CarboMet

Carbohydrates as Sustainable Materials for the Future

European Commission

Metrology of Carbohydrates for Enabling European Bioindustries

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Executive Summary

The advent of the European bioeconomy first presented in 2012 set out plans to transform the chemical industry in Europe to a more sustainable economy. One of the key underlying principles of the new bioeconomy framework was the utilization of waste resources, in particular food and agricultural waste. On average the EU produces 956 million tonnes of agricultural biomass per annum and a large constituent of this is carbohydrate.

This report highlights some of the key applications of carbohydrate materials in packaging, regenerative medicine, food and textiles. The structural diversity and complexity of polysaccharides make it difficult to evaluate new materials but also provides a tremendous opportunity to access novel materials with unique structural and functional properties. Subtle differences in the polymer backbone can profoundly affect folding and -molecular interactions between polymer chains. To address this challenge, several research areas were prioritised which required substantial investment in R&D across both industry and academia.[1] These were on advanced sequencing platforms, computational modelling, automated carbohydrate synthesis, access to waste biomass through efficient valorisation processes and remodelling of natural polymers using biotechnology. The report also focusses on how the three enabling technologies can be integrated into the design and development of new materials and how this will impact society and the European bioeconomy.

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[1] Research priorities were identified following discussions that took place at the CarboMet workshop ‘Glycomaterials’ on the 24th & 25th January 2019 in Grenoble, France. It reports on the technological challenges that were identified at this workshop and lists a set of recommendations which have been designed to help solve measurement, data management and metrological needs across the four bioindustry areas.

Overview & Specific Challenge

The development of bio-inspired sustainable materials from carbohydrates has steadily gained interest from the chemical industry as a strategy to produce new materials with unique properties from waste resources. Natural polysaccharides such as cellulose, hemicellulose, starch, chitin, pectins, and xyloglucan all have properties that make them useful for a variety of applications and their exploitation is crucial to reduce the dependence on fossil fuels and towards the development of the circular economy. Perhaps the biggest drivers have risen from environmentally conscious consumers and regulatory bodies which have accelerated a continuous and growing development of novel, sustainable and biodegradable materials.

Nature has provided an unlimited resource of carbohydrate-based materials and whilst the complexity and diversity of carbohydrates is challenging, this very diversity provides an opportunity to access new chemical and sequence space by tailoring the polysaccharide structure and functional properties for various applications. The inter-relationship between structure and function is perfectly highlighted when comparing cellulose and starch. Both are made of glucose residues but they play different roles in nature. Cellulose provides structural support to plants, whereas starch is primarily used as an energy source; key differences in these properties are due to the variations in the spatial arrangements of their molecules. The recognition of the importance of structure and its relationship to function is a prerequisite to developing a new generation of sustainable biomaterials that can address global challenges in packaging, healthcare, agriculture and personal hygiene. For example, natural biomaterials such as cellulose, chitin, pectin and starch have unique properties which arise from the structural organization of the micro- and macromolecular structure. Knowledge and an understanding of how these structures interact are central to the eventual manipulation and engineering of new materials. This information is vital to identifying future R&D priorities and topics aimed at modifying existing natural polymers using advances in chemical synthesis and synthetic biology, with the aim of enhancing and/or introducing additional properties and functionalities to the material.

We envisage a future where digitization is integrated into the R&D workflow and manufacturing processes themselves, with machine-based learning approaches being used to guide the design of new materials from current existing or new knowledge of the interplay between structure and function. This will be a powerful predictive tool for the European chemical industry and underpinning this will be the CarboMet initiatives on developing robust and appropriate measurement and analytical tools, as well as new metrological procedures and ISO-standards.

