CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188159

Implementing Green Chemistry Principles for Circular Economy Towards Sustainable Development Goals

Ziyang Guo[a], Alison Wang[b], WeiYi Wang[c], Yu-Lin Zhao[d], Pen-Chi Chiang[e,*]

[a] School of Environment and Energy, South China University of Technology, Guangzhou 510006, PR China
[b] Carbon Cycle Research Center, National Taiwan University, No. 71, Fanglan Road, Taipei City, 10672, Taiwan, ROC
[c] International Business, College of Management, Yuan Ze University, No.135, Yuan-Tung Road, Chung-Li 32003, Taiwan
[d] Department of Mechanical Engineering, National Taiwan University, Taipei 106, Taiwan
[e] Graduate Institute of Environmental Engineering, National Taiwan University, No. 71, Chou-Shan Road, Taipei City, 10673, Taiwan, ROC
pcchiang@ntu.edu.tw

Sustainable development goals (SDGs) were proposed for harmonious development for future, this aim is highly consisted with the idea of circular economy (CE) which can be achieved by applying green chemistry principles (GCPs). In this work the relationship between GCPs and SDGs are discussed from the perspective of input selection and reduction, sustainable design and safety management. And it also indicated the benefits of CE which creates a kind of green business model. By integrating GCPs and SDGs, the specific applications of renewable resources towards sustainable development are introduced. Afterwards, it explores the utilization of bio-derived resources and energy in bamboo industry, pulping industry and carbon neutrality for CE. Finally, the challenges and perspectives are proposed in governance, industry and academic aspects.

1. Introduction

The concept of Sustainable Development was first put forward by Gro Harlem Brundtland in the "Our Common Future" Report, defined as "the development that meet the needs of the present without compromising the ability of future generations to meet their own needs" (Harlem, 1987). Since then, the world has gradually moved to the sustainable development and made huge achievements in the past decades. On the economic front, the global GDP growth rapidly over last decade, but our current business model is becoming less sustainable. The major driver contributes to the economic growth are based on the use of fossil fuels, which are non-renewable. In particular, with the rapid increase of the global population and the accelerating industrialization process in developing countries, the demand for fossil energy on human activities is also gradually increasing. In order to conserve natural environment, CE and green chemistry to be considered as a promising method to solve the increasing conflicts among the resource shortage and economic growth. Green chemistry is the study and deployment of a set of principles to reduce or eliminate the use and production of harmful substances for human and environment with chemical design, development and production. The GCP can be used as guidelines to decrease or eradicate pollution in circular economy model.
The concept of circular economy was first present by two British environmental economists David W. Pearce and R. Kerry Turner in 1989 (Pearce et al., 1990). CE is a close-loop growth model which based on the principle of reduction, reuse and recycling. In Denmark, there is organizational collaboration between municipalities and local waste companies and knowledge institutes to explore options for textile waste collection and explore scenario analysis for future recycling systems which promote circular value chains in the local textile industry and to upgrade the recycling of textile waste. (Budde Christensen et al., 2021) In addition to helping companies form new green business models from upstream supply chain to downstream (B2C), the CE helps companies save costs while bringing economic benefits. In this paper, three case studies demonstrating bamboo production and consumption, bio-puling process and carbon neutrality for CE achieving SDGs by implementing GCPs.

Paper Received: 19 June 2021; Revised: 8 August 2021; Accepted: 11 October 2021
Please cite this article as: Guo Z., Wang A., Wang W., Zhao Y.-L., Chiang P.-C., 2021, Implementing Green Chemistry Principles for Circular Economy Towards Sustainable Development Goals, Chemical Engineering Transactions, 88, 955-960 DOI:10.3303/CET2188159

2. Green Chemistry Principles (GCPs) versus SDGs

Green Chemistry is the molecular science of sustainability to design chemical products/processes that aims to maximize the efficiency on chemical process and production and minimized the negative effect on environment and human health (Anastas et al., 1998). Chemical design, production, and applications may be hazardous and produce waste, which the GCPs aim to prevent; it is vital to ensure that the chemical development of materials and substances are sustainable (Burgman et al., 2018). The GCPs can be grouped into three broad categories: (1) input selection and reduction, (2) sustainable design, and (3) safety management. The implementation of these three concepts to the product life cycle, from the raw material to the finished good, should become the universal chemical convention. In addition to environmental benefits, green chemistry also yields economic benefits by reducing storage and treatment costs, minimizing energy, and preventing negative externalities (de Marco et al., 2018). From a broader perspective, the success of the framework relies on innovation in chemistry in alignment with the SDGs.

