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ORIGINAL PAPER

Sustainability and Circular Economy of Food Wastes: Waste Reduction Strategies, Higher Recycling Methods, and Improved Valorization

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Abstract
In this review, the issue of food recycling was comprehensively studied from the perspective of recent research. Firstly, the concept of circular economy and its application in reducing waste production and the strategies for waste reduction (waste prevention) were discussed. The concept suggests that we can produce less waste from the beginning to reduce costs for recycling, instead of generating much waste for recycling through specific approaches. Secondly, the results of several investigations on the recycling of various food wastes, which have been less considered important parts of waste management, such as university waste, agricultural waste, food industry waste, and spent coffee ground (SCG) waste, were discussed in detail. Finally, various methods for recycling and sustaining food wastes (improving the rates of recycling) and their application in aforementioned sections were comprehensively presented.

Keywords Food wastes · Circular economy · Recycling methods · Sustainability

Introduction

Nowadays, due to severe environmental problems such as water and soil pollution, it is crucial to find cost-effective and environmentally friendly methods for recycling, considering sustainability and the circular economy regarding food and plastic waste. Perhaps, creating a culture to produce less waste is far more effective than trying to recycle it. In addition, less waste generation seems to require less energy compared to recycling processes (UN 2015). For instance, researchers have conducted investigations on design ideas (Hebrok and Boks 2017), user behavior (Block et al. 2016), habit theory (Schanes et al. 2018), and discovery (Baron et al. 2018) to find the causes of this problem and also to discover a suitable and sustainable solution to reduce food waste. Also, the regional and global impact of food waste (FW) is known to be stretched over environmental, social, and economic levels (Gentil and Poulsen 2012; Thyberg and Tonjes 2017). Approximately 2.01 billion tons of municipal solid waste is generated worldwide each year, and among them 44% is food and green waste (Kaza et al. 2018a). It is estimated that from this amount, 37% is landfilled (only 8% of which have gas collection systems), 33% open dumped, 19% recycled or composted, and 11% incinerated as shown in Fig. 1. According to the high percentage of open dumping (33%) and landfilling without any gas collection systems (29%), paying attention to waste management is more felt than before (Kaza et al. 2018b).

Despite this high volume of waste, the development of modern and novel methods for waste recycling, which have some features such as fast, clean, sustainable, and cost-effective recycling, has received much attention. To achieve such an objective, the concept of the circular economy should be considered a mandatory approach for waste management.

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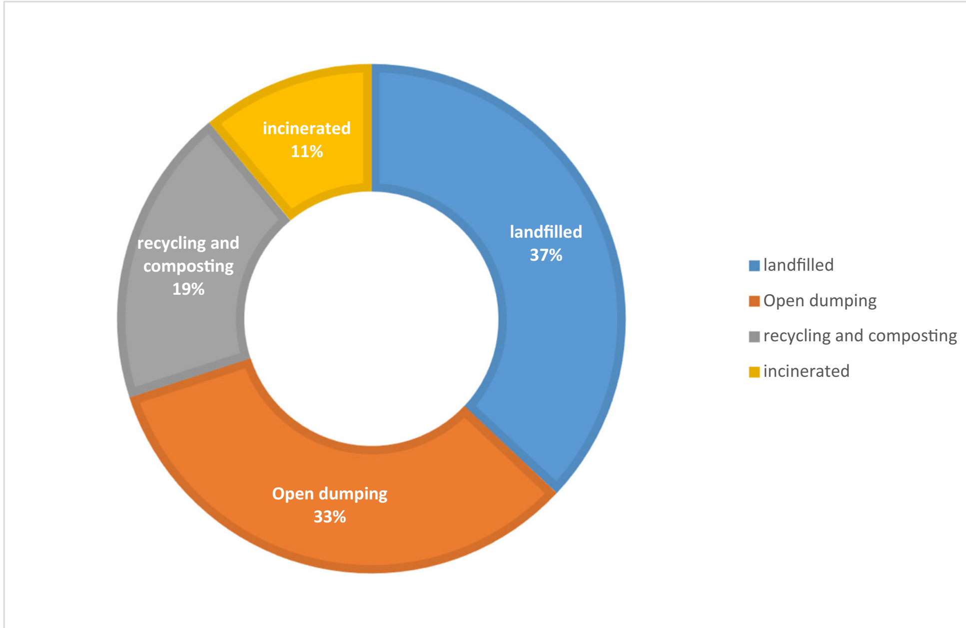