Current attempts to establish a comprehensive R&D framework for the development of new biomaterials has been hindered by a lack of funding opportunities for SMEs to support early development and the technology that is required to enable accurate measurements and analysis of the materials. Existing research programs in this area are dominated by the life sciences and to fully exploit the potential of carbohydrate polymers, knowledge sharing from disciplines such as maths, computer science, physics and engineering is vital. While the exact delineation of this area (glycomaterials engineering) remains to be established, its overall aim is to create, transform and enhance existing materials to confer better performance for specific applications. New analytical tools and advances in the physical and biological science will be needed to investigate the relationship between the structure of materials at the atomic and molecular scale and its varying influence on the macroscopic properties. This follows the materials paradigm represented in figure 1 showing the interactions between structure, properties, processing and performance all of which falls within the CarboMet scope of metrology – the process of measuring one or several specific parameters for a defined purpose.

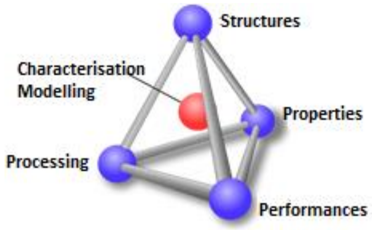

Figure 1. Interactions between structure, property, processing and performance for charactering new materials.

Carbohydrates constitute the largest biomass resource on earth and their exploitation as biodegradable polymers will be crucial to alleviating many of the environmental issues which are plaguing both developed and emerging national economies. Only recently has the attention shifted from traditional fossil-based materials to next-generation "smart" materials that are also biodegradable and with the potential to tailor properties based on the polysaccharide sequence. To achieve this, it is necessary at first to produce synthetic polysaccharides to explore the properties and function of well-defined carbohydrates. While mass production of custom-built carbohydrate polymers is still in its infancy the European glycoscience community has made giant strides towards this goal. For example, scientists from the Max Planck Institute of Colloids and Interfaces developed the first fully automated oligosaccharide synthesizer called THE GLYCONEER®. Analogous to the technology breakthroughs of the oligonucleotide and peptide synthesisers, the automated glycan assembly (AGA) method will have a similar impact if not more in the area of biomaterials. This has enabled the production of 50-mer polymannose,[2] a useful biomaterial used in drug delivery of antifungal agent Amphotericin B.[3]

Packaging, Films and Next-Generation Displays

The last decade has seen the pulp and paper industry undergo a challenging time, partly due to the advent of digital technology and the consequent decline of graphic papers such as newsprints.[4] The slow growth has led to a surplus of wood and forestry residues and to offset this, new applications and technologies are being developed to utilise the existing supply of waste biomass particularly in the packaging industry. For example, Futamura, a global company with a strong presence in Europe has been developing cellulose-based films for the packaging industry since 1947. Both NatureFlex™ and CELLOPHANE™ are biodegradable cellulose films made from renewable wood pulp with properties suited for food packaging. The product has been serving the European market for over 30 years with incremental advances in new technology and formulations to address this global demand.

New developments in converting cellulose from agricultural residues to microfibril nanostructures have now opened up new avenues for application in tunable optics. These nanoparticles can be produced on scale from the deconstruction and subsequent reassembly of cellulose to form liquid crystal phases with chiral nematic ordering.[5] These inexpensive materials can be used in the

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[2] Pardo-Vargas, A.; Delbianco, M.; Seeberger, P. H. Automated glycan assembly as an enabling technology. *Curr. Opin. Chem. Biol*. **2018**, 46, 48 - 55

[3] Francis, A. P.; Gurudevan, S.; Jayakrishnan A. *J. Biomat. Sci*. **2018**, 29, 529-1548.