2.1 Input selection and reduction

Input selection and reduction includes GCPs 1 (Waste Prevention), 2 (Atom Economy), 7 (Use of Renewable Feedstocks), 8 (Reduce Derivatives), and 9 (Catalysis). The chemical industry has traditionally relied on toxic and not biodegradable petroleum feedstocks, which account for 98 % of chemical feedstocks (Mulvihill et al., 2011). In contrast, green chemistry promotes inputs that are sustainably sourced and renewable, meaning ethical harvesting methods and transparent origins. The concept of atom economy is especially useful in the synthesis stage, where the waste of reagents should be minimized. For the environment aspect, many chemicals end up in the environment by intentional release during use (e.g., pesticides), by unintended releases (including emissions during manufacturing), or by disposal. Green chemicals either degrade to innocuous products or are recovered for further use (Relevant to SDGs 6, 9, 12, 14). Plants and animals suffer should less harm from toxic chemicals in the environment (Relevant to SDGs 12, 15). SDG focus on lower potential for global warming, ozone depletion, and smog formation (Relevant to SDGs 11, 13, 14), less or no chemical disruption of ecosystems (Relevant to SDGs 12, 14, 15) and less use of landfills, especially hazardous waste landfills (Relevant to SDGs 11, 12).

2.2 Sustainable design

Sustainable design includes GCPs 4 (Designing Safer Chemicals), 6 (Design for Energy Efficiency), and 10 (Design for Degradation). The design of goods should lend itself to remanufacturing, degradation, and consequent elimination of waste (Robért et al., 2002). Modular design, or design composed of independent material parts which can serve a variety of purposes, enables a closed-loop system, in which materials can be remanufactured at the end of their life cycle. There are several metrics to objectively measure the efficiency and toxicity indicates the sustainability of design. For instance, the e-factor, or environmental factor, quantifies the amount of waste generated by dividing the total waste generated by the mass of the product (Mulvihill et al., 2011). These tools can also indicate the extent to which green chemistry is useful for achieving specific SDGs. For economy and business aspects, SDG claim for higher yields for chemical reactions that consuming smaller amounts of feedstock to obtain the same amount of product (Relevant to SDGs 9, 12). Fewer synthetic steps which often allowing faster manufacturing of products, increasing plant capacity, and saving energy and water (Relevant to SDGs 9, 12). In order to eliminate costly remediation, hazardous waste disposal and end-of-the-pipe treatments a cleaner production technology with a lower cost and higher efficiency without generality secondary pollution should be developed.

2.3 Safety management

Safety management includes GCPs 3 (Less Hazardous Chemical Synthesis), 5 (Safer Solvents and Auxiliaries), 11 (Real-time Analysis for Pollution Prevention), and 12 (Inherently Safer Chemistry for Accident Prevention). This also requires the development of a regulatory framework. Safety regulations measure the exact impact of harmful chemical substances and compounds alongside ensuring workers and the environment are protected. In addition to maintaining scientific ethicality, sound safety management is crucial ensuring responsible development, most pertinent to SDGs 3, 5, 9, and 12 (Mehlic et al., 2017). A systematic LCA approach is also a stepping stone to realizing SDG indicators, since analyzing the costs and benefits of the product, including its externalities, measure the extent to which the goal is achieved (Axon et al., 2018). For the human health aspect, SDGs focus on cleaner air: less release of hazardous chemicals to air leading to less damage to lungs (Relevant to SDGs 3, 7, 11); Cleaner water: less release of hazardous chemical wastes to water leading to cleaner drinking and recreational water (Relevant to SDGs 3, 6, 11, 14); Increased safety for workers in the chemical industry; less use of toxic materials; less personal protective equipment required; less potential for accidents (e.g., fires or explosions) (Relevant to SDGs 3, 8, 12).

3. Use of renewable resources for Circular Economy

Compare to the “take-made-dispose” linear industrial model, the CE more focus on reclamation. The circular economy is an economical model that is designed to be recoverable, renewable and to maximize the usability and value of various products, components and material. The use of renewable resources as inputs not only accord with the three aforementioned concepts but also closes the material loop which is the key step for CE. This input can be used in industries, turned into fuel and produces, and released back into the atmosphere in the form of CO_2 via photosynthesis. In turn, the final output from non-renewable resources cannot be reabsorbed, accumulating in the atmosphere instead. Consequently, renewable resources satisfy each part of green chemistry and are critical to analyse for their properties, applications and uses. There are three case studies which used renewable input are introduced below.

