Journal of Cleaner Production 317 (2021) 128467

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management

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ARTICLE INFO

Handling editor: Cecilia Maria Villas Bôas de Almeida

Keywords:
Circular economy indicators
Environmental pollution
Global warming potential
Organic fertilizer
Recycling
Waste management

ABSTRACT

Organic waste management (OWM) currently follows the linear economy principle in most of the Gulf countries. Most CE studies to date revolve around the reduction, recycling, and reuse of the material in a production and consumption chain. In this study, the whole process chain's economic and environmental monetary values were investigated to convert organic food waste (OFW) into compost, following the CE indicators. The monetary savings from macronutrients (carbon and NPK) enrichment by applying compost to the soil and its replacement value of the mineral fertilizer have never been reported in the CE model. The OFW production of Makkah city is estimated to increase up to 1.60 Mt in 2030 because of domestic population growth and an increasing number of pilgrims traveling to perform religious rituals. This massive quantity of OFW can produce 0.23–0.40 Mt of compost in 2015–2030 and reduce 0.043–0.076 Mt of CH_4 emission. The implementation of this technology will generate net revenue of 240–419 MSAR from compost selling along with a potential substitute of 124–216 kt of chemical fertilizers during 2015–2030, following the CE. The environmental savings (waste dumping and carbon crediting related to CH_4 reduction) can be 618–1078 MSAR, while fertilizer replacement savings will be 74–129 MSAR in 2015–2030. In general, implementing the composting technology following the CE model has the potential to add a cumulative net revenue of 1626 MSAR to the national economy of the Kingdom of Saudi Arabia in 2030. Implementing the CE model in OFW generates compost, reduces waste management problems by closing the materials recycling loop, generating extra income, and adds net revenue to the national economy. It will also help the decision-makers devise a suitable sustainable waste management policy.

1. Introduction

The circular economy (CE) is a notion that supports the responsible circularity of the available recourses to attain sustainable development goals (Moraga et al., 2019). This concept involves a regenerative model where efforts are made to minimize the inputs (resources) and waste in any form of leakage or disposal to close or slow down the materials loop. CE led to the promotion of 10-Rs principle to reduce waste materials in the chain to achieve sustainable development (Klemeš et al., 2020). Most industrial enterprises and businesses follow linear economy concepts worldwide. The products manufactured in the industry are taken for utilization by the public and disposed of the unused, thus following the "make-use-dispose" consumption model. Such practice is not in line with sustainable development goals; therefore, most of the countries around the globe, with China as the first to implement CE law in 2008 (CIRIAG, 2015) and Germany and Japan among the pioneer to implement CE in their national policies (Geng et al., 2013). The EU countries recently proposed a CE monitoring framework (Mayer et al., 2019). The implementation of this approach is thought to reduce the environmental burdens of global warming and resource scarcity caused by the industrial revolution (Abad-Segura et al., 2020). According to the CE action plan in EU countries, by 2030, the food waste will be reduced to half per capita at the retailer or consumer level in production and supply chains (Flanagan et al., 2018). For this reason, CE is redefining the current waste management practices of food and other waste types to create new businesses and jobs. For instance, food waste can be utilized for compost (organic fertilizer) production (Waqas et al., 2018b), bioenergy (Dahiya et al., 2018), and several other value-added products (Teigiserova et al., 2019).

Recent studies showed a slight shift from the current linear or moderate recycling model (Närvänen et al., 2021) to better circular use

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https://doi.org/10.1016/j.jclepro.2021.128467
Received 29 December 2020; Received in revised form 14 July 2021; Accepted 26 July 2021
Available online 27 July 2021
0959-6526/

