International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; SP-9(12): 1138-1143
www.biochemjournal.com
Received: 17-10-2025
Accepted: 12-11-2025

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Integration of circular economy and zero-waste practices with hydroponics: Towards sustainable food production

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DOI: https://www.DOI.org/10.33545/26174693.2025.v9.i12Sn.6677

Abstract
This review study provides an overview of the circular economy, its framework in agriculture, as well as hydroponics, and various practices related to the zero-waste system. The circular economy offers a broad spectrum for sustainable farming by focusing on its key points: reduce, reuse, recycle, recover/regenerate, and redesign. Zero-waste practices are strategies that ensure nothing is wasted. The circular economy and zero waste practices are an integrated topic that aims for the same, i.e, no waste production and sustainability, unlike linear traditional farming, which revolves around a single input of resources and produces an abundant amount of waste. This concept helps in holding the closed loop of nutrients and resources while reducing the waste production and controlling the health of our environment. Circular agriculture is a predominant approach grounded in principles of the circular economy and its affiliated factors. Moreover, this review provides a systematic examination of the circular economy, its application in agriculture and hydroponics, and how it helps mitigate multiple associated risks in agriculture. It also reshapes the global food production system, addresses challenges associated with its implementation, and outlines strategies to bridge the gap in the agricultural sector. Well, this chapter also includes various zero-waste practices, their benefits, and a detailed discussion on the scalability with the help of hydroponics of the same to achieve sustainability.

Keywords: Circular economy, zero waste practices, sustainable agriculture, Hydroponics, risk mitigation, nutrient recycling.

Introduction
At present, the major challenge is to keep the world population fed in 2050. Mostly, it is estimated that we need to increase our ability to produce food by 5.1 billion tonnes by 2050 (FAO, 2017). This will generate a huge burden on the agricultural ecosystems, given that they are the principal food providers. Furthermore, this could cause adverse impacts on the natural environment as well as agricultural production consumes large amounts of water and energy from the earth, draining the planet entirely. More than 90% of environmental impacts due to land use are related to agriculture. Moreover, in 2019, agriculture, together with food processing, represented the second largest material footprint with 21.3 billion tonnes and a carbon footprint of 10 billion tonnes of carbon dioxide (CO2) equivalent, making it the third largest after transport and housing. The unsaid need to produce more with fewer resources is increasing with time (most probably due to scarcity) (Food and Agriculture Organization of the United Nations, 2018) [3]. While leaving the futuristic thing, the world is having a hard time with other aspects also, which are, t-he waste management is being a global issues as concern of the environmental health and economic and social sustainability (Gupta *et al.* 2015, Vitorino de Souza Melaré *et al.* 2017) [5, 22], which need an urgent attention and holistic approaches seek its solution for it .3 Unregulated disposal of the waste lead to release of heavy metals into the soil causing pollution in water, plant and in soil (Vongdala *et al.* 2019) [23], while burning them causes atmospheric pollution and climate changes related problems (Wiedinmyer *et al.*, 2014) [24]. Disposing of them in a particular dumping site or in water bodies will affect the people working in that area and the marine life, respectively (Gutberlet *et al*. 2008, United Nations Environment Programme UNEP) 2009) [6, 19]. The footprint of materials of the developing countries grew from 5 t inh 1 in 2000 to 9 t inh 1 in 2017, evidently seen in growing standards of living, for which sustainable management is

not effectively included in national regulations (United Nations (UN) 2018) [18]. To achieve sustainable development, keeping economic growth in mind, we need to change the way of produce-consume-waste of goods and resources (Sustainable Development Goals Fund (SDG-F) 2016).

