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Sustainability in a Global Circular Economy: An Integrated Modeling Perspective

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One of the UN Sustainability Goals is sustainable production and consumption. Global adoption of the Circular Economy (CE) is considered one of the critical methods of achieving this goal. Most of the studies in the field of CE investigate the economic benefits through material savings. The question of how CE, when adopted on a global level, can influence sustainability has been largely unexplored. We seek to examine the research into this question from an integrated perspective. A study looking into the systemic influences of the CE establishes its benefits. However, it also brings out the adverse ecological effects of very aggressive adoption of CE. Another study examines the role of consumer price sensitivity regarding CE in global sustainability. It suggests that though economic incentives can contribute to CE adoption, controlling the overall consumption growth rate is a more potent way of achieving sustainability. The stakeholders like the international organisations, multinational corporations, sustainability researchers and the public at large may find these insights helpful. This utility is discussed; along with the limitations and avenues for future research from these studies. To conclude, the importance of integrated modeling studies for CE is underlined through this article.

Keywords: agent-based modeling, consumers, consumption, global models, integrated modeling, stakeholders, sustainable transitions, system dynamics

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CIRCULAR ECONOMY AND SUSTAINABILITY

The circular economy (CE), which is rooted in the concept of industrial ecology Murray et al. (2017), is seen as a way of achieving sustainability while satisfying the resource demands by the human society. CE essentially focusses on retention of value of the energy and materials through looping them in the product life cycle. Increased resource efficiency is an important benefit of CE. Additionally, CE adoption can also have positive influence from an environmental perspective. According to Schroeder et al. (2019) the progress towards achieving several sustainable development goals, such as 6 - water and sanitation for all, 7 - sustainable energy for all, 11 - sustainable cities and communities, and 12 - sustainable production and consumption, can be accelerated by the adoption of the CE (Geissdoerfer et al., 2017; United Nations General Assembly, 2015). Such studies are based on the alignment between the principles of the CE and that particular goal. Hence, it is prudent to question whether CE can help in achieving global sustainability.

An examination of the literature regarding CE brings out several observations. First, the majority of the studies focus on the process improvements and benefits achieved by CE adoption in terms of material savings or avoided cost of waste disposal (Ghisellini et al., 2016). Secondly, these studies focus on one single product or process. For example, Nechifor et al. (2020), Zabihi et al. (2020), Garlapati et al. (2020) and Blank et al. (2020) analyse CE in context of steel, glass, lignin and plastics, respectively. Ahn et al. (2020), Tayeh et al. (2020) and Ma et al. (2015) examine CE benefits in the process of recovery of rare earth materials, olive oil and phosphorous production, respectively. Consequently, the spatial scale of such studies is limited; that is, their scale is either restricted to a production unit or at maximum to a regional level. Moreover, as the environmental systems take time in responding to the changes, a sustainability study should have a timeframe long enough to allow us to observe such changes. Studies such as the ones by Asif et al. (2015), Asif et al. (2016), examine environmental aspects of CE adoption. However, they have a restricted spatial and temporal scale.

This analysis brings forth the need for an assessment of the global CE from the sustainability point of view. A study of systemic influences of CE adoption can shed light on the effect of CE on a global scale and whether it has any undesirable and unanticipated consequences. Modeling and simulation tools are suitable for such a study as they allow us to investigate the effects of a proposed policy without implementing it on the ground. Little et al. (2016) has recognised the utility of integrated modeling for such an assessment.

The integrated model should include an explicit ecological dimension, and it should be interlinked with the economic and societal dimensions. Additionally, the model should consider adequately long time horizon. Hanumante et al. (2019) and Hanumante et al. (2020) carried out such investigations. Hanumante et al. (2019) investigated various growth patterns of a global CE and its sustainability implications. Hanumante et al. (2020) built upon the earlier work and scrutinized the influence of consumer decision-making on CE growth and consequently on global sustainability. The objective of our paper is to examine these studies from the point of view of the insights they bring, the utility of such insights, the limitations of these studies and the future directions for CE researchers, which are presented in the discussion section. The key contribution of this paper is a discussion on these aspects that can help different stakeholders in making informed decisions. Specifically, this paper aims to inform policy-makers of potential unsustainable scenarios associated with adoption of CE and trade-offs to avoid them. In this regard, following this introduction, the integrated modeling studies on CE are described briefly in the next section. It is followed by the implications of the insights from these studies, their limitations, prospects and concluding remarks.

