Carbohydrate as Sustainable Materials for the Future

CarboMet

Relevance and Problem

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. Exploitation of this waste is crucial in reducing the dependence on fossil-based products and creating a circular bioeconomy. The investment and funding made in the next 5-10 years will profoundly affect the European bioeconomy in the future. Harnessing waste biomass as a feedstock source will create new supply chains across the continent impacting both growth and development in EU member states.

Challenges and Opportunities

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. This relationship is a prerequisite to developing a new generation of sustainable biomaterials that can address global challenges in packaging, healthcare, agriculture and personal hygiene. We envisage a future where digitization is integrated into the R&D workflow and manufacturing processes, with machine-based learning approaches being used to guide the design of new materials. This will be a powerful predictive tool for the European chemical industry and underpinning this are the CarboMet initiatives on developing robust and appropriate measurement and analytical tools, as well as new metrological procedures and ISO-standards. We identified 4 key industry areas where carbohydrate materials will play a crucial role, these are packaging, films and displays, healthcare and prosthetics, food and beverage and textiles. Key areas were highlighted as priority research to accelerate the development and commercialization of next-generation biomaterials.

- **Develop new processing capabilities for carbohydrate based polymers.**
- **Increase production capacity of biodegradable raw materials.**
- **Modification of natural biopolymers using enzymes.**
- **Development of machine learning and predictive algorithms to determine structure-function-property relationship.**
- **Industry - academic networks for collaboration.**

Biomaterials applications

Biodegradable films for food packaging are being produced from wood and forestry residues.[1] In addition cellulose nanofibers are being used in next-generation display systems.[2]

Carbohydrate polymers are being used in bio-inks. These are polymeric material housing viable cells and are being used in tissue regeneration.[3]

References

1. Futamura cellulose films division: http://www.futamuragroup.com/divisions/cellulose-films/products/cellophane/
2. LTG ULM GMBH, Bistable ChLCD displays press release: https://www.bmgmis.de/en/products/bistable-chlcd-displays/
3. Gao, B.; Yang, Q.; Zhao, X.; Ma, Y.; Xu, F. Trend Biotechnol. 2016, 34, 746-756.

Acknowledgements: CarboMet would like to thank Kompuestos and Futamura for the valuable feedback.

CarboMet is a four-year Collaborative Support Action ['CSA'] funded by the EC Horizon 2020 Future and Emerging Technologies initiative

E-mail: projectmanager@carbomet.eu
Website: carbomet.eu
Twitter: @CarboMet_EU

CarboMet

Carbohydrate as Sustainable Materials for the Future

European Commission

Metrology of Carbohydrates for Enabling European Bioindustries

A horizon 2020 coordination and support action (CSA) 2017-2021 funded by the European Commission under FET-OPEN

Background

CarboMet is a four-year Collaborative Support Action ['CSA'] funded by the EC Horizon 2020 Future and Emerging Technologies initiative. The primary aim of the CSA is to mobilise the European academic and industrial community to identify measurement, data management and metrological challenges that need to be addressed in order to advance and exploit carbohydrate knowledge and applications. Carbohydrates constitute the largest source of biomass on earth and their exploitation in the application of sustainable materials is crucial in reducing the dependence on fossil-based products and creating a circular bioeconomy. Therefore as a first stage CarboMet has organised some open, Europe-wide workshops to identify key topics where our understanding needs to be advanced urgently, and where current limitations in our measurement, data management and metrological capabilities are hindering progress. Workshop participants were asked to recommend appropriate work programmes and key research priority areas that should be supported by Horizon 2020 and its successor, Horizon Europe. One of these workshops addressed the topic of carbohydrates as sustainable materials of the future. This paper reports on the technological challenges that were identified at this workshop and lists a set of recommended areas as high priority research across four different industries where sustainable materials is likely to have a major impact in the future.

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. 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 wider European bioeconomy.

Introduction

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 been 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.

Societal and Environmental Impact

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[1] 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. 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. 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 is common practice.

Challenges

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 (TRL 1 and 2) 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. 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. 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.

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. 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.