[4] "Pulp, paper, and packaging in the next decade: Transformational change", McKinsey & Company, 2017: https://www.mckinsey.com/industries/paper-and-forest-products/our-insights/pulp-paper-and-packaging-in-the-next-decade-transformational-change

[5] Elazzouzi-Hafraoui, S.; Putaux, J-L.; Heux, L. Self-assembling and Chiral Nematic Properties of Organophilic Cellulose Nanocrystals, *J. Phys. Chem.* B. **2009**, 113, 32, 11069-11075.

production of cholesteric liquid crystal displays ('ChLCD'), a next-generation technology with high resolution and very low power consumption which is particularly suited towards information display systems in airports and train station.[6] Cellucomp, an SME based in Scotland has developed an innovative technology to convert food waste to cellulose nanofibers (CNF). The marketed Curran® fibres are light, strong and have properties that are comparable to carbon fibre with excellent rheology modifying properties and have been used as an additive in commercial paints and coatings.[7] Other applications of carbohydrate polymers include toiletries, cosmetics and food. For example, cyclodextrins (CDs), a cyclic oligo-saccharide composed of glucose units, are excellent stabilizers and bulking agents for food application. They are also used as protecting agents in cosmetics and hygiene products by complexing with the guest molecule to shield against light, heat and oxidation.[8] CDs have also been exploited for drug delivery through their ability to form self-assembled nanostructures and also displaying cooperativity between cyclodextrin polymers and DNA. This has been exploited in the transfection of siRNA in gene splicing.[9]

Concerning carbohydrates as feedstocks, advancements in the field of enzymology and chemistry have led to the introduction of new technologies to better valorise biomass waste. For example, researchers have exploited the abundance of lignocellulosic material to produce high-value speciality chemicals and polymers. Polysaccharides obtained from softwood have been modified using an array of glycoenzymes to produce polymers with the preferred properties[10] or shorter chain oligosaccharides for use in bio-surfactants.[11]

While there have been tremendous achievements and developments in this area over the years, the field is at a point that it requires innovation and cross-sector collaboration to develop new biorenewable materials that are competitive in terms of price to fossil-based products with similar properties to conventional plastics. Simulating properties similar to current fossil-based material is extremely difficult and is a major technical challenge in the food packaging industry. The films are not suitable to efficiently prevent moisture from crossing the barrier. While they do exhibit favourable tensile strength and elasticity, the poor moisture barrier and dimensional stability are currently impeding its use. New technologies in particular computational modelling are required to simulate these properties and to help guide the development of new hybrid materials.

New Materials for Tissue Engineering and Repair.

Tissue engineering and regenerative medicine is a rapidly evolving area in healthcare with a projected global market outlook of $16.82 billion by 2023.[12] Recent medical advancements, government initiatives and increased R&D funding have helped the market mature and are the key factors for growth. As a multi-disciplinary field, it also brings with it a set of challenges across both academia and industry. With a high demand for biomimetic scaffold materials, additional investments are required to keep up with developments in this field. These new materials need to be mechanically strong yet also flexible as well as providing optimal biological environments to guide the maturation and integration of cells toward tissue formation. Currently many applications use synthetic polymers, yet naturally derived materials such as those based on polysaccharides offer the advantages of biocompatibility and biodegradability whilst also allowing a suitable medium for cellular adherence and infiltration. At present, carbohydrate polymers lack the processing abilities of synthetic polymers and this has largely hindered their application in biomedical science.

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[6] LTG ULM GMBH, Bistable ChLCD displays press release: https://www.bmgmis.de/en/products/bistable-chlcd-displays/

[7] Revolutionary Technology: Vegetables used for high-performance materials, Cellucomp: https://www.cellucomp.com/products/curran

[8] Buschmann, H-J. and Schollmeyer, Eckhard. *J. Cosmetic. Sci.* **2002**, 53, 185-191.

[9] Sollogoub et. al. *Angew. Chem. Int. Ed.*, **2018**, 57, 7753-7758.

[10] Rosengren, A.; Butler, S. J.; Hernandez-Arcos, M.; Bergquist, K-E.; Jannasch, P.; Stalbrand, H. *Green. Chem*. **2019**, 21, 2104-2118.

[11] Stallbrand et. al. *Appl. Microbiol. Biotechnol*. **2018**, 102, 5149-5163.