Fig. 1 Global treatment and disposal of waste

The circular economy, which has become increasingly crucial due to several factors such as the increase of wastes especially in every 5 years (Jose et al. 2020), is the sustainable solution for using these available wastes as the valuable materials (Dahiya et al. 2020).

Owing to what was mentioned above, the transition from a linear to a circular economy is vital (Mu'azu et al. 2019). Switching to the circular model will bring many economic, environmental, and social benefits (Maina et al. 2017). With the widespread use of the economic cycle, the economy is improved, which brings quite a few benefits namely a lot of job opportunities, lower storage costs for raw material, less pressure and adverse impacts on the environment, and reduction of price fluctuations (Kalmykova et al. 2018). Recently, the circular economics, with the aim of helping to preserve products, materials, and components at the highest level of efficiency, is increasingly being considered by the international scientific and political community. In other words, the important goals of the economic cycle are to achieve greater prevention of waste production and better management of natural resources by developing and closing material cycles (Ingrao et al. 2018; Zeller et al. 2019). A basic idea of a circular economy is illustrated in Fig. 2.

This review was divided into two general sections: The first section is concerned with food waste prevention and the second section with the categorization of waste materials into four important subsets of agricultural waste, university waste, food industry waste, and spent coffee ground (SCG) waste, which have played important parts in waste management. In each of the four cases mentioned above, the type of recycling method, the reason for using this method for recycling, and the recovery mechanism are fully presented for avoidable and unavoidable food waste (Papargyropoulou et al. 2014) as shown in Fig. 3. The results show how recycling methods could be beneficial for the economy as well as the environment so much so that these recycling methods could be considered a mandatory factor for any section which produces waste food.

Strategies for Waste Reduction

The universal food system, with almost 15–20% of total energy use, is a significant energy consumer (Beckman et al. 2013). This amount of energy consumption requires thoughtful planning for maximum use of resources for future generations. The essential purpose is less waste production or avoiding food becoming waste because with less waste production, less energy will be needed to recycle it, which can ultimately help create a clean environment. In this respect, Bala et al., by using eight separate materials, examined the comprehensive Spanish waste management plan for food packaging waste, from the collection stage of each section in special packages to final recycling. Also, particular life cycle influences per materials in each step were examined. This research can help identify current drivers that significantly help develop a combined strategy to waste packaging control and as a basis for investigations comparing technologies and waste return systems.

One of the most effective waste reduction strategies that has received much attention in recent years is the reduction of household food waste. The main idea, in this case, is to establish a culture and pay attention to household waste management to minimize the amount of wastes. Besides, paying

