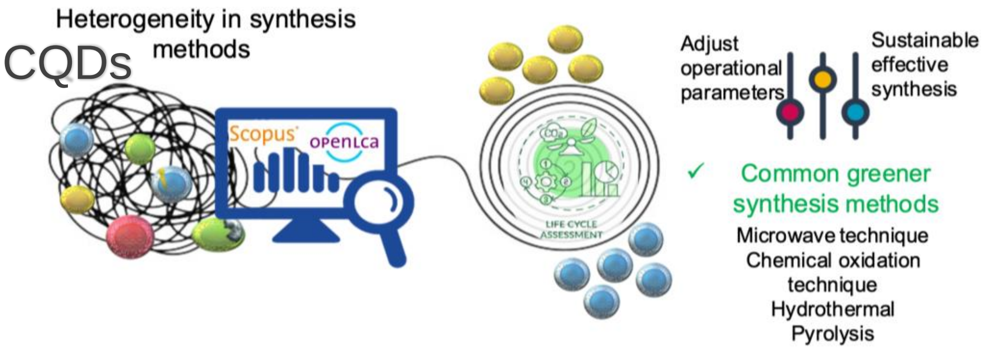
Guidelines of Green Carbon Quantum Dots Synthesis through Life Cycle Assessment

Valentina Arias[1], Dachamir Hotza[1] and Sergio Yesid Gómez Gónzalez[1*]

[1] *Chemical Engineering/CTC/Department of Food and Chemical Engineering/ Federal University of Santa Catarina, Florianópolis, Brazil.*
** Corresponding author's email address: sergio.gomez@ufsc.br*

ABSTRACT

The drive for sustainability can be advanced by adopting novel technologies promoting circularity, waste management, and efficient energy use. Carbon Quantum Dots (CQDs) hold promise for applications in several biotechnologies related to bioimaging, biosensing, waste treatment, generation of renewable energy, and detection and degradation of pollutants. Although perceived as a green nanomaterial due to the potential use of biomass as a carbon precursor, the actual environmental impact of CQD production remains uncertain. This study evaluates the sustainability of common CQD synthesis methods using Life Cycle Analysis (LCA). Synthesis methods identified from Scopus database reports were assessed using Open LCA software, with data from Ecoinvent® 3.7 and the ReCiPe 2016 endpoint method. The most sustainable method was microwave synthesis, followed by chemical oxidation, while pyrolysis and hydrothermal methods were less sustainable. Using biomass waste as a carbon source proved more sustainable than chemical reactants despite potential challenges in storage and stability. The study concludes that optimizing synthesis methods and using waste biomass can significantly reduce the environmental impact of CQD production.



Keywords: Biomass, green chemistry, nanomaterial, environmental impact, environmental assessment.

1 INTRODUCTION

Sustainability can be achieved by implementing novel technologies for circularity, waste management, and efficient energy use. Nevertheless, these technologies must undergo environmental assessments like Life Cycle Analysis (LCA) to prove their viability and find opportunities to reduce the negative environmental impacts. Carbon Quantum dots (CQDs) are an example of a novelty in nanotechnology, which stands out among other nanomaterials for their optical and fluorescence properties, biocompatibility (low toxicity and good biodegradability), electronic structure, chemical stability, and versatile chemistry (easily functionalized with various chemical groups). These features make CQDs excellent candidates for biotechnological applications such as bioimaging, biosensing, drug delivery, water treatment, renewable energy production, antimicrobial activity, and detection and degradation of pollutants[1]. The synthesis procedures of CQDs are highly varied and offer the option to use biomass (like organic waste from the agricultural and food industries) as a carbon precursor, making CQDs perceived as a "green nanomaterial" [2]. Nevertheless, few studies have focused on the actual environmental impact that can be caused by CQD production, causing uncertainty on how green CQDs are. Establishing clarity on this issue is essential because using a biological agent in synthesizing nanomaterials does not necessarily denote low environmental impact[3]. This study aims to assess the sustainability of CQD common synthesis methods by performing a LCA.

2 MATERIAL & METHODS

The most common green synthesis methods and parameters for CQD production were identified according to research reports found in the Scopus Database. The synthesis parameters found with the statistical mode were selected as the base for the scope and system boundaries of the cradle-to-gate LCA. The OpenLCA software was used considering the laboratory scale and 1 g of CQDs produced in Florianópolis, Brazil. The database used for the life cycle inventory was Ecoinvent® 3.7, and the impact assessment was done using ReCiPe 2016 endpoint method H (Hierarchist version). Additionally, two scenarios concerning the origin of the carbon source were evaluated, using a chemical reactant and a residual biomass for the synthesis.

3 RESULTS & DISCUSSION

The most common synthesis methods reported for CQD obtention were chemical oxidation, hydrothermal treatment, microwave, and pyrolysis. The methods present variability in the operation parameters, and no standard processes exist. Comparing the different techniques, the more sustainable option is microwave synthesis, followed by the chemical oxidation process. Lastly, pyrolysis and hydrothermal methods are less sustainable. The specific environmental categories on the overall environmental performance of evaluated CQD synthesis were Global warming, Toxicity Potential, Human Non-Carcinogenic Toxicity, and Water Consumption. Remarkably, the GW for the microwave method represents a generation of 10.1 kg CO_2 eq, the chemical oxidation of 11 kg CO_2 eq, the pyrolysis of 12 kg CO_2 eq, and the hydrothermal of 16 kg CO_2 eq.

In the scenario analysis, biomass waste was demonstrated to be the more sustainable option. Nevertheless, it can present disadvantages in the manufacturing processes related to storage and stability that can be overcome by the drying process and still show a lower impact than using reagents like citric acid.

4 CONCLUSION

The more sustainable synthesis methods for CQDs synthesis were identified, finding that the microwave method reduces the environmental impacts generated, which cause greater affectations in terms of global warming, toxicity potential, human non-carcinogenic toxicity, and water consumption. Nevertheless, there is an opportunity to carry out methods like chemical oxidation, pyrolysis, and hydrothermal treatment by redefining operational parameters (reducing the reaction time). Using waste biomass in CQDs synthesis is essential for obtaining the nanomaterial with a low environmental cost that can be later used in several biotechnological applications.

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