List of abbreviations

Million Ton Mt
Carbon C
Carbon credit CC
Carbon Dioxide Equivalent $CO_{2\ Eq}$
Circular economy CE
Diammonium Phosphate DAP, P_2O_5
European Union EU
Global Warming Potential GWP
Green House Gas GHG
Intergovernmental Panel on Climate Change IPCC
Kingdome of Saudi Arabia KSA
Life Cycle Assessment LCA
Million Saudi Riyal MSAR
Ministry of Environment, Water, and Agriculture MEWA
Municipal Solid Waste MSW
Nitrogen N
Operational and Maintenance O&M
Organic food waste OFW
Organic waste management OWM
Phosphate P
Potassium K
Sulphate of Potash SOP

of the materials which under normal circumstances treated as waste (Teigiserova et al., 2020). The leading causes for the hindrance of circularity under waste management are economic, socio-cultural, and institutional factors (Salmenperä et al., 2021). The current waste management practices still do not entirely back the CE model since the novel, and advanced techniques for utilizing waste as a resource in CE have not been recognized so far (Zhang et al., 2019). The role of waste management strategy is significantly crucial in transitioning from the linear model of the economy to a circular one (Närvänen et al., 2021), where key directions are designing a system to eradicate waste through prevention (Ciccullo et al., 2021), regenerating biomaterials and restoring the technological materials (Stahel, 2016). Following the CE model, the food waste materials have been recycled into various products. Some studies about these conversions include; slaughterhouse waste into feed and fertilizer (Kayikci et al., 2019), used vegetable oils into biodegradable detergents (Lucchetti et al., 2019), conversion of wheat bran into biodegradable tablewares (Donner et al., 2020), grape skin and seeds along with stems into bio compost (Sehnem et al., 2020) and household food waste into compost (Slorach et al., 2020). The application of LCA-based footprints (Maier et al., 2017) can help ecologically optimize these products' transformation processes (Klemeš et al., 2020). The main focus of most CE studies revolves around reducing, recycling, and reusing the material along the production and consumption chain (Oliveira et al., 2021).

In most Gulf countries, including the Kingdom of Saudi Arabia (KSA), food waste is the mainstream of municipal solid waste (Nizami et al., 2017). Recent estimates suggested that this waste was up to 50 % of the MSW in the city of Makkah (Shahzad et al., 2017b). Food waste is generally mixed with MSW in KSA and disposed of in landfills without being processed for any material or energy recovery from this precious organic source (Mu'azu et al., 2018). Such management practices are a source of pollution to water bodies (Baun et al., 2000) and the atmosphere. About 76 % of the Kingdom's methane gas is emitted from landfills (Khan and Kaneesamkandi, 2013), causing severe environmental issues. In the future, following the linear economic model, this current waste management, based on the notion of "take, make, use and dispose of" (Barros et al., 2020), is not working in the region. To cope with these waste management-related environmental issues and decrease its dependence on the oil-based economy, the government of KSA has launched a policy initiative known as Vision (2030) (Vision-2030, 2020). Seeking sustainable solutions, to manage huge waste production and minimizing its disposal to landfills for the generation of economic benefits is among the key objectives of this vision. To comply with this vision in food waste management, CE would be the best strategy to adopt. Waste can be minimized, reused, or recycled in production and consumption chains by applying CE indicators utilizing the Life Cycle Approach (Moraga et al., 2019). The implementation of environmental footprints based on the LCA providing more revealing quantification, which become crucial with the arrival of the COVID-19 pandemics (Klemeš et al., 2020).

The circularity of the product or material influenced the economy, both direct and indirect (Potting et al., 2018). As a result, circularity assessment could be relied on direct and indirect indicators, especially when data about the products or materials are not available. Moraga et al. (2019) defined CE indicators with specific and nonspecific strategies to consider the life cycle thinking approach and technological development modeling level. They used three scopes (i.e., 0, 1, and 2) for the indicators classification. According to them, scope 0 indicators did not use the life cycle thinking approach to measure the technology cycle's physical properties, for instance, the recycling rate (Graedel et al., 2011). On the other hand, scope 1-indicators utilized life cycle thinking to measure the previously mentioned properties employing partial or complete life cycle thinking approach with the indicator reusing, recycling, and recovering mass/materials (Ardente and Mathieux, 2014). However, scope 2-indicators measure the influence on the technology cycle of social, economic, and environmental disquiets. These indicators measure reuse, recycle, or recoverable effects of products/materials on the environment (Huysman et al., 2015). In this study, scope 1 and 2 indicators of CE were utilized for the food waste management system. It includes compost production from OFW and estimating how much savings (environmental and recycling) can be achieved. The conversion of food waste into compost and its application in agriculture as the end product would be the first step towards transitioning the linear model of the economy to a circular one by closing the material loop without producing any other side product or so-called waste material. The process will follow cleaner production principles to achieve sustainable waste management goals in KSA for promoting CE in this sector. The proposed current and future OFW managements, including recycling this waste and its environmental and economic values as an indicator of CE of Makkah city, are shown in Fig. 1.