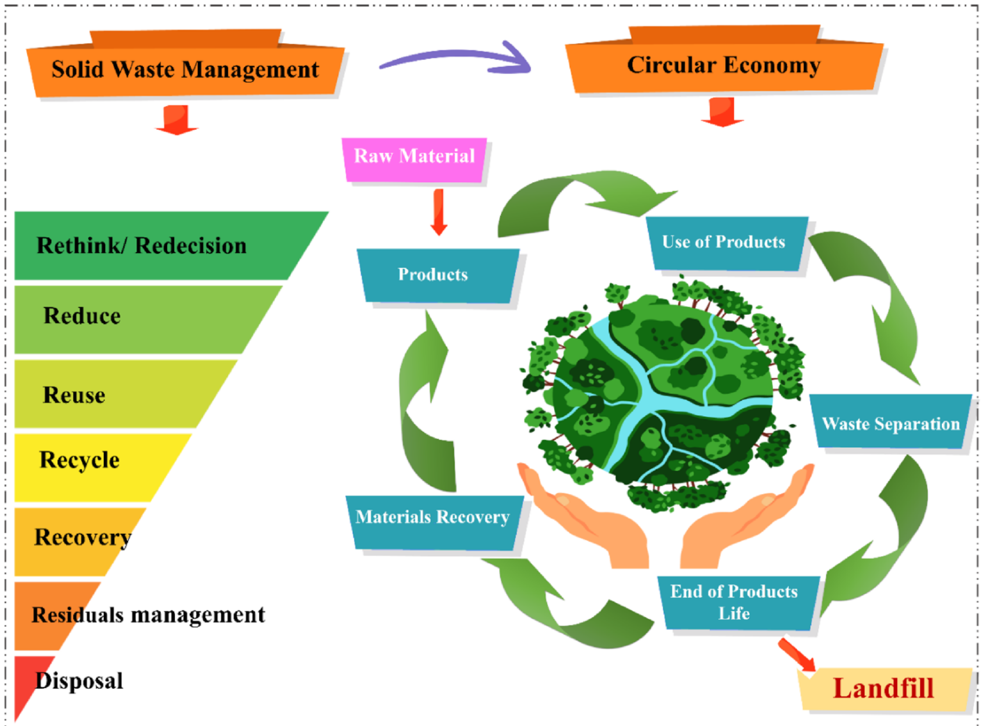


Fig. 2 A basic idea of a circular economy

attention to household waste management can potentially initiate beneficial changes at the individual, community, and even global levels (Dietz et al. 2009). In a related study, Kim et al. investigated various consumer perspectives on household food waste reduction in Australia. This study introduced to consumers the research pathways traditionally used in social marketing and proportion processes to reduce household food waste (Kim et al. 2020).

Today, due to population growth and the development of the construction industry, attention needs to be paid to waste management of construction workers. In this regard, Yang et al. investigated effective behaviors and factors to reduce construction waste generated by workers. The aim of this study was to identify the main factors affecting waste reduction behaviors of construction workers based on the theory of planned behavior (TPB) and to prepare a simulation model for their waste reduction behaviors through a system dynamic approach (SD) (Yang et al. 2020).

Improving the Rates of Recycling

University Wastes

Every year, a large amount of food is turned into waste, especially in countries with less scientific and technological progress. On the one hand, there is a need for research on this issue, particularly in universities, because universities are one of the producers of food waste due to a large number of students and ample food consumption. Therefore, this food waste in the university can be examined through various methods for recycling, sustainability, and evaluation. For this purpose, there are a number of food waste treatment technologies, such as landfilling (Ma et al. 2019), thermal/incineration (Elkhalifa et al. 2019), anaerobic digestion (Zhang et al. 2014), composting (Guo et al. 2018), and protein recovery treatment (Nguyen et al. 2015). To enumerate, Brenes-Peralta et al. performed a similar study at five universities in Latin America (Costa Rica). The outcomes demonstrated that the waste landfill scenario entails a greater global warming potential and freshwater Eutrophication impact than valorization scenarios. However, other impact divisions and costs are affected (Brenes-Peralta et al. 2020). In the same vein, Keng et al. performed a life cycle estimate advanced case study at the University of Nottingham Malaysia about composting food waste (Keng et al. 2020). The schematic diagram of this work is illustrated in Fig. 4.

Additionally, Fig. 5 explains that the main recycling process (taking into account the most optimal states) consists of 4 main steps (Keng et al. 2020).

Also, in this study, some equations were used for special purposes. For example, Eqs. 1 and 2 are used to achieve the initial W at approximately 50% (proper feed rate) and the optimal ratio of carbon to nitrogen (30:1). Besides, Eq. 3 is used to obtain the compost efficiency.