INSIGHTS FROM THE INTEGRATED MODELLING STUDIES

The first step towards such a study is model selection. Global and dynamic nature of the model, depth and breadth of modeling of the ecological and economic dimensions, long simulation horizons are critical model selection criteria. Based on these criteria, Hanumante et al. (2019), Hanumante et al. (2020) selected the integrated-planetary model (Whitmore et al., 2006; Shastri et al., 2008b; Kotecha et al., 2013). It has several unique features such as multiple trophic levels, intra-trophic level diversity and an explicit market mechanism based on price-setting approach (**Figure 1**). The industries fundamental to human civilisation, agriculture (P1), livestock (H1), energy production (EP) and industrial manufacturing producing consumer goods (TI), are included. The agricultural produce, along with natural resources, is a raw material essential for the functioning of the consumer goods industry; the livestock feed upon the open access grasslands (P2) and the agricultural produce. The human population (HH) may choose to work in one of these industries. The ecological dimension is modeled based on the predator-prey dynamics, and the presence of the intra-trophic level diversity gives rise to a food web. Forests (P3) are included along with wild herbivores (H2 and H3) and carnivorous animals (C1 and C2). The nutrients essential to primary producers are supplied from the Resource Pool and fossil fuels used by the human society are supplied from the Fuel Source. The model also includes a traditional industry (TI) producing consumer goods using virgin raw materials; and a sink for the used consumer goods in the form of Inaccessible Resource Pool.

Hanumante et al. (2019) included the CE in the form of a circulation industry (CLI). CLI utilizes the waste stream generated after human consumption of industry goods to produce consumer goods identical to the ones produced through the traditional route. Goods produced by the circulation industry (CE goods) are preferred by human society. If the demand for consumer goods could not be met by the CE goods alone, then the traditional products satisfy the residual requirement. Since consumer preferences were not incorporated, this represents a top-down implementation of the CE.

Systemic Influences of Global CE

Hanumante et al. (2019) investigated two questions using this model: first, what happens when CE is incorporated and second, how does the system respond to different patterns of CE growth. They carried out a comparison between the scenarios without CE and with CE to answer the first question. Typically, the scenarios were configured to showcase different consumption growth rates (a linear increase over the simulation horizon of 200 years with timestep of 1 week) and a population dynamics model based on the UN projections (United Nations, Department of Economic and Social Affairs, Population Division, 2004). In the case CE was not adopted, increasing consumption rate and population led to over-exploitation of the agricultural sector as it provided raw material to the consumer goods industry, which eventually led to its collapse (**Figure 2A**). As the ecological components are connected through the food web, the effects of such breakdown cascaded to other compartments as well. When CE was incorporated, at a constant level (17% of the post use waste is circulated), the time of this collapse was delayed (by 20-40 years), this showed the systemic benefits of CE adoption. These benefits were attributed to the fact that, with CE in place, the burden of

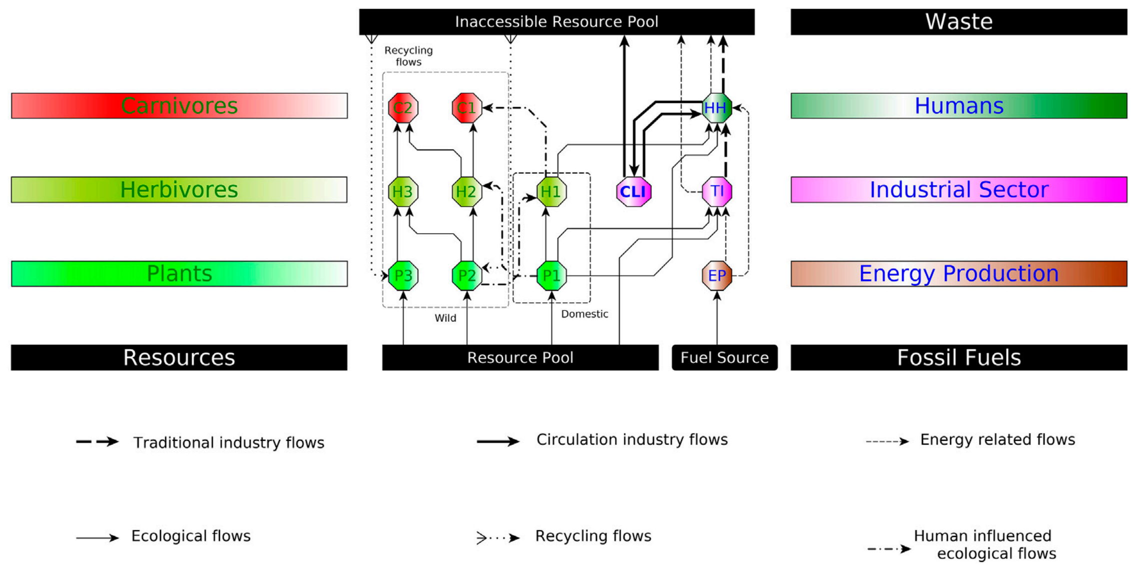

FIGURE 1 | The integrated planetary model: Used consumer goods are processed by the circulation industry and it produces products for consumption. Waste generated in this process is also transferred to the inaccessible resource pool.