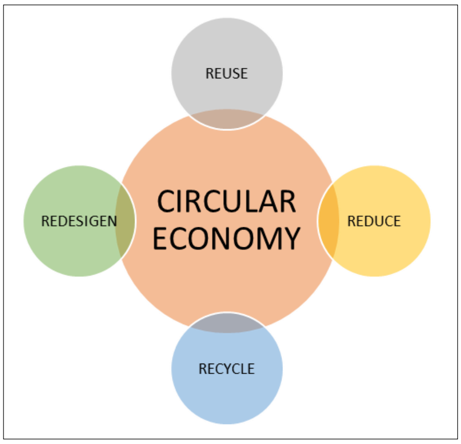

Fig 1: Tell the four major pillars of the Circular Economy

To overcome the following problems, the concept of circular agriculture is highly needed to be followed. Circular agriculture has 4 pillars (fig.1), which are reduce, reuse, recycle, and recover/redesign the materials being used in production or consumed. Circular agriculture aims to reduce the CO2 emissions and depletion of raw materials used, which can eventually lead to the tipping point of the natural ecosystem and depletion of resources. (Verkerke, 2012) [29]. As a solution of both fewer resources and uncertain risks, protected cultivation (the practice where the crops are grown under a controlled environment), especially soil-less hydroponics (the process of growing the plants without the soil in a controlled environment), is a very resource-intensive solution to the above problems (Katsoulas, N. 2017) [9]. It can be considered circular agriculture as they are cultivated in a closed system where the water and nutrients are being recirculated. This approach stands mainly on one pillar of circular agriculture, which is recycling (Schulker *et al.* 2020) [15]. But there is a problem with the pillar of reuse, as the associated risk of pathogen spread is high. To avoid that, producers periodically discharge the nutrient solution (Varlagas *et al.* 2010) [20]. This creates another issue with reuse, use is that the drained nutrient solution can cause soil and underwater pollution, too, for which we need to use crops having high salt tolerance and the ability to accumulate sodium (Kumar *et al*. 2014, García-Caparrós *et al.* 2018, Katsoulas, N.*et al.* 2020) [13, 4, 10]. This is the benefit of circular economy integration with hydroponics; the sequential reuse or combining the drainage could be a useful tool for reusing used water in crop production, especially in dry areas.

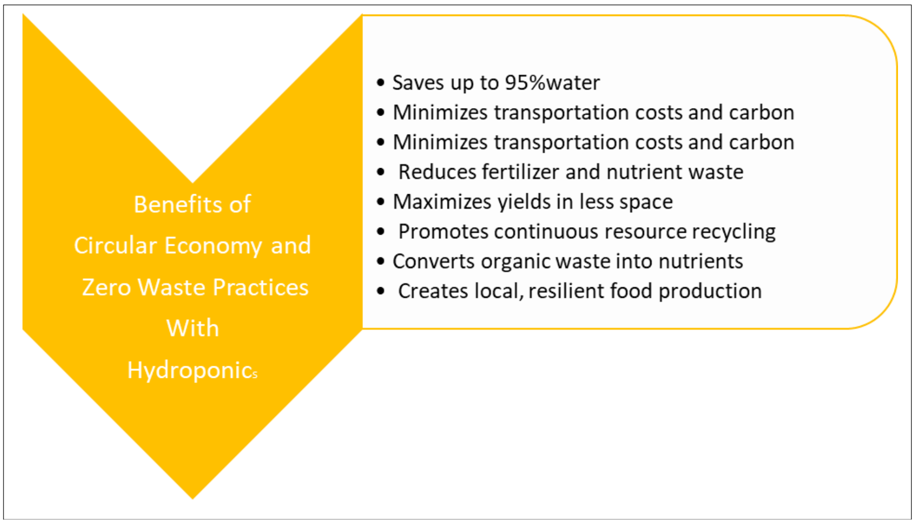

Fig 2: Enlist the benefits of the integration of the Circular Economy and zero Waste Practices with Hydroponics.

These soilless CE approaches lead to a zero-waste scenario of ecological and economic growth, and practices performed to attain the following can be titled as zero-waste practices, which are based on empirical and semi-scientific concepts with the integration of today's modern technologies (Jawahir *et al*., 2007; Kirchherr *et al*., 2017; Ramakrishna *et al*., 2020) [7, 11, 14]. These practices align with different sustainable goals like United Nations' Sustainable Development Goals [UN SDG] in various ways (reducing waste production and again introducing it into the economic cycle) epescially SDG 2[Zero Hunger] associated with zero hunger and zero food waste(addressing issues like hunger and food security), SDG 12 (responsible Consumption and Production) by enhancing resource efficiency) while at the same time making a breakthrough in SDG 13 (reduction of waste-related greenhouse gas emissions). Zero-waste practices are an effective alternative to using landfills and waste-to-energy plants, which will raise awareness in the civil society about the importance of measures needed to be taken to protect environmental, social, and economic growth. i.e, help to achieve the goals of CE (fig 2). The objectives in this study are several: i) to determine the various stages. Of the production of crops life cycle, and execute a. modification of them according to the CE features; ii) to give a provisional. A summary of the knowledge sharing in circular agriculture. Of the number of documents, journals, authors, and countries in which the participation occurred. In the studies, and iii) to examine the development undergone in the various stages identified, principal adopting circular models. Donations in every one of them, and the possibilities and restrictions. Connections that have been ranked in their quest to foster the uptake of circular models in the agricultural sector. Context. To accomplish this, a compilation of the studies of the CE in agriculture was selected. Has been built out of the reference database. Such studies followed later. Analysed in depth. The primary innovation of this review, in comparison to Past research have is that it is founded on the agricultural life cycle stages. To receive some data on the degree of circularity and the possibilities of application. Connections and shortcomings, and drawbacks of both. The results of this study help to increase the knowledge on the implementation of circular models as initiatives to ensure the sustainability of the. Agriculture is also in its various phases of the life cycle.