[12] "Tissue Engineering - Global Market Outlook 2017-2023", Research and Markets, 2017: https://www.researchandmarkets.com/reports/4449999/tissue-engineering-global-market-outlook-2017

3D printing technology has gained significant interest due to its ability and versatility to create objects of virtually any shape. When applied to printable polymer materials that incorporate viable living cells (called bio-inks), the polymeric scaffold can also provide an organized cellular microenvironment for cells to thrive. Alginate, a polysaccharide composed of mannuronic and glucuronic acid, has proved to be a suitable candidate as a bio-ink due to its efficient gelation properties under mild conditions. The biopolymer has a global annual production of 30,000 tonnes and is typically used as a food additive or in drug formulations. Calcium-alginate gels are well suited to cell immobilization and show enormous potential in the design of an artificial pancreas using alginate biopolymers as a biocompatible matrix.[13]This requires optimizing the capsule to provide mechanical strength, elasticity and porosity by tailoring the chain length and the ratio of glucuronic and manuronic acid of the polymer. For example, high glucuronic acid produces brittle gels with good thermostability while high mannuronic acid content displays elastic properties.[14] Optimization of these properties requires the accurate analysis of the polysaccharide backbone alongside simulation studies of polymer folding and cooperativity between strands and metal ions.

Polysaccharides belonging to the glycosaminoglycan (GAG) family are major components of the extracellular matrix as well as many types of soft tissues and these are potential candidates for use as bio-inks. Despite their enormous potential in 3D bioprinting and in tissue regeneration, they remain largely unexploited. Research on customizable GAG biomaterials exhibiting fast crosslinking properties is an essential prerequisite toward advancing 3D printing applications in tissue engineering. Such biomaterials are also of primary interest for cell-based therapy where the key challenge is to enhance stem cell engraftment by providing a favourable environment for a successful transplant. In addition, these biomaterials have a major role to play in the emerging field of 4D bioprinting,[15] which is the printing of artificial tissues capable of undergoing structural and/or functional changes upon external stimulation. In addition, glycoconjugated supramolecular gels are being explored for biomedical application such as wound dressing. For example, chitosan hydrogels have shown excellent wound recovery on animal models with no pathological abnormalities and with increased thickness in the epithelial layer.[16] Production of next-generation smart materials requires a combined effort from multiple disciplines including engineering, medicine and computer science. Integrating big data and AI in future research collaborations and industrial R&D will be a vital step to developing tools to predict sequence-structure-function of new materials and its interaction with living systems.

Glycomaterials in the Food Industry

The last century has seen the food industry mature into a hugely successful market with global revenues expected to reach $9.4 trillion by 2022.[17] Advancements in food technology can be related to the development and transfer of knowledge from chemistry and engineering – a multidisciplinary approach adopted very early in the development of the food industry. Carbohydrates play a crucial role in food processing, particularly in the development of new ingredients that provides superior mouthfeel - a physical sensation distinct from a taste but which is fundamental to the overall taste and feel of the food. Their roles include acting as gelling agents, emulsion stabilizers, and in controlling the rheological properties of the overall product. They are central to the formulation of food which creates and maintains a stable microstructure made up of a complex mixture of polysaccharides, protein assemblies, crystals and starch granules to give a specific texture to food.[18]

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[13] Pareta, R. A.; Farney, A. C.; Opara E. C. Pathobiology, **2013**, 80, 194-202.

[14] Donati, I.; Holtan, S.; Morch, Y. A.; Borgogna, M.; Dentini, M. Biomacromolecules, **2005**, 6, 1031-1040.

[15] Gao, B.; Yang, Q.; Zhao, X.; Ma, Y.; Xu, F. *Trend Biotechnol*. **2016**, 34, 746-756.

[16] Liu, H.; Wang, C.; Li, C.; Qin, Y.; Wang, Z.; Yang, F.; Li, Z.; Wang, J. *RSC Adv.,* **2018**, 8, 7533.

