

# Investigating the integration between life cycle thinking, green chemistry principles and sustainability policies

Daniela Camana<sup>1\*</sup>, Sara Toniolo<sup>1</sup>, and Alessandro Manzardo<sup>1</sup>

<sup>1</sup> CESQA, Department of Industrial Engineering, University of Padua, Via Marzolo 9, Padua, Italy

**Abstract.** Green chemistry and life cycle assessment are two methodologies used in environmental studies, both theoretically and practically. The purpose of this analysis was to assess whether and how green chemistry principles could be integrated into the life cycle assessment methodology and to local and international industrial policies to achieve sustainability goals at the territorial level. First, some contributions that life-cycle thinking gives to green chemistry and vice versa are proposed, based on existing research. Data are provided using tables to summarise contents and graphs to outline interconnections, also considering the four steps of life cycle assessment, showing some available references of previous studies. Secondly, some possible points of integration between the 12 principles of green chemistry and environmental policies are listed. For each principle of green chemistry, a possible integration with international and local strategies is proposed. A list of references that might be useful to investigate possible patterns of study for territorial and industrial uses, is provided too. The results show that life cycle thinking and green chemistry can be integrated into theoretical and practical case studies, since many interconnections exist. These interconnections permit one to use the best characteristics of each method to improve the reliability of the other method and, finally, to solve environmental, industrial, and engineering problems with a more comprehensive approach. In addition, green chemistry principles can be easily associated with main environmental policies at the international, national, regional, and local levels. This allows one to use results, knowledge, and expertise of the green chemistry framework and apply them to industries, territories, and communities. The similarities highlighted in this analysis need further investigation in future studies since they can help decision making process in sustainability policies.

## 1 Introduction

Sustainability, defined as the development that "meets the needs of the present without compromising the ability of future generations to meet their own needs", has become in the last years a reference point for industrial strategies at local, regional, and international levels<sup>1</sup>.

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\* Corresponding author: [daniela.camana@phd.unipd.it](mailto:daniela.camana@phd.unipd.it)

Many tools and approaches have been proposed to promote and measure sustainable development, both by policy makers and by the academy<sup>2</sup>. However, different approaches may lead to different priorities and results<sup>3</sup>. Thus, integration or a combination of different tools offers a wider perspective on the effects of policies. Green chemistry (GC), defined as the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances, and life cycle assessment (LCA), defined as the compilation and evaluation of the input, output, and the potential environmental impacts of a product system throughout its life cycle, are two leading methodologies in the approach to environmental sustainability and accounting<sup>4,5</sup>.

The purpose of the present analysis was to assess whether and how green chemistry principles might be integrated into LCA methodology and local and international industrial policies to evaluate best priorities and achieve sustainability goals at the territorial level.

## 2 Materials and method

This study was conducted by analyzing existing publications in two leading databases, Scopus and Web of Science<sup>6</sup> in September 2020. A literature review was performed, using keywords, as “green chemistry”, “life cycle assessment”, “LCA”, “life cycle thinking”, “LCT”, “policies”. Relevant publications sorted were grouped into areas and briefly examined.

The analysis consisted of two parts. First, some contributions that life cycle thinking (LCT) may give to green chemistry, and vice versa, were proposed. Second, some possible points of integration between green chemistry and policies were listed. Data, contents, and available references were summarized using tables and graphs. The information collected provides some suggestions for further systematic reviews and for future research agenda.

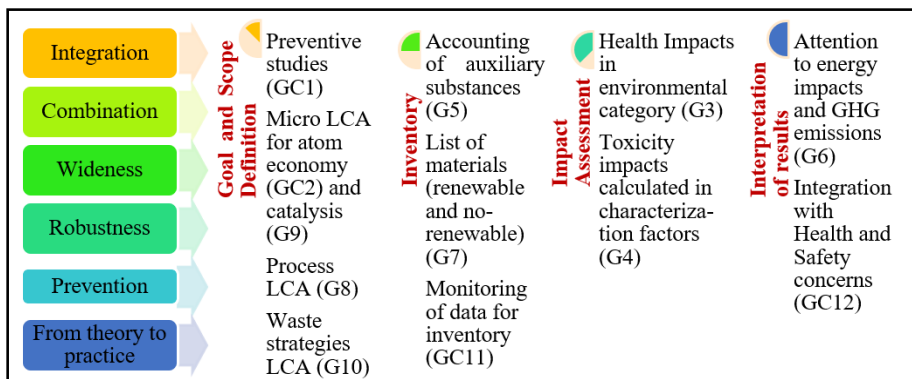
## 3 Integration between green chemistry and life cycle thinking