Framework of circular economy, zero waste, and hydroponic system in Agriculture

Introduction of hydroponics

To meet the need for nutritious, reasonably priced, and sustainable food, those prolific areas where arable land and water are getting scarce are turning to intense high-yielding agricultural techniques and technology like hydroponics. The most significant quantities of hydroponically grown tomatoes are expected to come from Europe and the Asia Pacific region by 2028. (Velazquez-gonzalez *et al*., 2022) [28] Concentrating on climate resilience, effective resource use, and disease-free crop production, hydroponics is an alternative agriculture technique. Plants in hydroponics get a nutrient-rich water solution directly, so giving them the necessary components for development instead of soil. This method has several advantages, including better control over nutrient levels, more efficient use of water, and the ability to grow plants in areas with poor soil quality. (Rajendran *et al*., 2024) [27]. Advantages of hydroponic systems include (a) Soil-free cultivation, which simplifies maintenance and cleaning, allowing for the effective management of pests and pathogens between growth cycles; (b) improved resource efficiency achieved through the management of inputs and recirculation of nutrients and water; (c) reduced carbon footprint, particularly when using renewable electricity, compared to traditional agriculture practices that largely rely on fossil fuels; (d) accelerated crop production per unit area compared to conventional agriculture; (e) reduced shipping costs when hydroponic systems are located within or near urban areas; and (f) year-round operation, even in northern locations when electric lighting is used to supplement or replace sunlight. (Wang *et al*., 2024) [30].

Let us now the benefits of the hydroponics-

1. **Higher Yields & Faster Growth:** Direct nutrient availability speeds plant development by 30–50%
2. **Water Efficiency:** Recirculating systems reduce water consumption by up to 90%, therefore making hydroponics perfect for water-deficient areas.
3. **Land Conservation & Urban Farming:** Urban farming and land preservation Suitable for degraded territories, cities, and deserts.
4. **Reduced Chemical Use:** Controlled conditions help to minimise herbicides and insecticides, hence producing food free of contaminants.
5. **Year-round cultivation & Climate Resilience:** Controlled systems guarantee ongoing food production.
6. **Precise Nutrient Management:** Optimized nutrient solutions enhance plant vigor and nutritional value via exact nutrition management.
7. **Renewable Energy Integration:** Solar and wind power can help to cut reliance on fossil fuels.

However But hydroponics center on nutrient flow and water recycling. With flow rates influencing root morphology and hormone production, nutrients in hydroponic systems are given right to plant roots via a nutrient solution, hence affecting plant growth and yield. The efficiency and sustainability of these farming methods have been much improved by the inclusion of sensors in hydroponic and aquaponic systems. Sensor fusion and internet of things technologies are used in hydroponics to automatically monitor and control environmental circumstances, therefore improving plant output and lowering human interference. For instance, a clever hydroponic system using sensor fusion and the Random Forest algorithm can rank and change ambient factors, hence maximizing energy efficiency in light, temperature, and water level management.

Additionally, the use of spectroscopic sensors, such as the AS7265x, in micro indoor smart hydroponics allows for precise monitoring of nutrient concentrations, particularly nitrogen, which is crucial for plant growth. This system has demonstrated significant accuracy in predicting nutrient levels, thereby optimizing plant growth. . Ion Selective Electrodes (ISEs) are also pivotal in hydroponics, offering precise monitoring of specific nutrients like nitrates and potassium, which are essential for crop optimization. Various sensors are employed in hydroponics and aquaponics systems to monitor critical water quality parameters essential for the health and productivity of plants and aquatic life. (Dennison *et al*., 2025) [26]