Key Industries and Priority Research Area

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. We identified 4 key industry areas where carbohydrate materials will play a crucial role, these are packaging, films and displays, healthcare and prosthetics, food and beverage and textiles.

Packaging, Films and Next-Generation Displays

Agricultural waste has been seen as a major source of valuable feedstocks for carbohydrate based materials. Several research programs and industrial investment has been dedicated to biomass valorization for speciality chemical production. The lack of commercial products coming form these processes has been insufficient for the global bio-polymer market. However, a number of products have been successfully commercialized such as Futamura’s NatureFlex™ and CELLOPHANE™ biodegradable films for use in food packaging[2] or Cellucomps CURRAN® (cellulose nanofibers) used as additives in paints and coatings.[3] While there have been tremendous achievements and developments in this area over the years, the field still requires further exploration to develop materials with substantially better properties than fossil-based polymers. The priority areas highlighted are:

- **Use of enzymes to modify existing carbohydrate polymers for further functionalization.**
- **Improve the dimensional stability of biodegradable films for food packaging.**
- **Application of cellulose nanocrystals in displays.**
- **Develop modelling tools to predict structure-function relationships.**
- **New legislation to enable collection and recycling of compostable materials.**
- **Increase in academic-industry networks for collaboration and knowledge transfer.**

Glossary

Biodegradable: A material capable of being broken down by the actions of microorganisms.

Dimensional stability: The ability of a material to maintain its original shape and while being used for its intended purpose. Biodegradable films for food packaging currently lack this property which makes food preservation difficult.

Prosthetics and Regenerative Medicine

Tissue engineering and regenerative medicine is a rapidly evolving area in healthcare with a projected global market outlook of $16.82 billion by 2023.[4] 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. Carbohydrate polymers also lack the processing abilities of synthetic polymers and this has largely hindered their application in biomedical science. For example, 3D printing technology can be used in a clinical setting to provide bio-compatible and biodegradable scaffolds for cells providing immense value in regenerative medicine. To achieve this, further developments are required in the following areas:

- **Improving processing capabilities of carbohydrate based polymers to obtain the desirable microstructures, properties and shape of the finished product.**
- **Smart biomaterials which can undergo structural and/or functional changes upon external stimulation. These materials can be used in 4D bioprinting, an emerging technology that can print artificial tissues.**[5]

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.[6] 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.[7] New areas of interest are:

- **Discovery and development of glycomaterials with similar tastes and texture properties as the replacements, in for example their physical properties (i.e., as bulking agents, stabilizers and structurants).**
- **New analytical techniques including carbohydrate sequencing to enable the development of novel platforms to predict structure-function-property relationships.**

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.[8] For example, harvesting cotton for clothing requires a huge amount of water (approximately 20,000 litres), land, fertilisers and pesticides.[9] 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.[10] 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.

- **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.**

Conclusions

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 that will significantly boost the European bioeconomy.

References

1. “Innovation for Sustainable Growth: A Bioeconomy for Europe”: https://ec.europa.eu/research/bioeconomy/pdf/official-strategy_en.pdf
2. Futamura cellulose films division: http://www.futamuragroup.com/divisions/cellulose-films/products/cellophane/
3. Revolutionary Technology: Vegetables used for high-performance materials, Cellucomp: https://www.cellucomp.com/products/curran
4. “Tissue Engineering - Global Market Outlook 2017-2023”, Research and Markets, 2017: https://www.researchandmarkets.com/reports/4449999/tissue-engineering-global-market-outlook-2017
5. Gao, B.; Yang, Q.; Zhao, X.; Ma, Y.; Xu, F. Trend Biotechnol. 2016, 34, 746-756.
6. “Food And Beverages Global Market Report 2019”, The Busines Research Company 2019: https://www.thebusinessresearchcompany.com/report/food-and-beverages-global-market-report
7. Aguilera, J. M. J. Food. Eng. 2005, 67 , 3-11.
8. “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
9. “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
10. Ziajahromi, S.; Kumar, A.; Neale, P. A.; Leusch, F. D. Environ. Sci. Technol., 2017, 51, 22, 13397-13406.