$$w = \frac{M_1 W_1 + M_2 W_2 + \ldots}{M_1 + M_2 + \ldots} \quad (1)$$

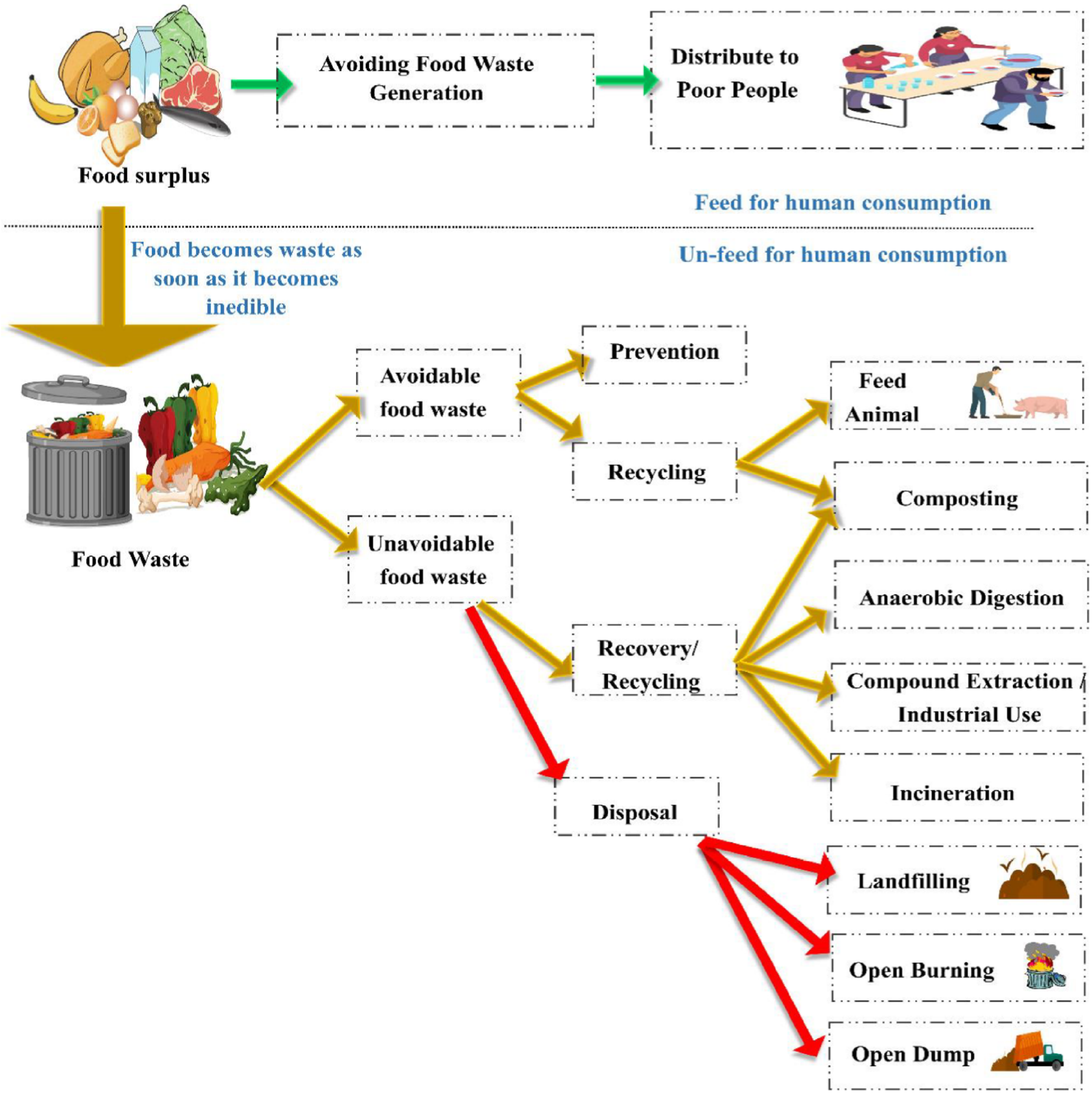
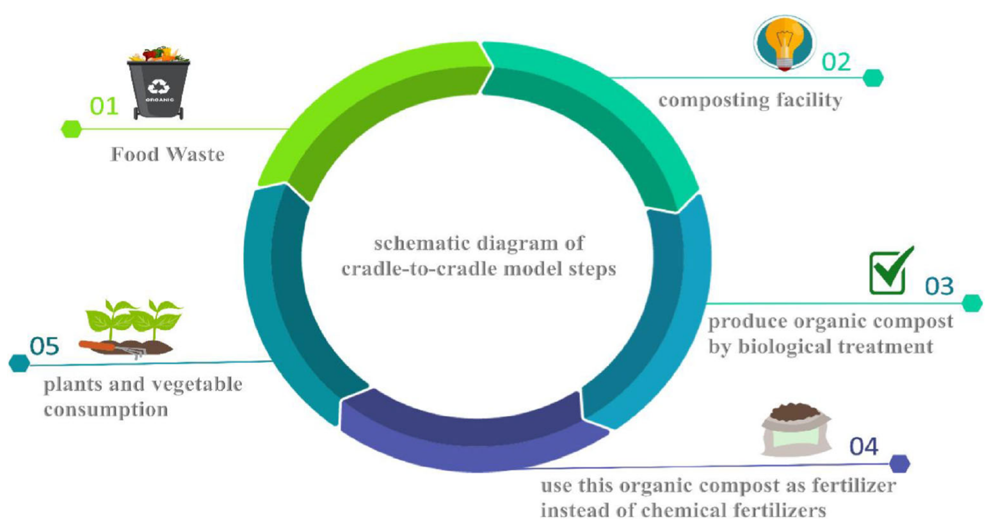