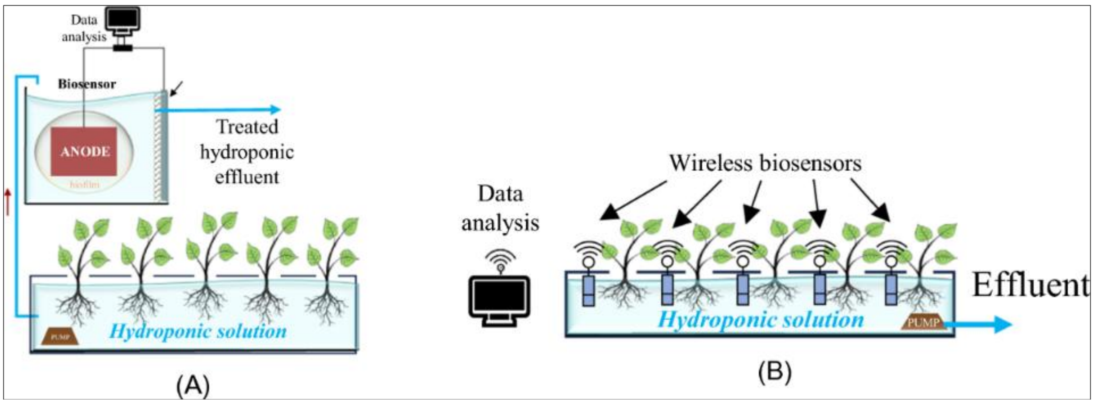

Fig 3: Current hydroponics for food production practices. (Wang *et al*., 2024) [30]

Circular Economy in Agriculture

The basic human civilization foundation is agriculture, which provides us with food, fiber, and fuel (Sharma U. *et al.*, 2022) [16]. However, the traditional linear method of farming practices has come under assessment because of its hazardous effect on the different components of the environment, such as soil degradation, water pollution, and GHG emissions in the air. To mitigate or control the historical impact of traditional farming practices, the integration of the circular economy concept and zero-waste practices is recommended, which emphasizes the sustainable production and management of agricultural products and waste, while simultaneously contributing to their reuse and reclamation. The CE and zero waste practices can be applied at various stages of the food system: production, consumption, waste, and surplus management (Jurgilevich *et al.* 2016) [8]. The CE approaches address various issues, like cultural. Financial, technological, and supply chain shortfall (Jurgilevich *et al.* 2016) [8]. CE helps to transform conventional production into sustainable models by incorporating the 4Rs: reuse, recycle, recover, and recovery/redesign. For example, crop residues, waste produced by the food industry, and animal excreta are converted into valuable inputs like biofuel, manure and compost, and biofertilizer, respectively. While zero-waste practices help convert waste back into the production cycle, they also regulate resource use. These products reduces our dependency on conventional resourses like fossil fules, synthetic fertilizers, etc, not so eco-friendly, while these conservational products are obtained through CE practices and Zero waste practices, are closed loop system of resources, also severs to attain organic farming i.e improves soil fertility, promotes biodiversity and replenishes the nutrient and water through recycling it, it also reduces the GHGs, which stabilizes climate change. The main issue is seen within the emerging economies like India, Pakistan, and Bangladesh, where the government policies are not efficiently able to incorporate the use of CE into their policy structure (Ada *et al.* 2021) [1]. With continuous time, the growing literature and awareness about food waste by many businesses, the government, and individuals support the implementation of CE as a basic solution to overcome the food waste problem (Kumar *et al.* 2022) [12].

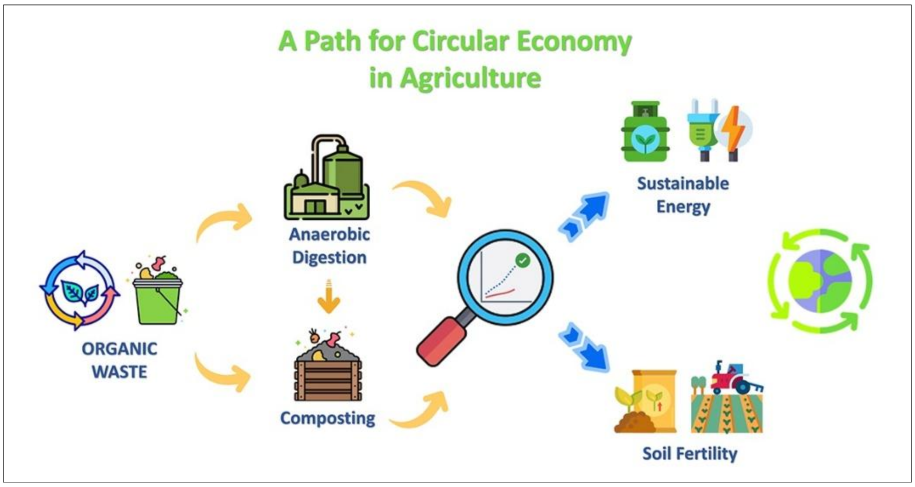

Fig 4: A Path for Circular Economy in Agriculture: From Organic Waste to Sustainable Energy and Soil Fertility (Constantinescu-aruxandei *et al*., 2025) [25].