[17] "Food And Beverages Global Market Report 2019", The Busines Research Company 2019: https://www.thebusinessresearchcompany.com/report/food-and-beverages-global-market-report

[18] Aguilera, J. M. *J. Food. Eng*. **2005**, 67 , 3-11.

[19] "Expectations to be met for application of maltotriosyl transferase to food processing" Amano Enzymes, company report.

For example, hardening of bread or cooked rice is ascribed to the fundamental changes in the microstructure of the polysaccharide network and is specifically due to the retrogradation of starch. However, this process can be minimized by introducing or converting linear amylose polymers to highly branched amylopectin polysaccharides in the trans-glycosidation of triose units using maltotriosyl transferase.[19]

The development and discovery of new food ingredients is a challenging prospect and requires a multidisciplinary approach to develop new formulations. Perhaps the greatest challenge is developing polymers with a similar taste profile and texture properties as the replacements, in for example their physical properties (i.e., as bulking agents, stabilizers and structurants. This requires designing new analytical techniques including carbohydrate sequencing to enable the development of novel platforms to predict structure-function-property relationships. This also requires cross-collaboration with computer scientists and infrastructure investment to develop next-generation AI computing and machine learning capabilities.

Textiles

A textile is a material comprising a vast network of intertwined synthetic or natural fibres. The environmental impact of textiles and clothing is extremely difficult to quantify due to the diversity of the market and its global consumer base. However, a recent report by Global Fashion Agenda estimated a footprint of 4-6% in Europe after housing, mobility and food and beverage. This is a result of the energy expenditure in material resourcing and chemical production of fibres and to end of life treatment.[20] For example, harvesting cotton for clothing requires a huge amount of water (approximately 20,000 litres), land, fertilisers and pesticides.[21] Currently, the other option is the use of synthetic polyesters obtained from fossil fuel with a significantly lower carbon footprint than natural fibres such as cotton. However, the non-biodegradable nature of polyester clothing poses significant environmental issues in the long-term. A study conducted in 2017 highlighted the impact of microplastic beads from polyester clothing releasing up to 700,000 microbeads per wash.[22] To minimise the environmental impact, the textile industry is evolving to address some of these challenges through investments in key enabling technologies and circular business models. Due to the diverse market of the textile industry, it becomes increasingly difficult to design new fibres with the appropriate technical performance and functional properties for multiple or specific applications. To address these challenges, an interdisciplinary approach is required bringing together advances from chemistry, biology, engineering, mathematics and computer science.

The 1980s saw the trend towards "inter-textualization", i.e the widespread use of chemical and natural fibres in all sectors of textile production. As a result, the partitioning that previously existed between different branches of the textile industry seemingly disappeared and the widespread use of the same raw material was common for many products. The importance of cross-sector collaboration has been realised in recent years and many new products have emerged from a collaboration between different disciplines. For example, Singtex's functional fabric is derived from the waste coffee ground, creating a new cross-sector supply chain to minimise waste and maximise value creation. The next decade will see very similar innovation with the production of next-generation functional fabrics with minimal environmental impact. To achieves this, four areas have been highlighted which require further investment and integration in the R&D workflow. These are:

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[20] "A call to action for a circular fashion system" Policy Brief, 2017: https://www.globalfashionagenda.com/wp-content/uploads/2017/04/GFA17_Call-to-action_Poluc-brief_FINAL_9May.pdf

[21] "Cleaner, greener cotton - Impacts and better management practices" World Wildlife Fund, Report 2013: https://www.worldwildlife.org/publications/cleaner-greener-cotton-impacts-and-better-management-practices

[22] Ziajahromi, S.; Kumar, A.; Neale, P. A.; Leusch, F. D. Environ. Sci. Technol., **2017**, 51, 22, 13397-13406.

- The production of new materials using chemistry and biotechnology – synthetic, cellulosic and other natural and non-natural carbohydrate-based fibres.
- The use of physics and mechanics to study the properties of fibres.
- The development of machine learning/artificial intelligence approaches to predict materials properties from component molecular structures.
- Integrating mathematics and computer science to predict and simulate material function including molecular interlacing.
- Using biology to imitate or genetically optimize production and yield of natural fibres.