production of goods using virgin raw materials is reduced, thus, decelerating the exploitation of the agricultural sector.

Sigmoidal/logistic trends are generally used to model technology/innovation diffusion. Hanumante et al. (2019) used these to represent different worldviews of the growth of CE. They parameterised these worldviews with the delay for the beginning of adoption, rate of adoption, and maximum achievable level of circulation. Simulations carried out using these pathways for different consumption growth rates (**Figure 2B**), bring forth some interesting observations. For several routes with very late adoption or low CE growth (Worldview 1), agriculture collapses (Collapse Mode 1) but with significant delays. For many other pathways, with aggressive enough CE growth (Worldview 2), the collapse of the agricultural sector was avoided altogether. However, as the consumption growth rates increase, fewer patterns lead to sustainable behaviour. For example, for scenarios where consumption becomes five and ten times of the initial value, the proportion of the sustainable scenarios was more than 75% and less than 15%, respectively. For pathways with a very aggressive expansion of CE (Worldview 3), an ecological breakdown was observed. However, the unsustainability is initiated in the open-access grasslands (Collapse Mode 2). High circulation of the used goods prevents reliance of the society on the traditional industry. The traditional industry significantly influences the overall wage rate in this industrialised world. Hence, the wage rate reduces. The system falls into a cycle of decreasing wages leading to an increasing population and a higher population pushing the wages down further. As a result of low wages, more labour is employed in the agricultural sector, leading to more agricultural production. The agricultural sector and the grasslands compete for nutrients. Hence, increased agricultural production adversely affects the grasslands, eventually leading to its collapse. This description can be translated to a real-world analogy as a change in the land use from grasslands to agriculture.

Consumer Price Sensitivity and CE Adoption

In the study mentioned earlier, though there were two identical products, one produced through CE and the other traditionally using virgin raw materials, the role of consumers' choice in determining the demand was not modeled. Further, the circulation of the used goods was enforced as a predefined growth pattern and did not depend upon the economic variables or human preferences. Therefore, it can be argued that this model simulated a highly controlled CE where the adoption of recycled goods was enforced in a top-down manner or government-controlled mechanism. The results provide information about the desirable and undesirable trends but are unable to address several vital factors that affect the implementation of the CE. Some of these limitations were addressed in the next part of this research by Hanumante et al. (2020). A market for the CE goods was developed. The consumers' choice was incorporated in the form of their "willingness to pay" or the price sensitivity. It referred to the fraction of the population willing to pay for the CE goods at a particular price as compared to its traditional counterpart. As a result, the demand fraction of the CE goods was not predetermined, but instead depended on the dynamics of the prices and the willingness to pay or the consumer price sensitivity patterns. The production process was modeled similar to the traditional industry with appropriate scaling. The CE goods price was modeled to portray the technology development which would reduce the fixed cost associated with CE industry to its traditional counterpart.