3.1 Bamboo production and consumption for Circular Economy

Bamboo is a rapidly-growing grass which has strong potential for integration into the CE through applying GCPs as a material as shown in Figure 1. Bamboo is not only productive, cellulose rich, has little moisture but also tolerates a variety of growing conditions given precipitation (Ceballos et al., 2015). Bamboo reaches peak strength during full maturity, which is only 3 - 5 y depending on the species. Moreover, the natural fibres in bamboo, or cellulose, can form biodegradable composites as a superior alternative to petroleum-based polymers and materials. Considering these characteristics, the versatility of bamboo lends itself to a multitude of applications and incorporation into various industries. Particularly, the abundance of biomass in bamboo and many environmental benefits make it a viable material for biorefinery. In fact, bamboo-based bioethanol is more environmentally friendly than petrol emissions by 45 - 93 % (Wang et al., 2014). It is also more sustainable than wood biomass, which supplies roughly 13 % of global energy, but is dwindling in supply. Bamboo has a multitude of inherent benefits demonstrating from the aspects of social wellbeing, environmental conservation and economic grow. Bamboo naturally continues to grow after harvesting without the need to replant seeds and does not cause soil depletion or deterioration. As a material, the strength of bamboo is comparable to that of steel and concrete (Sharma et al., 2014). Moreover, every portion of the bamboo can be utilized, including the waste. This lends bamboo to a variety of uses and translates to resource efficiency (Sharma et al., 2014). The CE can not only help the economy reach a new development node, but also make industry, society and the environment reach a balance toward SDGs.