Fig. 3 The four stages for food waste management and treatment including reduce, reuse, recycle/recovery, and disposal

Fig. 4 Schematic diagram of cradle-to-cradle model steps



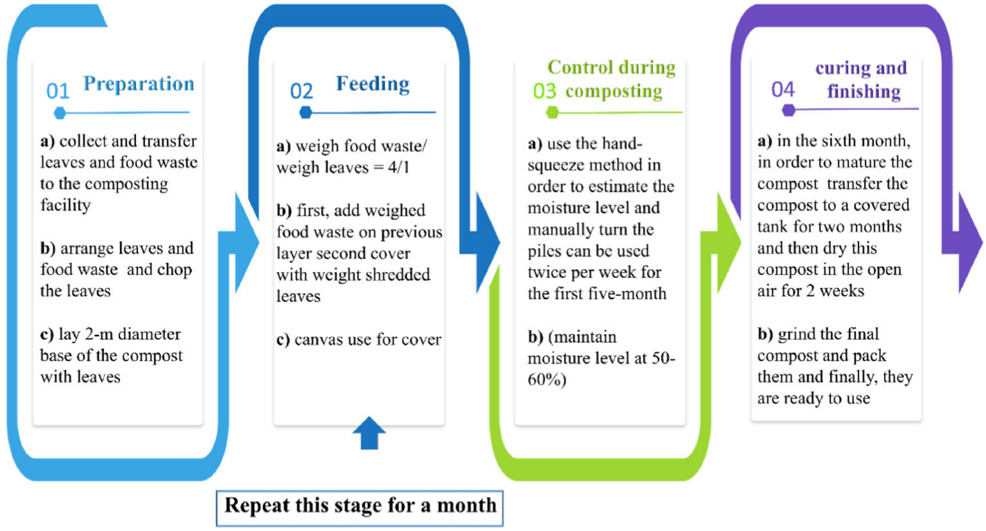


Fig. 5 The food waste treatment process

$$\frac{C}{N}\text{ratio} = \frac{M_1C_1(100-W_1) + M_2C_2(100-W_2) + \ldots}{M_1N_1(100-W_1) + M_2N_2(100-W_2) + \ldots} \quad (2)$$

$$\text{Compost yield (dry basis, \%)} = \frac{\text{Amount of compost produced}}{M_1(100-W_1) + M_2(100-W_2)} \times 100\% \quad (3)$$

where M determines the weight of the feed in kilograms per day, also the subscripted symbol shows the feed count (1 stands for the food waste and 2 for the leaf waste); W is the humidity; C is the whole organic carbon value; and N is the total nitrogen amount, all are expressed in percent. Furthermore, an accurate comparison between the process of composting and the landfilling of waste in detail was done by Keng et al. On the one hand, they realized that the most impressive option is the landfilling of ecotoxicity with the impact number of 1.44. More interestingly, ecotoxicity has the highest effect on composting with an impact number of 0.78. On the other hand, they realized that the lowest impact scores in the two parts of landfilling and composting were for the ozone depletion option, with 0.14 and 0.18, respectively. Therefore, the prepared compost is in accordance with the Malaysian organic fertilizer standard, so it exhibited the feasibility of this low-cost technology (Keng et al. 2020).