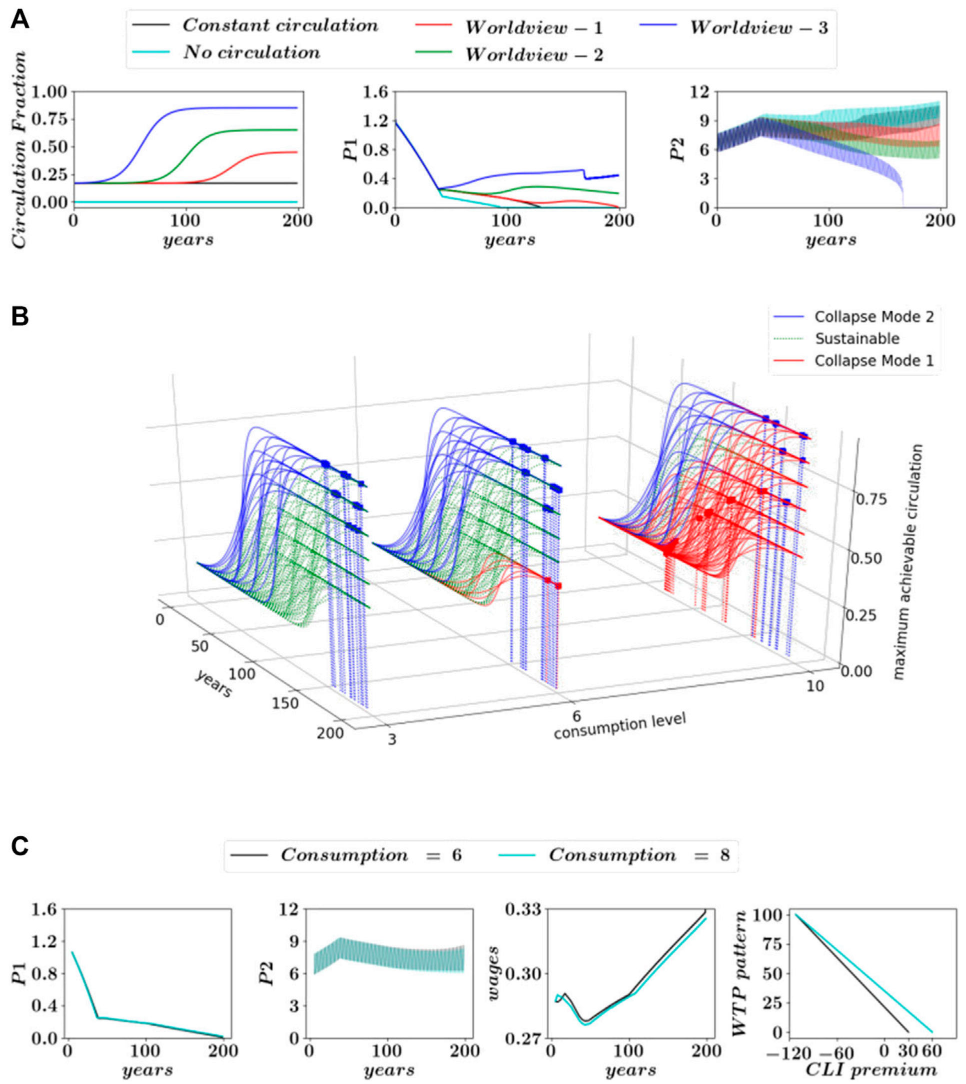

FIGURE 2 | (A) shows the comparison of CE adoption routes, **(B)** depicts simulation outcomes for combinations of worldviews and consumption growth rates, and **(C)** compares the results of high consumption growth rate with economic incentives and low consumption growth rate without them.

In the absence of availability of the global level data on consumers' willingness to pay, Hanumante et al. (2020) modeled these patterns to be linear. These patterns were developed such that at higher relative price of new products consumers prefer CE goods. The detailed model was used to simulate combinations of these patterns. Specifically, the strategy to incentivise the purchase of the CE goods was assessed by comparing the scenarios of price sensitivity pattern with economic incentives and no economic incentives but a lower rate of consumption growth (**Figure 2C**).

These scenarios indicated that the positive influence of incentivising the purchase of CE goods by increasing the consumers' maximum willingness to pay by 100% (from 30% to 60%) and the negative effect of increasing the consumption growth rate by 33% (from 6 to 8) balance each other out. In other words, to obtain a similar ecological response, a substantial amount of stimulus is required as compared to a lower consumption growth rate scenario. Moreover, even with these incentives, the population becomes comparatively less wealthy (lower wages). This unique insight suggests that from ecological as well as an economic perspective, more benefits can be gained by minimising consumption growth (or even reducing consumption) than promoting the CE by subsidising its products.

DISCUSSION

The studies assessed the broader impacts of the adoption of CE and the role of consumer decision making on CE adoption and global sustainability. It should be noted that such global models considering long time horizons cannot be used for predictions. Instead, the results represent a subset of the vast number of future pathways. Moreover, the quantitative results provided by these models represent what are typically known as "ballpark" estimates. These caveats notwithstanding, specific insights relevant for different stakeholders can be discussed.

International Organizations

Both studies indicated that CE adoption alone could not achieve sustainability. The adoption of CE must be complemented with a reduction in consumption growth. Economic incentives can also be used for promotion and accelerated adoption of CE. Lastly, agriculture is expected to be adversely affected, owing to rapid exploitation. These insights should be considered by international organisations such as the UN, EU, IMF, World Bank and so on whose decisions influence the lives of billions of people across the globe.