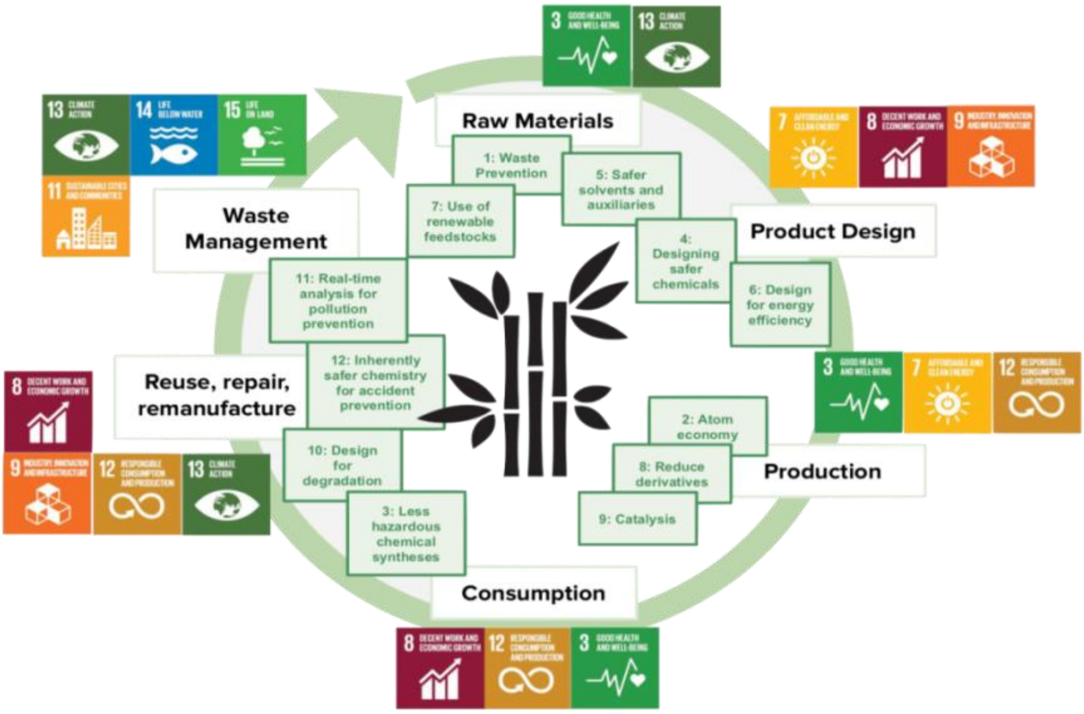

Figure 1: Bamboo industry for Circular Economy: production and consumption

3.2 Bio-pulping process for Circular Economy

Circular economy is an appropriate way for development of pulp and paper industry which have intensive resources consumption and environmental pollution. The concept of CE emphasizes effective management of resources from cradle to grave. As shown in Figure 2, straw was used as input in bio-pulping process where enzyme was used and paper products were produced after thermal and mechanical process. (GCP 7, 9). Then the pulp waste was utilized in the production of biogas or it can be burned for energy production. The generated power and biogas can be applied for paper products again. (GCP 1, 6) The fly ash from power plant can be effectively utilized as fertilizer for corps. After harvesting crops, grain and straw can be obtained where straw can be used as the input of the bio-pulping process to close the loop. On the other hands, crops and straw as bio-feedstock can convert into energy by combustion to CO_2 in atmosphere. Finally, the emitted CO_2 will be consumed via photosynthesis of crops. (SDG 2, 3, 13, 15).

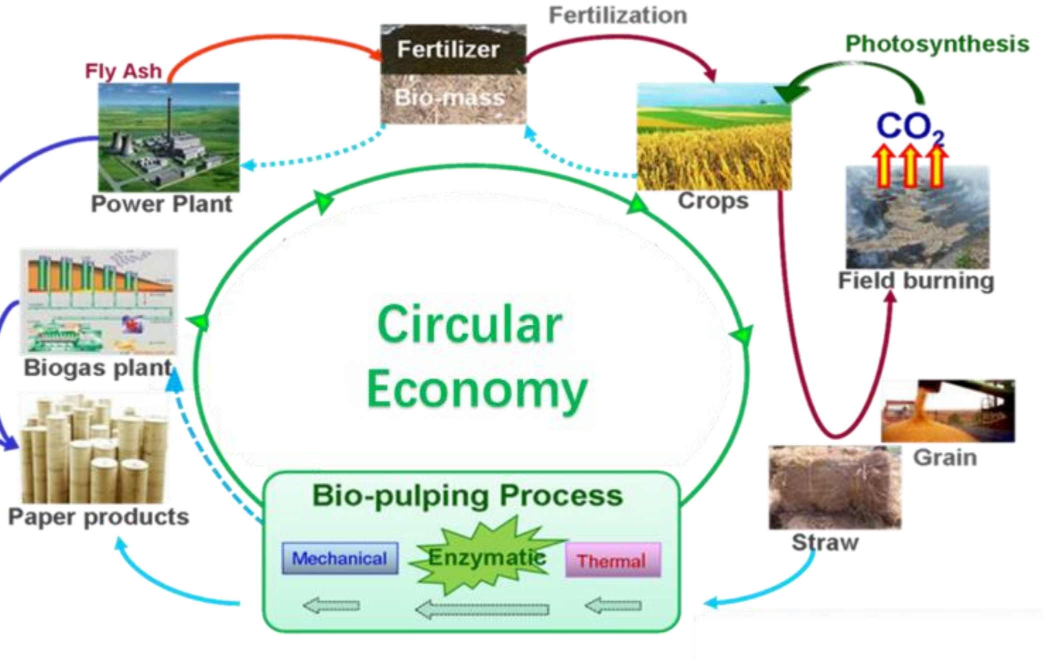

Figure 2: Paper and pulping industry for circular economy

Recycling 1 t of straw can reduce 0.9 t of CO_2 emission, produce 0.55 t of pulp (is equivalent to reducing 0.5 t of CO_2 emission) and produce 0.325 t of organic fertilizer (is equivalent to reducing 0.4 t of CO_2 emission). CE can contribute to the development of science biotechnology cooperate with other social sectors including ecological sciences, construction engineering, sociology, financial economics, territorial and urban planning.