Carbohydrates will play a vital role among the next generation of natural and synthetic textile products. The diversity and abundance of polysaccharides in natural biomass will accelerate development in this area to access new fibres with superior properties in texture and strength, with sustainable sourcing and manufacturing a key driver for consumers and the environment. For example, the TENCEL^{TM} and the ECOVERA^{TM} brand from Lenzing are produced from renewable wood pulp with 50% lower carbon emission and water consumption compared to generic fibres.[23] Advances in nanotechnology and in particular the production and manipulation of cellulose nanofibers (CNF) will have a profound effect on the textile industry. The lightweight properties, electrical conductivity and optical properties (vide supra) of CNFs make them attractive in the development of smart fabrics. For example, textiles in the near future may have certain properties such as self-cleaning (lotus effect), flame retardant and UV blocking. Composite CNFs with silver nanoparticles (a common antimicrobial agent used in cosmetics)[24] can provide clothing for hospital and care home use, significantly reducing bacterial infection to vulnerable patients and controlling infection rates. In addition, new research on the characterization and preparation of chitosan nano-crystals and nano-fibres are being explored. Applications include antistatic and antimicrobial properties (due to the charged amino groups) including hydrophobicity for stain-resistant material.[25] The non-toxicity of cellulose and chitin nanomaterials and the uniqueness of their structure and properties (a feature that that is difficult to achieve synthetically) make them attractive for the production of smart and responsive textile fibres with minimal environmental impact.

This introduces the integration of biotechnology in the field of textiles, and this close collaboration with other materials is a source of innovative projects. In biomedicine, textiles lend themselves to tissue engineering, wound healing applications and implants. Biologists and engineers work closely to develop 3D resorbable fibrous biomaterials adaptable to the physiology of the patient. Traditional textile techniques such as knitting, weaving and braiding are used with such synthetic durable PEEK fibres having high tensile strength. Textile engineers can measure the flexibility of the fabric according to the desired therapeutic goal. Each geometric structure confers mechanical and physical properties, making it possible to obtain a more porous material or, on the contrary, a barrier effect. The polymers, the metals and the filaments of biological material can constitute a composite textile structure corresponding exactly to the desired characteristics and in accordance with the biological treatment.

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[23] Lenzing press release: https://www.ecovero.com

[24] Kokura, S.; Handa, O.; Takagi, T.; Ishikawa, T.; Naito, Y.; Yoshikawa, T. Nanomedicine: NBM, 2010, 6, 570-574.

[25] Jagadish, R.; Fabien, S.; Stephane, G.; Ada, F.; Jinping, G. Chitosan-Based Sustainable Textile Technology: Process, Mechanism, Innovation and Safety, chapter 12, 2017.

New R&D Platform using Digital Technology and an Interdisciplinary Approach

Carbohydrate based biomaterials have slowly emerged as a leading contender to help reduce the dependence on fossil fuel-derived plastics. Sugar-based polymers are highly tunable and by carefully selecting the renewable feedstock and introducing the appropriate downstream processing, new materials with diverse and unique properties can be obtained.

The vision is to integrate new technologies and cognitive processing capabilities in the three enabling technologies, measurements and analytical, synthesis of standards and bioinformatics and database to accelerate discovery and development of novel materials. Integrating a design-build-test cycle in the R&D programme will expedite this process. A crucial feature of this R&D framework is the measurement and analytics platform, which at its current level is not sufficient to drive the innovation required to design and build new materials. This requires a multidisciplinary approach by drawing experience from other sectors with more extensive experience in AI and building cross-sectoral teams to jointly develop new techniques and analytical capabilities to address this challenge. The resulting database will be used to design and build new fragments and using a machine learning approach to be able to predict properties from changes introduced in the polysaccharide sequence. This R&D workflow should be accompanied by automated oligosaccharide synthesis platforms and/or methods to efficiently modify existing polysaccharide backbones obtained at scale from biomass. Design and engineering of these bespoke new materials from nature requires a collaborative effort from multiple disciplines. Chemists and biologists are required to construct and modify the polymer backbone using either chemical or biotechnological approaches. Material scientists play a crucial role in the structural assessment and testing of the material for different applications. Computational scientists and software engineers design and build predictive tools with cognitive processing capabilities to expedite the discovery of new materials. By combining disciplines and skills, the whole will truly generate more than the sum of the parts.