Multinational Corporations and Conglomerates

Studies focussed on consumer behaviour indicates that, with other conditions remaining the same, economic incentives to purchase circulated consumer goods positively influence system sustainability. This insight is particularly useful in the case of developed countries where reduction of the consumption growth rate is difficult. In such circumstances, in the interest of global sustainability, multinational companies should consider incentivisation of the circulated goods as a step in the product pricing process (Hamzaoui-Essoussi and Linton, 2014).

Sustainability Researchers

The sustainability researchers can consider improving certain modeling aspects of this model: wage rate, circulation efficiency, global data of willingness to pay patterns. Enhanced modeling of these aspects can provide an opportunity to understand the CE influences better.

Global Citizens

Owing to the global scale of the model, the recommendations for this category of stakeholders cannot be tailor-made for individuals. Affluent individuals should prioritise preventing consumption growth rather than spending resources and energy in marginally improving the CE. On the contrary, less affluent individuals should focus on recycling as much as possible such that it can counter their consumption. The recommendation to reduce the consumption by the affluent section of the society is against the concept of trickle-down economics (Arndt, 1983).

Before utilising this research as a tool to support decision making for different stakeholders, the model scope and limitations need to be discussed. Key limitations are presented below, along with corresponding avenues for future research work in this field:

- The current research models the consumer goods in an aggregate form with fixed lifespan. Consumer goods with different lifespans may be modeled to investigate the effect of life extension programs.
- The goods produced through CE are assumed to be identical to the new products and that they provide the same service. It is quite possible that the recycled product is inferior, either in terms of features or durability. This brings an additional factor in decision making by consumer vis a vis the price of the products. Modeling of downcycling through the incorporation of a different product category may be considered to examine these aspects.
- The current research is a subjective assessment of the global implications of CE adoption. This limitation can be addressed by quantifying the CE benefits using tools such as Fisher Information (earlier employed by Shastri and Diwekar, 2006; Shastri et al. 2008a; Shastri et al. 2008b).
- This work models consumers in an aggregate fashion; as a result, the influence of their individual choices on a global level cannot be observed. Methods such as Individual-Based Modeling or Agent-Based Modeling (Bonabeau, 2002; Young, 2009) can be used to address this limitation.

CONCLUDING REMARKS

To summarise, these integrated studies provide guidance on how much support is required by CE for different consumption patterns of the human society to ensure a sustainable future. The following conclusions bring out the essence of the integrated studies on CE:

- The integrated studies underline the importance of the role of CE in preventing the world from becoming unsustainable. In particular, the studies indicate that CE could satisfy the demand for the products, thus, reducing the stress on the primary raw materials. In other words, CE provides the eco-system services with a recess from exploitation for industrial production, by satisfying a fraction of its demand.
- The capability of the integrated models to model the interactions between the economic and ecological dimensions is particularly critical in understanding these causalities. The use of an integrated model also brings out potential negative ecological implications of very aggressive CE adoption, something that would not have been possible with a unidimensional model.
- CE growth depends upon its adoption by the general populace which is influenced by their price sensitivity. Consumers can be incentivised by economic means to purchase goods produced through CE. However, such incentives have limited efficacy. Rather, pragmatically, it might be easier to reduce the consumption growth rate than to provide economic incentives. The integrated model shows how an economic factor can be used to affect an environmental dimension and therefore it is an excellent tool to analyse the multidimensional effects of policy decisions.
- These insights can be found useful by various stakeholders such as international organisations, multinational companies, sustainability researchers and also ordinary people across the globe. In particular, insights regarding this work can provide

pointers to the decision-makers from international organisations to understand the limitations of CE and identify areas for further investigations. Hence, on a global scale, it can help in transforming our world to have a sustainable future.
- The insights obtained from these studies scratch only the surface of the systemic understanding of the CE that can be obtained through studies using integrated models. Potential avenues for research include further refinement of modeling of products to capture lifespans and features, control and opimization of CE growth and individual based modeling of the consumers.

It may be concluded that as all good things in life, the benefits of the circular economy are subject to certain limitations which can be investigated using an integrated model.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

NCH performed the modeling development and analysis work that is the foundation of this perspective paper. He also performed a detailed literature review and juxtapose the findings of his research with the existing literature on circular economy. The manuscript writing was primarily done by this author. YS was one of the supervisors of this work and contributed towards providing conceptual inputs to the work and refining the manuscript. AH was one of the supervisors of this work and contributed towards providing conceptual inputs to the work and refining the manuscript.

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