3.3 Carbon neutrality for Circular Economy

The energy structure nowadays is highly relay on petroleum feedstocks. Although the emergence of renewable energy brings light to the solution shortage of resources, energy storage is the bottleneck of low-carbon energy application and development. In the sustainable organic fuel for transportation (Figure 3) concept (Pearson et al., 2009), the overflowed or off-peak electricity produced from solar, wind, hydro and nuclear energy are used to avoid waste in energy in carbon neutrality cycle (GCP 1, 6, 7, 12). The electricity was introduced for hydrogen production: $H_2O \rightarrow H_2 + 1/2\ O_2$. Then the hydrogen reacts with CO_2 through $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$ to synthesis methanol which is a bio-derived fuel. The consumption of CO_2 in this process is a good commitment for being carbon-neutral (SDG 3, 9, 13, 15). In addition, specific catalyst is essential in the hydrogen production process to overcome the reaction energy barrier (GCP 8, 9). Methanol as alternatives of petrol is able to provide energy for transportation via $CH_3OH + O_2 \rightarrow CO_2 + H_2O$. The CO_2 from transportation sector was emitted into atmosphere, which can take part in photosynthesis to give oxygen under the sunlight and biomass. Following by gasification of biomass to give syngas which is a mixture of CO and H_2, it can be converted into liquid fuel or further transformed to hydrocarbon (such as dimethyl Ether (DME) and olefins). CO_2 from transportation and other emission source (power plants and industry) can also be collected via carbon capture and utilization (CCSU) process. The captured CO_2 is recycled for further usage or directly used back in synthetic fuel processes where to close the loop of circular economy cycle. CE can minimize natural disasters caused by energy consumption and excessive carbon emissions while reduce the cost consumption of enterprises and increase their revenue through additional products which contributes to the development of green economy and green business.

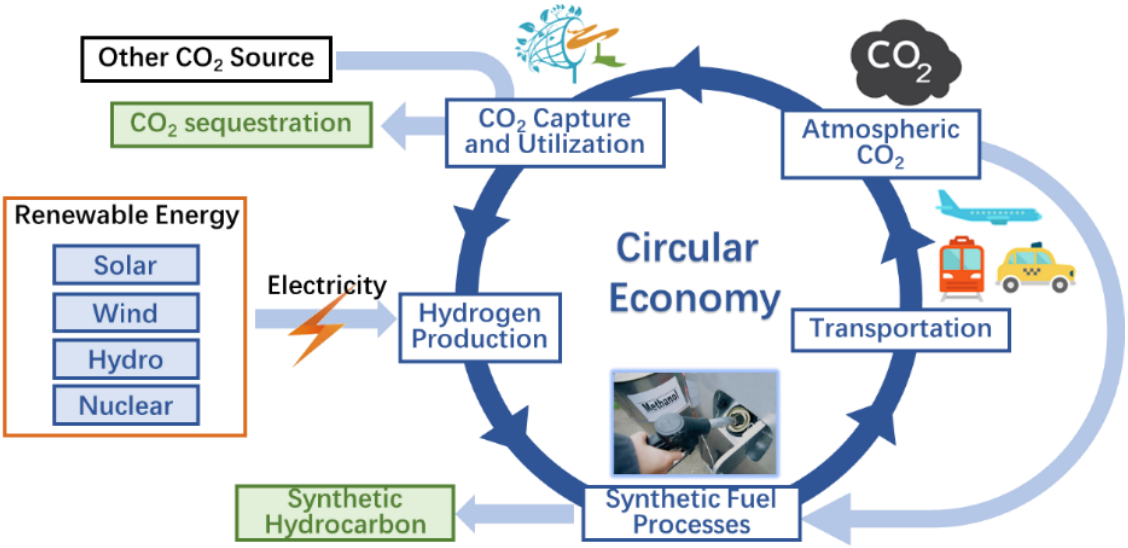

Figure 3: Carbon emissions neutrality for circular economy: sustainable organic fuel for transportation

4. Conclusion: challenges and perspectives

The major uses of green chemistry can be implemented and utilized in the area of energy, global change, resource depletion, food supply, and toxics in the environment. In addition, green chemistry will be essential in developing the alternatives for energy generation (photovoltaics, hydrogen, fuel cells, bio-based fuels, etc.) as well as continue the path toward energy efficiency with catalysis and product design at the forefront. In this paper, three case studies demonstrating bamboo production and consumption, bio-puling process and carbon emissions neutrality for CE achieving SDGs by implementing GCPs.

By implementing GCPs for CE achieving SDGs is significant for ensuring resource sustainability, carbon neutrality, and construction of ecological civilisation. At present, however, there is no circular economy governance system aimed at achieving SDGs. Immature recycling industries and technological systems are hard to achieve SDGs. Moreover, the green and low-carbon lifestyle has not yet formed due to lack of guidance. The overt environmental information of corporate is not complete, which is unable to meet the information sharing needs of building a circular economy.