The economic assessments for waste to value able products have been published, such as food waste to compost (Chen, 2016), slaughterhouse waste to biopolymer (Shahzad et al., 2017a), slaughterhouse waste to biodiesel (Shahzad et al., 2017b), organic waste to biogas (Al-Wahaibi et al., 2020), MSW to value-added products (Nizami et al., 2017). These studies focused on the economic analysis of a single process/technology or biorefinery concept. According to the best of our knowledge, the whole process chain's economic and environmental monetary values had not been reported so far to convert organic food waste (OFW) into compost, following the CE indicators.

This study's main aims were, i) to investigate the CE indicators i.e., economic, environmental impact assessment and quantitative analysis of compost production potential from food waste produced in Makkah city. ii) To assess the quantity and economic benefits of compost nutrients (C, N, P, and K) produced from OFW to replace chemical fertilizers. This economic assessment from nutrients (carbon and NPK) enrichment and their alternate mineral fertilizer savings have never been reported in the literature. This analysis includes the conversion of food waste to compost as the starting material. The tipping fee saving by diverting food waste from the landfill. Carbon credit-earnings equivalent to the

Fig. 1. The proposed circular economy concept for organic waste management in Makkah city.

GHG emission savings by avoiding landfill dumping. The revenue obtained by selling fertilizer and its application to the soil to enrich macronutrients, i.e., C and NPK. The estimation of potential economic savings by replacing the alternate commercial fertilizers, i.e., Humic acid for C, Urea for N, Diammonium Phosphate for P, and potassium phosphate for K in the compost.

2. Methodology

The estimation of MSW generation in the holy city of Makkah is carried out based on the number of domestic residents and the number of pilgrims (domestic and international) visiting Makkah to perform religious rituals. The Umrah pilgrims come to Makkah throughout the year to perform Umrah while Hajj pilgrims visit around the month of Dhu al-Hijjah (the last month of the Islamic calendar) because the Hajj ritual is performed on the 10th of Dhu al-Hijjah. In this study, 2015 is considered the base year. The number reported a local population of Makkah was 2.0 M people in 2015 (Population-city, 2014). During 2015, the cumulative number of Hajj pilgrims was 1.9 M, domestic Umrah pilgrims were 12.7 M, and 6.1 M pilgrims traveled internationally to perform Umrah (GAS, 2015). The MSW generation rate for the domestic population is assumed to be 1.4 kg person^{-1} d$^{-1.}$ In comparison, the MSW generation rate for domestic and international pilgrims is considered 2.4 kg person^{-1} d^{-1} as reported by Ali et al. (2020). The waste generation by the pilgrims is estimated based on their duration of stay in Makkah. It is assumed that the average length of the visit for Hajj pilgrims is about 21 d. Similarly, the average visit duration for international Umrah pilgrims is considered 15 d and 7 d for domestic Umrah pilgrims.

The future projections of MSW generation for the local population are calculated using a 5.76 % population growth rate, which is the average population growth rate in Makkah from 2010 to 2014 (Population-city, 2014). Following the Saudi Vision 2030, the government aims to expand its facilities to accommodate 5 M pilgrims for Hajj and 30 M internationals pilgrims for Umrah every calendar year. It is assumed that the domestic number of Umrah pilgrims will follow a more or less similar trend. The projected number of pilgrims until the year 2030 is estimated using a linear function. The relevant MSW generation will also increase accordingly (Vision-2030, 2020).

