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Mini Review

Materials Science, Circularity and Sustainability: The need for Fundamental Change in Materials Science Research.

Michael A Morris*

Department of AMBER and the School of Chemistry, Trinity College Dublin, Ireland

***Corresponding author:** Michael A Morris, Department of AMBER and the School of Chemistry, Trinity College Dublin, Ireland.

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Abstract

The world is facing an unprecedented and worsening climate crisis. Global emissions of carbon dioxide and other greenhouse gases have led to rising temperatures and more intense weather events. The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report suggests that the agreed global temperature limit of warming to 1.5 ^{0}C is more than 50% chance likely to be exceeded before 2040 [1]. A survey this year of IPCC scientists suggests that a global temperature increase is likely to be above 2.5 ^{0}C. The need for urgent action is clear. However, progress towards a net-zero emissions target by the middle of the century is slow. The UN finds that there is insufficient progress across 168 nations towards meeting the agreed 2050 targets [2]. Materials science will play an important role in meeting climate change targets by providing sustainable and circular materials, new recycling and recovery methods and improving technologies that enable longer product use lives and products that support multi-use life cycles. A new focus for research is needed in these and other areas.

Introduction

Whilst many reports and authors point towards the combustion of fossil fuels as the greatest source of anthropogenic emissions and indeed this is true, fuel emissions continue to rise [3]. However, products and the materials being used in their manufacture plays a major role in the sources of those emissions. Recent data by the carbon majors group shows that 57 companies are responsible for 80% of all emissions [4]. Much of modern emissions and the climate problem are linked to the age of mass production and mass consumerism following the industrial revolution [5]. It is clear that materials science must play an increasing role in developing the technologies and products we use that are consistent with climate and wider environmental goals.

The first need is for materials to be more circular and consistent with the need for a transition to a circular economy. Raw materials are being used at an ever-increasing rate placing increasing demands on the environment and climate [6]. However, there is not universal or comprehensive understanding of the concept of circularity amongst materials scientists. Often the view of materials scientists is that if something is recyclable it is circular. This separates the key issues of the practicality of recycling (the process, energy and resources used, side-products etc. as well as issues such as collection and cleaning) and whether this lowers the environmental footprint as well as how many cycles can be carried out without material degradation and end of life. Thus, the term recyclability is often misleadingly used and instead terms such as amount recycled are quantitative and therefore preferred. Circularity focuses on different concepts such as slowing and closing the loop and a hierarchy of practical strategies such as (a non-inclusive list):

- Extending the life-time of materials and products made therefrom (slowing the loop)
- Refurbishment to an improved condition (slowing the loop)
- Reuse i.e. design for reuse in the same or a new application (slowing the loop)
- Recycle, as distinct from repair and refurbishment, ideally closing the loop (permanent recycling) but more often slowing the loop
- Use of renewable materials such as biomasses resources that are regeneratively grown (closing the loop if processing is energy and resource efficient)
- Recovery, diverting materials from waste towards new uses (closing or slowing the loop).
- Product sharing or product as a service strategies (slowing the loop).

Whilst circularity is conceptually simple, as indicated by slogans such as reduce, reuse, recycle, achieving as high a circularity as possible and by what strategy can be complex requiring, research, planning, capital investment and monitoring, not only within an organization but across value chains. Recent ISO standards (ISO 59004 and ISO 59020) provide a framework for understanding and applying those strategies. Materials science plays a critical role in the innovation, development, commercialization and application of circular materials, processes and the products from which they are made-up. It is imperative that materials science and materials science research shifts perspective from how we might recover or recycle waste and used materials/products to how do we avoid waste in the first place. It is no longer sufficient to assume that future generations will be able to recover materials from waste using new technologies or technologies that become more economically viable. It should also be emphasised that more circular, less impactful material processing methods are often less well considered but need careful consideration particularly where those processes are energy and resource intensive.

A further question is raised in developing circular materials, processes and products; how do we compare the most effective and impactful strategies? Calculation of circularity can in itself be complex and multifaceted needing quantifiable materials and resource inventories. The use of a single indicator, i.e. this material is 50% circular, once a popular approach is being replaced by a 'dashboard' of indicators e.g. % renewable resource, amount of material actually recycled, product or materials durability, formation of toxic byproducts etc. The ISO circularity standard ISO 59020 provides detailed guidance on how circularity should be expressed and reported. However, clear guidance and standards on the measurement of bio-circularity for biomass derived sustainable/renewable materials is much less well developed [8]. To support circularity measurements and estimates, the environmental impacts such as climate, ecological and biodiversity need to be carefully considered. Life cycle assessment (LCA) and life cycle costing (LCC) are core tools which must also be considered. However, LCA can be challenging and prone to error. The use cycle(s) of the materials and their processing require careful and quantifiable documentation. Datasets needed for calculation of carbon footprint, toxicology and other environmental impacts are often incomplete (especially for complex materials and processes [7]) and require 'estimation', data needs careful verification and traceability as well as the need to account for second and further use cycles. It is a truism that many current LCAs for materials are not reliable.

Clearly, in materials science there is a need for all practitioners across a materials value chain to understand how circularity and sustainability can be achieved and measured and the information shared. That value chain should not be related to product manufacturers, suppliers and users but also to researchers who develop the materials and designers who select appropriate materials. This will require changes in education and training across practitioners.

Of course, materials science plays a critical role in the development of the materials required for the technologies that will underpin the transition to a net-zero economy. Without being prescriptive or inclusive some of the more important needs are:

- Technologies that reduce the use of fossil fuels in manufacturing and processing. The plastic industry has an over-reliance on these carbon intensive resources and advances in recycling, the use of biopolymers and replacement by renewable materials are urgently required.
- Technologies involved in renewable energy including solar energy generation, recyclable wind turbine blades, more efficient heat recovery and waste heat recovery systems etc.
- The urgent need for energy storage materials (supercapacitors etc.) particularly towards efficient grid energy storage (that maximises efficiency of renewable energy generation), avoidance of critical raw materials (lithium and cobalt for example), recycling of battery materials, extended battery durability amongst others.
- More efficient information and communication technology with an emphasis on low power use, lower resource intensity in device fabrication and manufacture, more readily recycled or reused materials, more efficient cooling of devices and e.g. data centres using thermal nanofluids to assist heat transfer, etc.
- Lower carbon footprint construction materials and technologies. Whilst cement and iron are widely recognized as important contributors to climate change, all current construction materials, methods and processes require more intensive research.

- The materials associated with emerging carbon capture technologies especially smart adsorbent materials that are highly selective to CO_2 and can be sourced, prepared and used with low carbon footprints.

The quest for sustainable technologies meeting ecological and environmental targets requires an increased effort in materials science. It also places new demands of practitioners in terms of greater experience and use of methods to measure and predict sustainability. More importantly it will demand a new perspective where scientists target not only technological advances but that those technologies allow future generations to live in an environment improved from the present date. It is a daunting challenge but one we must rise to.

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Conflict of Interest

None.

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