The results of the literature review confirm that LCA and Green Chemistry can be integrated, combined and used together in theoretical studies and practical policies<sup>7</sup>.

In fact, some key features are shared in the two methodologies: the scientific method, the comprehensiveness approach, the key role of prevention, the minimisation of waste, the optimisation of processes, the effort to achieve environmental gains and more sustainable development preserving technical characteristics of products, services, and organisations.

Figure 1 illustrates possible interconnections between the twelve green chemistry principles and the four phases of LCA defined by the ISO 14040 international standards. Each phase of LCA can be linked to many principles of Green Chemistry (GC).

In detail, novel system boundaries of LCA studies and original framework for interpreting results can be suggested by green chemistry approach. Moreover, data from green chemistry studies can be useful for populating inventory databases and impact assessment factors.



**Figure 1.** Common general features of approaches and possible interconnections between phases of LCA and Green Chemistry (GC) Principles

On the other hand, Table 1 shows that, for each principle of green chemistry, some LCA studies have been performed. Some principles dealing with waste management (Principle 1 and 10 for example) have been deeply investigated through many LCA studies. Other principles are less investigated through LCT (i.e. 5 and 8). Therefore, integration and a combination between LCA and green chemistry are possible and desirable and new fields of research and exploring challenging perspectives are open.

**Table 1.** Green chemistry principles and LCA methodology

Principle of Green Chemistry	LCA methodology
1. It is better to prevent waste than to clean up waste after it is formed	LCA for preventive studies <sup>8</sup>
2. Synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product (atom economy)	LCA used at micro-level → possibility of implementation of micro-LCA <sup>9 10</sup>
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment	Accounting of Human Health impact using impact assessment models and characterisation factors <sup>11</sup>
4. Chemical products should be designed to preserve efficacy of function while reducing toxicity	Accounting of toxicity to water, air and soil (impact assessment models and characterisation factors) <sup>12</sup>
5. The use of auxiliary substances (e.g. solvents, separating agents) should be made unnecessary wherever possible and innocuous when used	Calculation of impacts of auxiliary substances in a life cycle perspective <sup>13</sup>
6. Energy requirements should be recognized for their environmental and economic impacts and should be minimized	Material, energy flow, global warming potential accounting, energy use and other impact assessment categories such as ionizing radiation, cumulative energy demand etc. <sup>14</sup>
7. A raw material or feedstock should be renewable rather than depleting, wherever technically and economically practicable	Use of renewable and non-renewable sources with a LCT approach <sup>15</sup>
8. Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible	Life cycle perspective in processes application <sup>16</sup>

<b>Principle of Green Chemistry</b>	<b>LCA methodology</b>
9. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents	LCA for analysis of syntheses and chemical reactions <sup>17</sup>
10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products	Impact category of waste. LCA of overall waste management <sup>18</sup>
11. Analytical methodologies need to be further developed to allow for real-time, in-process monitoring, and control prior to the formation of hazardous substances	These methodologies allow the collection of inventory data <sup>19</sup>
12. Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions and fires	Integration with health and safety– need of integrating environmental aspects with safety ones <sup>20</sup>