It is presumed that the MSW composition in Makkah was similar to the MSW analysis carried out by Khan and Kaneesamkandi (2013) for KSA. It reveals that the OFW fraction constitutes 50.6 % of the overall annual MSW (Khan and Kaneesamkandi, 2013). In a business as usual scenario, the MSW is dumped in the landfill without any material or energy revcovery (Mu'azu et al., 2018). The composting technology's organic fertilizer (compost) production potential is calculated by considering a 25 % compost production yield with 40 % moisture content (Shah et al., 2017).

The environmental savings include dumping fees and carbon credits. The dumping fee is the amount of money paid to the waste disposal site for waste transportation and dumping. The dumping fee value of 572.36 SAR/t (Nizami et al., 2017) is considered to calculate savings due to the waste diversion from the disposal site to the composting facility. The approximation of the carbon credit value for the waste diversion is dependent on the methane emission potential. The methane emission potential of the OFW fraction is computed by using the method endorsed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2007). The mathematical equation for the specified is given in equation (1) (Noor et al., 2013).

$$Q = \left[MSW_T \times MSW_F \times MCF \times DOC \ \times DOC_F \times F \times \frac{16}{12} R \right] (1 - OX) \tag{1}$$

The simulation of methane emission potential for the OFW fraction is carried out considering parametric values for uncategorized organic waste following published literature (Noor et al., 2013). A global warming potential (GWP) of CH_4 emissions in CO_2 equivalents ($CO_{2eq.}$) Mt, over 100 years, is calculated using a factor of 25. The carbon credit (CC) value is estimated considering US$ 23.20 (equivalent to 86.25 SAR)/t CO_2 eq. (Ali et al., 2020). The CC trading is not functional at present in the KSA. The estimated saving value represents the amount of additional revenue generation in executing the trading system in KSA.

The estimation of fertilizer savings is calculated by considering four essential nutrients, namely carbon (C), nitrogen (N), phosphate (P), and potassium (K). In business, as usual, these nutrients are delivered to the crops through commercial fertilizer application. The alternate sources for the provision of these nutrients were selected as humus for C, urea for N, diammonium phosphate (DAP) for P, and sulphate of potash (SOP) for K. It is assumed that mature compost contains about 40 % moisture content and 60 % compost dry matter (DM). The selected nutrients reported values are 21.02 % for C, 0.935 % for N, 0.235 % for P, and 0.32 % for K (Shah et al., 2017). These values are equivalent to 0.210 t C, 9.35 kg N, 2.35 kg P, and 3.2 kg K per t of compost DM. The alternate C provision source humus contains about 24.18 % C content with a market price of about 562 SAR/t (DTNPF, 2020). The inorganic source of N provision to the crops is urea, which contains 46.6 % N content. The market price for urea was about 1534 SAR/t (DTNPF, 2020). Typically, P is provided in the form of DAP containing 46 % P content as P_2O_5. The cost of DAP was about 1879 SAR/t (DTNPF, 2020). The SOP is usually utilized as an additional source of K to the crops. It contains about 46 % of K content with a market price of about 1384 SAR/t (DTNPF, 2020).

The monetary cash flows are considered as revenue. The selling price of 1.5 SAR/kg of compost is used to calculate the facility's income. The gross revenue is the sum of income arising from environmental savings (tipping fee and carbon credit value), compost selling, and cumulative fertilizer savings due to the application of compost as an organic fertilizer. The net revenue value is obtained by subtracting the composting facility's operational and maintenance (O&M) cost. The O&M cost is considered 30 % of the revenue generated by compost selling. The O&M cost included the waste collection, transportation, and O&M, and maintenance of the composting unit. The steps followed in the revenue estimation are given in equations (2) and (3):

Gross revenue = Environmental savings (dumping fee saving + carbon credit value) + compost selling + cumulative fertilizer savings (2)

Net revenue = Gross revenue – Operation and maintenance cost (waste collection + Operation and maintenance cost of the composting facility) (3)

The schematic methodological framework of this study is illustrated in Fig. 2.

3. Results and discussions

3.1. Current scenario and future projections (2030) of the local population, hajj and Umrah pilgrims, and MSW in Makkah city

The current population of Makkah city is 2.03 M people, so at the current growth stage, this population is expected to be around 2.7 M people in 2030 (Fig. 3).

