. Tests are carried out with an analytical method based on EN 16640 or / and EN 16785-1 standard.

Figure 6 – CTC Ars Tinctoria's ^{14}C analysis facilities in Santa Croce sull'Arno, Italy laboratory

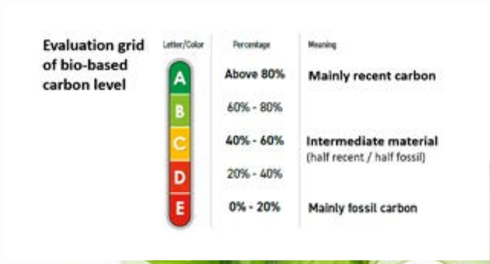
Our testing procedure

To conduct the assessment, a sample quantity of 10 grams of chemical or material is required. We determine the content of bio-based carbon towards ^{14}C analysis, defining the organic and inorganic carbon, nitrogen content, and bio-based and fossil proportions.

By restricting the inspection to the proportion of bio-based raw materials, the testing outlay is minimized, and a clear and unequivocal statement is made in an economically efficient way.

Thanks to our state-of-the-art equipment, we're able to deliver a testing report in 5 days.

Figure 7 – CTC Ars Tinctoria bio-based content labelling scheme.



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The CTC bio-based material certificate

Following the assessment, CTC issue a bio-based material certificate, valid for 3 years, which states the percentage of total organic carbon in your material. This certification serves as a transparent and reliable validation of your product's bio-based content, reinforcing your commitment to sustainability.

Holding a CTC certification enhances your credibility within the industry, providing a competitive edge by demonstrating compliance with recognized bio-based standards. It also strengthens consumer trust, assuring customers that your materials align with their expectations. This certification can be a key asset in marketing your products and meeting regulatory requirements.

6 Conclusion

Bio-based carbon content is necessary to understand the intrinsic biomass content of a material and thus the fraction that comes from a renewable origin. However, while this metric reflects the material's origin, it does not inherently guarantee a virtuous end of life for the finished product. The ultimate environmental impact depends on the entire lifecycle of the product, including its design, usage, disposal, and recycling processes.

One promising path for sustainable waste management is the valorisation of metal-free leather waste. **Scraps from vegetable tanned leather can be repurposed into biochar through pyrolysis, providing an innovative solution to reduce waste. Biochar, when used in agriculture, improves water and nutrient retention in the soil, promoting soil fertilization.**

Additionally, if future European regulations establish incentives for storing bio-based carbon in soils, this practice could even generate fiscal benefits, further encouraging circular economy strategies in the leather industry.

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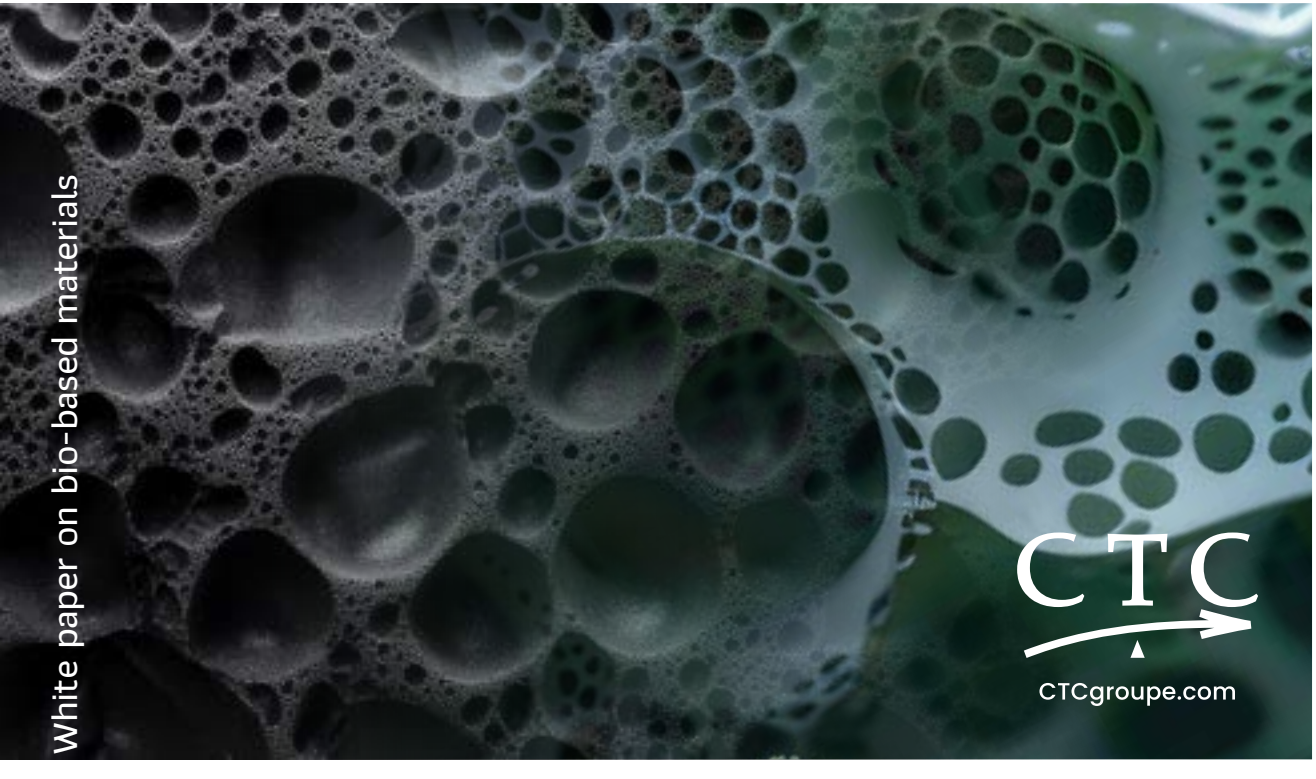

Gustavo Adrián DEFEO FSLTC
Direttore scientifico / Scientific director
CTC ARS TINCTORIA SRL
Laboratorio accreditato ISO/IEC 17025 - P.IVA 02029150501
Sede Legale: Via del Bosco, 125 - 56029 - Santa Croce sull'Arno (PI) - Italia
Tel. +39 0571-35 110 / **+39 348 892 4726** / gdefeo@ctcgroupe.com

Thierry PONCET
Director of Industrial Expertise and Sustainable Development
CTC Groupe - 4 rue Hermann Frenkel - 69367 Lyon cedex 07 - France
Tel. +33 (0)4 72 76 10 10 / **+33 (0)6 45 74 41 80** / tponcet@ctcgroupe.com

CONTACT BIO-BASED TESTS
Valentina RANDELLINI
CTC Ars Tinctoria
Tel. +39 0571-35 110 / +39 0571-32459 / vrandellini@ctcgroupe.com

CTC Groupe
4, rue Hermann Frenkel - 69367 Lyon Cedex 07 - France
Tel. +33 (0)4 72 76 10 10 - ctclyon@ctcgroupe.com - www.ctcgroupe.com