Based on all factors mentioned above, one of the most environmentally friendly treatment and technologies for food waste management is composting (Awasthi et al. 2020). Some studies have been carried out on home and industrial composting, considering their environmental impact, and chemical properties and the stability of the compost. Compost stability has been defined as the rate of decomposition of degradable organic materials. There were no considerable differences in chemical parameters regarding its agronomic usages like nutrient content and organic material. However, there were considerable differences in the rate of stability achieved. Home compost can achieve a better level of stability than industrial compost. It requires much effort in some composting plants, in terms of stability, to make a better quality of industrial composts (Barrena et al. 2014).

Overall, to achieve maximum efficiency of food waste management with a circular economy approach, waste sorting as a key factor in food waste management is inevitable. Recently, researchers are seriously considering automated sorting techniques for efficient waste management such as the state-of-the-art actuators, sensors, control algorithms, and sorting processes for recycling source-separated. Developed countries try to find the most optimal way to separate waste from the source and to recycle it. On the other hand, source segregation is not considered in developing countries, usually due to lack of motivation or limited systems such as door-to-door collection. In this way, the mixed form of collected waste is dumped in landfills without segregation, hence a need for automated waste sorting (Gundupalli et al. 2017; Padilla and Trujillo 2018).

According to the findings of this review, efforts are needed to provide scientific value to food waste management and making sure that the profitability of the circular economy will be approached, which is also emphasized by International Standards (ISO 2006).

Agricultural Wastes

Continuation of agricultural and rural activities requires the advancement of new processes for the valorization of industrial food residues in order to produce social and economic advantage (Goula and Lazarides 2015; Scheel 2016). Today, due to the importance of a vegetarian diet, many people around the world are consuming more vegetables and agricultural products. The United Nations Food and Agriculture Organization (FAO) estimated the value of waste from vegetables and fruits at higher than 60%, while the amount of waste related to these materials is 45%. Definitely, this high consumption requires intelligent and advanced management for recycling and sustainable waste production. Recently, powders derived from fruit waste have captured the attention of many researchers as a new method of using these wastes (Bhandari et al. 2013; Karam et al. 2016; Neacsu et al. 2015). In like manner, Bas-Bellver et al., using vegetable waste from the fresh production lines of a cooperative (carrots, leeks, celery and cabbage), produced powders for food use as additives and functional food ingredients.

As compared to non-processed waste, phenolic content increases significantly during the process, particularly when air drying is used to remove water. Unlike leeks, this sequence is quite obvious for carrots and white cabbage. In contrast, celery and green leeks revealed a decrease in phenolic content during the process. In the case of flavonoid content, the results were more complex (Bas-Bellver et al. 2020).

Accordingly, to achieve better results in obtaining more stable powders, drying or preserving a little amount of water are suitable methods. These powders are utilized in a variety of food industries such as grain and flavorings, natural preservatives, and additives to increase the nutritional value of several products. Similarly, Ortiz et al. examined how to manage production waste in small industries producing orange water. In this study, authors studied whether burning and anaerobic digestions are potential options for burying waste from a technical, economic, and environmental perspective. Results revealed that if these powders are properly dried, their stability and value will be considerably enhanced (Ortiz et al. 2020).

Production Industry Wastes

Today, for various economic and environmental reasons, the improvement of production methods and culture of optimal and correct consumption has been one of the main challenges facing government officials (Huysman et al. 2015).