Future Impact on Society and the Environment

Any assessment of the future impact of glycomaterials within the European economy and society needs to be set in the context of current European policy. The key policy issue here was presented to the European Parliament and Council early in 2012[26] in which a major effort was proposed to grow a bioeconomy in Europe. It was recognised that a future sustainable Europe should greatly enhance the share of the economy that is built on biobased, renewable resources as opposed to one that is still primarily fossil-based. This Declaration influenced strongly both the following FP7 and Horizon 2020 Research and Innovation priorities and a continuing and growing emphasis on the Bioeconomy is reflected even more strongly in the putative funding plans for Horizon Europe (2021-2017), especially in its five current Missions.

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[26] "Innovation for Sustainable Growth: A Bioeconomy for Europe": https://ec.europa.eu/research/bioeconomy/pdf/official-strategy_en.pdf

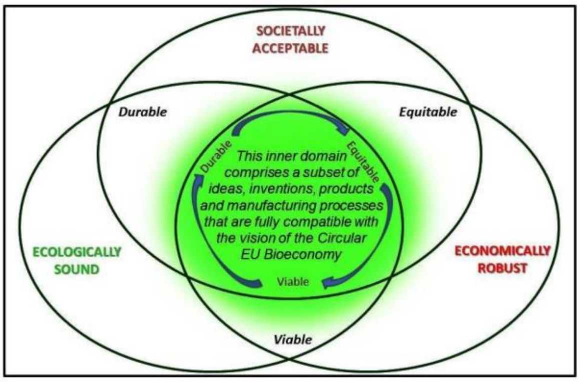

Figure 2. A Venn diagram to show the relationship between the three pillars of sustainability; Social, Environmental and economics.

At the core of this Bioeconomy initiative is the recognition that a robust sustainable future must satisfy substantially three different criteria, namely that new processes, products and systems must simultaneously be environmentally sound, societally acceptable and economically robust (see accompanying figure). Attaining this for any project is a very demanding primary objective, as recognised in a European Parliament Briefing Paper, which reviewed critically progress over the first five years and noted areas of potential conflict, particularly in terms of competing calls on resources.[27] Novel solutions for a sustainable future must take comprehensive overviews of resources, competition for those resources, be attractive to all strata of society, be part of circular (recycling) economy and environmentally friendly. In short, this requires a systemic approach coupled with positive regulation and appropriate financial incentives to ensure positive, life-enhancing changes in common practice.

There can be no doubt whatsoever that for the successful growth of such a European Bioeconomy, glycan science and technology will play a crucial role and indeed does so already. Carbohydrate-based materials, in particular, are of course ubiquitous and abundant on earth, yet many familiar ones (for example cellulose and starch) may not compete well in performance terms as do commercially available synthetic polymers, based on fossil-based feedstocks. These matters are elaborated further in the introductory parts of this paper, where a compelling case is made for the funding of substantially more glycoscience research coupled with the development of innovative glyco-engineering technologies. Undoubtedly, such support will make a major contribution to the attainment of a truly sustainable European Bioeconomy.

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[27] “Bioeconomy: Challenges and Oppportunities”, European Parliament Briefing Paper, January 2017: http://www.europarl.europa.eu/RegData/etudes/BRIE/2017/595890/EPRS_BRI(2017)595890_EN.pdf