As the degradation of soil with time, alarm has raised the futuristic perspective to find a dependable alternative medium, the need soil soilless culture, i.e., hydroponics, is a method of growing plants without soil, the medium is water-based mineral nutrient solutions. Thus, integration of circular economy with hydroponics is such a multilaterally beneficial perspective, as it will help to resolve multiple problems related to the soil, food security, agriculture residues management, thereby reducing the dependency on the non-renewable substrate and promoting the waste utilization. Also, the hydroponic system recirculates the water and nutrients from the primary to secondary plants in NFT units, which gives a major reduction in the amount of water required and nutrient inputs, increasing the efficiency of resources used. Hence, we can say that this approach is a resilient and sustainable method of food production with less waste and more profitable to both humankind and planet Earth.

The Challenges and Future Prospects of Hydroponics in Relation to the Circular Economy

In today's highly populated urban areas, hydroponic farming with zero waste management, following the principle of the circular economy, is an ideal solution to resolve the limited land availability problem with sustainable outcomes. But it comes with multiple challenges, which are the initial setup cost of the hydroponic unit, which is around 3 – 5 lakh for small commercial units, while it can increase to cores according to the area and technologies involved in it. While some people are not aware of the concept, there is a huge knowledge gap; either people don't know about the integration with circular economic practices. To overcome the knowledge and financial gap the approaches like training programs, educational initiatives, and extension services can be followed. The policy gaps are also an evident challenge, where to promote the concept, the government should make and impose policies to overcome the gaps. The government must adopt polices like tax relaxation in installations, certification for using the concepts, subsidies for adopting circular practices, and create a sustainable framework for soilless agriculture.

Further, there is a promising future ahead, especially as an evident alternative to degrading soil health and land scarcity in the context of the increasing global awareness of eco-friendly conservation and sustainability. Emerging technologies such as integration of resources and nutrient management, digital and AI tools, and innovations related to biotechnology play a significant role in enhancing the hydroponic unit with the circular economic practices in use for attaining both ecological and financial profit.

Buying the needed equipment and infrastructure such as hydroponic systems, greenhouses, and lights requires a considerable financial commitment. Furthermore expensive energy expenses related to operating the system can add up. The need for a regulated atmosphere within their greenhouses or other indoor facilities presents yet another difficulty for producers. Keeping plants healthy and developing calls for close observation and management of humidity, airflow, temperature, and other environmental elements. Producers must also make sure their buildings have adequate ventilation to avoid accumulation of carbon dioxide or other conceivably toxic gases. (Yulie, 2023) [31].

The need for exact regulation of environmental variables including pH levels and nutrient levels is one of the main obstacles; hence, sophisticated technologies like auto-calibrated pH sensors and wireless sensor networks are needed to guarantee ideal plant development. Managing these complex systems demands considerable technical expertise and know-how. Furthermore complicating maintenance is the synergy of hydroponics with other systems, including aquaponics, which calls for regulation of water chemistry and management of possible infections in both plants and fish. (Dennison *et al*., 2025) [26].

Conclusion

The fusion of the circular economy and zero-waste practices with the hydroponic system gives a transformative path towards sustainable food production practices. This approach not only addresses the challenges of limited arable land, infertile soil, and water scarcity, but also promotes biodiversity, improves resource utilization, and minimizes waste production through its closed-loop system but also maximizing long-term profit for the farmer. The 4Rs of circular agriculture (reuse, reduce, recycle, and recover/redesign) help to reduce the environmental footprint, while hydroponics seamlessly minimizes multiple factors of pollution and gives production of high-quality crops with lower inputs. Though there are challenges related to the high cost of installation and a knowledge gap, they can be bridged but the collective efforts of government polices and training programs. Overall, integration of the following provides us with a future-ready and visible solution to achieve food security for the population, plant sustainability, and economic viability. With the continuation of research, innovations in the same and new policies establishment will refine modern agriculture, helping in attaining the ideal scenario of sustainable, eco-friendly and economical way of food production.

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