Also, studies conducted in urban (Rodrigues et al. 2020), rural (Ramírez-Islas et al. 2020) agricultural, and industrial fields (Guan et al. 2019) suggest that factors such as technological progress and development, changes in various production patterns in industries, and subsequent waste management (in term of volume) play a key role in socioeconomic management of waste recycling. Additionally, in various sectors of the industry, much planning and research have been performed in recent years for greater productivity, sustainability, and a circular economy. Likewise, Orrico et al. by carefully studying the waste produced based on the age of the chickens in a meat broiler industrial unit conducted an investigation on the intelligent management of this waste. In addition to the age of the birds, the waste collection involves the hatching process, during which either hatching eggs (at the time of admission) or hatching eggs (as shown in Fig. 6) were performed (Orrico et al. 2020).

The first step began with the collection in the egg acceptance salon. The steps are performed according to Fig. 6, so that the eggs are sent to the incubator in the last stage, where they remain until 21 days from the incubation when most of them lay eggs. In addition, the temperature reached during composting for more than 15 continuous days in all treatments is above 40 °C. From an economic point of view, this temperature was the most optimal temperature, because the process of composting at this temperature had minimal casualties. For this reason, due to the burning of the egg shell among the discarded materials, there was a large amount of calcium in the resulting compost (Orrico et al. 2020).

In a similar study, with a different stance towards egg waste, Jung et al. used it as a preservative for vegetables and fruits. Thus, this is a sustainable and economically efficient way to reduce food vulnerability. Animal eggs are a particular product for preserving fruit because they are high in protein and lipid content. Moreover, food waste in the USA consists of 2% eggs, which is remarkable (Jung et al. 2020). In another investigation, Laso et al. attempted to find an economical and environmental stability in value chains in the fish canning industry based on circular economy. This scientific research has identified an optimal way by using a new method that takes into account the cost and longevity of the recycling cycle, to minimize waste from the fish canning industry. Moreover, there was much discrepancy in the results obtained based on the type of fish. Thus, this research introduces the cradle-to-cradle idea (Laso et al. 2018). Moreover, in one study, Garcia-Garcia et al. focused on barley straw which is one of the huge portions of beer production waste. Barley straw partly has been used for animal feed; however, by using supercritical CO_2, wax can be produced on the pilot-plant scale. Recently, the huge demand for wax in global markets leads to industrial attraction to this process (Garcia-Garcia and Rahimifard 2019).

Spent Coffee Grounds

Coffee is the second largest beverage after tea in the world (Scully et al. 2016); it is an example of a product with a high level of unavoidable waste after consumption, producing 1.88 kg of spent coffee grounds (SCGs) per kilogram of coffee beans used (Cameron and O'Malley 2016). SCGs are the initial unavoidable (inedible) waste from ground roasted coffee (Esquivel and Jiménez 2012). They have different origins but have two main sources: (1) consumption for cafes and restaurants and (2) home use (Scully et al. 2016).

This high amount of waste is destructive to the environment. Besides, most people throw SCGs directly into the trash, but this may not be the only way, but it is the last resort. SCGs can be used as fertilizer in agriculture or in conversion