Therefore, for the governance, it is required to establish national governance framework for a new waste management policy including sustainable production and consumption, resource efficiency maximization and environmental impact minimisation at every stage of the product and service lifecycle for CE. For the industry, it needs not only to manage materials and products on a life-cycle basis and adopt the Extended Producer Responsibility (EPR) policy, but also to promote SDGs by establishing CE business model – RESOLVE (Regenerate, Share, Optimize, Loop, Virtualize, Exchange). For the academic sectors, it is necessary to implement “Green Chemistry for Green Industries”, reducing the use/generation of hazardous substances, while ensuring their performance, cost and safety. To strengthen the energy and resource sustainability, the intelligent recycling system based on smart device, Internet of things (IOT), big data and intelligent sanitation system for CE should be developed. In addition, the performance of the existing system should be evaluated and enhanced by applying system engineering models and system assessment tools (e.g., Green Screen for Safer Chemicals). In the future, the synthetic chemist will need to use atom efficiency as the synthetic route, while the process chemist has to utilize the waste generated as the product to be made. It is evident that the more successful chemical manufacturing companies can exploit the economic, legislative and public image advantages through use of a clean technology based on green chemistry principles. Also, the more successful chemistry researchers and educationalists can appreciate the value of green chemistry in innovation, application and teaching.

References

Allen, C., Clouth, S., 2012, A guidebook to the Green Economy. Division of Sustainable Development, UNDESA. New York, USA.
Anastas, P. T., Warner, J. C., 1998, Green chemistry: theory and practice. New York: Oxford University Press. New York, USA.
Axon, S., James, D., 2018, The UN Sustainable Development Goals: How can sustainable chemistry contribute? A view from the chemical industry. Current Opinion in Green and Sustainable Chemistry, 13, 140-145.
Budde Christensen,T., 2021, Denmark Towards a circular economy in cities: Exploring local modes of governance in the transition towards a circular economy in construction and textile recycling.Journal of Cleaner Production, 305,127058.
Burgman, M., Tennant, M., Voulvoulis, N., Makuch, K., Madani, K., 2018, Current Opinion in Green and Sustainable Chemistry. Current Opinion in Green and Sustainable Chemistry, 13, 130-136.
Ceballos, R., Chan, M., Batchenkova, N., Duffing-Romero, A., Nelson, A., 2015, Bioethanol: Feedstock Alternatives, Pretreatments, Lignin Chemistry, and the Potential for Green Value-Added Lignin Co-Products. Journal of Environmental Analytical Chemistry, 2(5).
de Marco, B. A., Rechelo, B. S., Tótoli, E. G., Kogawa, A. C., Salgado, H. R. N., 2019, Evolution of green chemistry and its multidimensional impacts: A review. Saudi Pharmaceutical Journal, 27(1), 1-8.
Harlem, B.G., 1987. Our common future. Report of the World Commission on Environment and Development.
Leggett, J.A., Carter,N.T., 2012, Rio+20: The United Nations Conference on Sustainable Development, June 2012. Congressional Research Service 7-5700.
Mehlich, J., Moser, F., Van Tiggelen, B., Campanella, L., Hopf, H., 2017, The Ethical and Social Dimensions of Chemistry: Reflections, Considerations, and Clarifications. Chemistry: A European Journal, 23, 1210-1218.
Mulvihill, M. J., Beach, E. S., Zimmerman, J. B., Anastas, P. T., 2011, Green Chemistry and Green Engineering: A Framework for Sustainable Technology Development. Annual Review of Environment and Resources, 36, 271-293.
Pearce, D.W., Turner, R.K., Turner, R.K., 1990. Economics of natural resources and the environment. Johns Hopkins University Press, Baltimore, USA
Pearson, R. J., Turner, J. W. G., Eisaman, M. D., Littau, K. A., Taylor, G., 2009, Sustainable Organic Fuels for Transport (SOFT)–A Concept for Compatible Affordable Mobility Using Carbon-Neutral Liquid Fuels. Proceedings of SIA (Société des Ingénieurs de l'Automobile), Paris, France.
Robèrt, K.-H., Schmidt-Bleek, B., de Larderel, J. A., Basile, G., Jansen, J. L., Kuehr, R., Wackernagel, M., 2002, Strategic sustainable development — selection, design and synergies of applied tools. Journal of Cleaner Production, 10(3), 197-214.
Sharma, B., Gatoo, A., Bock, M., Mulligan, H., Ramage, M., 2015, Engineered bamboo: state of the art. Proceedings of the Institution of Civil Engineers - Construction Materials, 168(2), 57-67.
Wang, L., Littlewood, J., Murphy, R. J., 2014, An economic and environmental evaluation for bamboo-derived bioethanol. Royal Chemistry Society Advances, (4), 29604-29611.