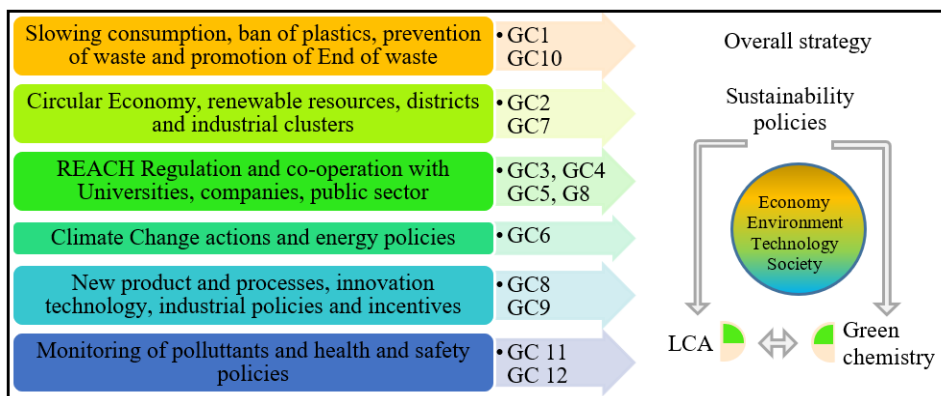
## 4 Green chemistry and policies in a life cycle perspective

Green chemistry and LCT appear useful in evaluating improvements in environmental policies and promoting more sustainable strategies. In Table 2, a possible integration between the twelve principles of green chemistry (GCP) and policies is proposed. A preliminary list of references (Ref.) that might be useful to investigate possible patterns of study is provided too.

**Table 2.** Possible integration between the twelve green chemistry principles and policies

<b>GCP</b>	<b>International policies</b>	<b>Local policies</b>	<b>Ref.</b>
1	Policy of Prevention of waste	Stop the growing trend of waste production in city	21
2	Circular Economy	Promotion of districts and industrial clusters	22,23
3	REACH framework and policies on chemicals	Cooperation with regional Universities for new design of chemicals and products	24
4	Industrial strategies	Cooperation with near firms to improve processes	25
5	REACH framework and policies on chemicals	Monitoring of material flows. Incentives for innovation at regional and national levels	26
6	Policies on Climate change	Energy manager in private and public sector	27
7	Renewable resources support	Local circular flows for biomaterials and biowaste	28–29
8	Optimisation, technology, information technology	Cooperation with Universities for new design and with factories to implement processes	30
9	Industrial policies, incentives	Cooperation with Universities for new synthesis processes	31–33
10	Plastic reduction policies	End of waste framework	34
11	International monitoring of pollutants in atmosphere	Monitoring of substances by local agencies and by enterprises	35
12	Policies for high-risk sites	Local plans for emergency in high-risk factories	36

On the other hand, Figure 2 illustrates possible interconnections between environmental strategies and green chemistry principles and gives a visual suggestion of the comprehensive strategy.



**Figure 2.** Environmental strategies and twelve green chemistry principles (GC)

In a broader context, the combination of different environmental tools and frameworks is particularly interesting and desirable to have a more complete picture of the strategies analysed and to minimise rebound effects and promote fair communication<sup>37</sup> and true sustainability<sup>38</sup>.

## 5 Conclusions

Raw material shortages and planetary boundaries' awareness have promoted, in the last decades, international and local policies to become more and more environmentally sustainability oriented. Life cycle assessment is a leading method used globally for environmental studies in many fields, including organisations and territories. Moreover, green chemistry principles are scientifically robust and widely applied in the international community to improve environmental sustainability of products and processes. The possibility of integration between life cycle thinking and green chemistry is investigated through a brief literature review. This analysis shows that life cycle thinking can be profitably mingled with green chemistry principles, and vice-versa. These interconnections permit to use the best characteristics of each method to improve the reliability of the other method and finally, to assess environmental problem with a more comprehensive approach. Moreover, green chemistry principles can be easily connected to main strategies at international, national, regional, and local levels. This permits to use results, knowledge, and expertise of the green chemistry framework and to apply them to territories and communities in a life cycle perspective. Findings are usable and thought-provoking both for researchers and for decision makers. The combination of local policies, life cycle assessment and green chemistry needs further investigation since it might help decision making processes based on sustainability issues, technical data, and interdisciplinary consensus.

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