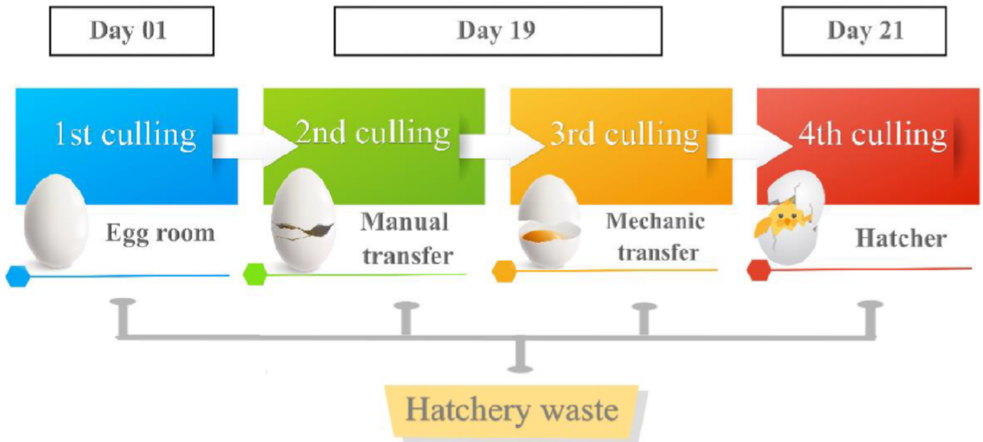


Fig. 6 Culling steps during broiler chicken egg incubation

systems. For instance, Chen et al. used a combination of SCGs and silver skin in the energy storage system (Chen and Jhou 2020). In this regard, Ximena C. Schmidt Rivera et al. used this waste in the industry to produce heat with intelligent management of their recycling cycle instead of wasting it in a large scale. In this study, the unit of activity was "correction of 1 tone of SCGs." Besides, most people now consider SCGs as a waste, and improving this mindset requires smart management (Rivera et al. 2020) (as shown in Fig. 7).

The scope of this study included the following steps:

i. Transportation: transportation of SCG trucks from the source to the treatment plant with an average distance of 45 km
ii. Preparation: preparing for use in the production unit
iii. Exploitation: waste recycling management for use in various industries
iv. Use of products produced from waste in the required sections

Conclusions

Waste is one of the environmental problems in today's world, and its lack of management has consequences on human life and health. "Landfilling" is one of the oldest and most traditional ways to deal with the "phenomenon" or "problem" of waste, but this (and other similar approaches) is not a way to solve the problem of waste, and it is only a temporary solution. On the one hand, one of the most economical investments is to be able to produce the desired products without spending money on raw materials (or at the lowest cost). Thus, the issue of waste recycling is very similar to this subject. On the other hand, from the point of environmental pollution and global warming, it is essential to pay attention to optimal waste management recycling procedures.

Therefore, the presented article focused on recent studies for food waste management with the circular economy perspective. In the first part, the fundamental issue of preventing the production of waste was examined which has been playing

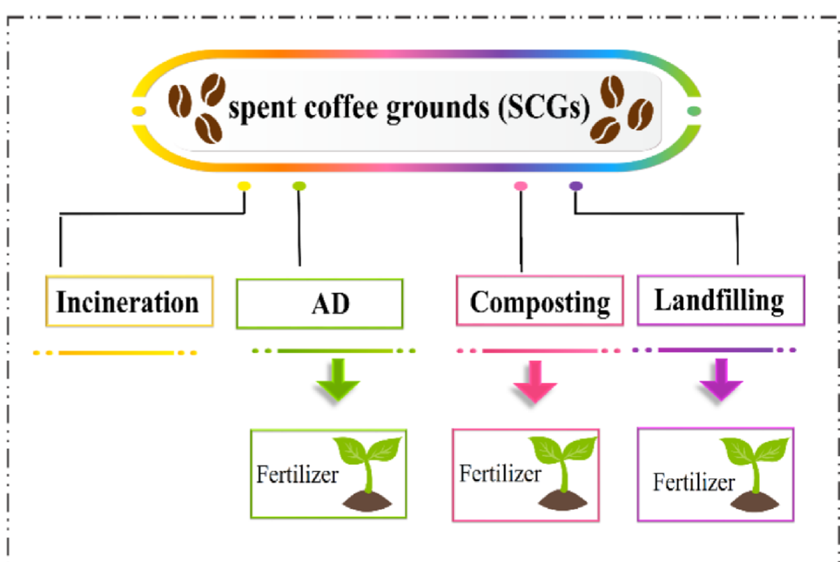


Fig. 7 System boundaries considered in the study

the important role in decreasing the mass of food waste so much so that contributes to the remarkable decrease in food waste treatment costs. The second part of this article dealt entirely with four different types of waste, including agricultural waste, spent coffee grounds (SCGs), food production waste in various industries, and university wastes. In this section, some of the methods of waste recycling were discussed with particular attention to sustainability and the circular economy. For example, universities can use their food wastes with the special treatment method as fertilizer for growing eatable plants on their campus and use these plants again in their daily meals. By doing so, not only can universities manage their waste, but also they can reduce their costs for preparing food which this approach is one of the basic goals of the circular economy. Thus, all of these sections remind us that the disposal of food waste is not a wise decision, and sustainable methods should be applied for food waste management in order to have a cleaner environment.

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