In the present scenario, the hajj pilgrims who performed Hajj (religious rituals Muslims performed every year in Makkah) in 2019 were 2.5 M (MoHU, 2019). In order to comply with the ongoing reforms under

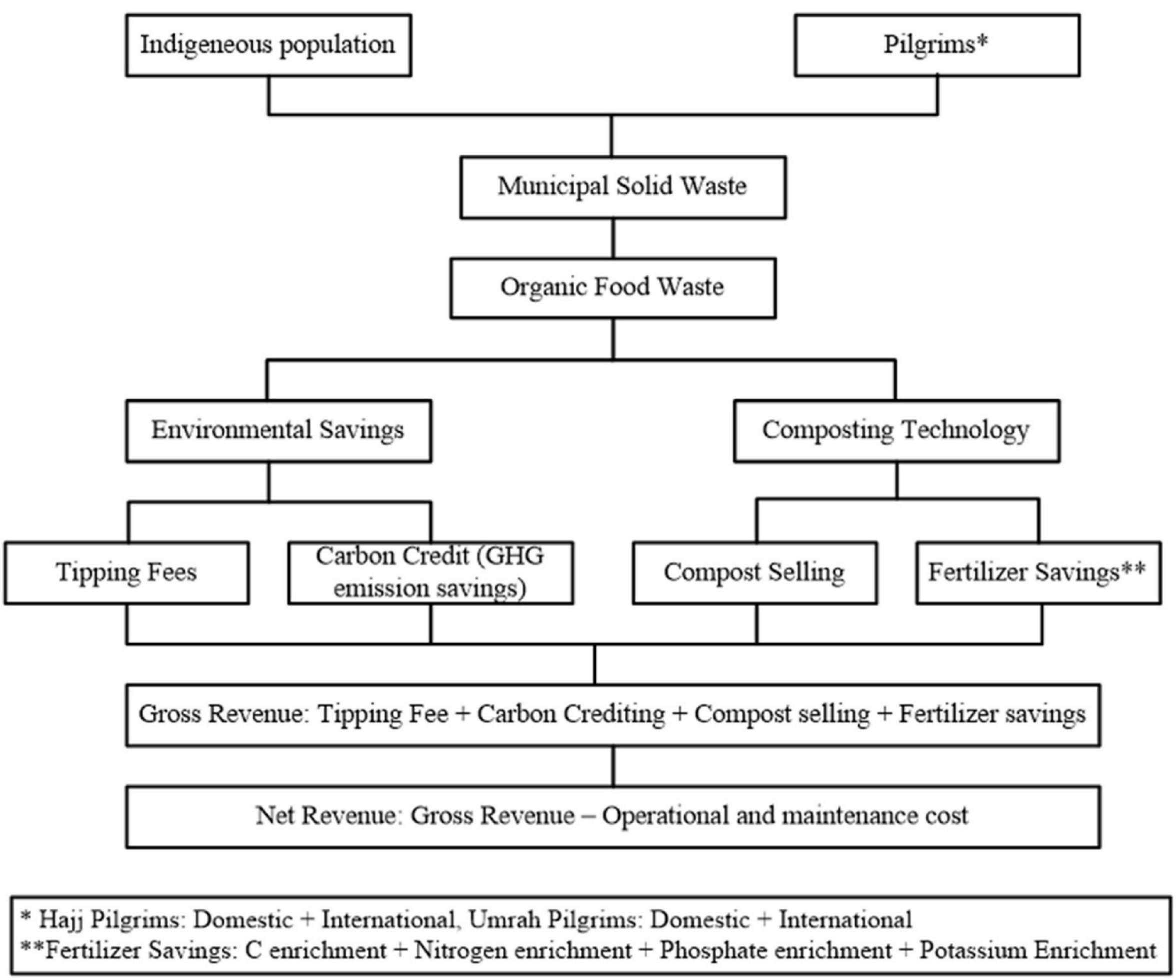

Fig. 2. The Schematic diagram of the methodological framework.

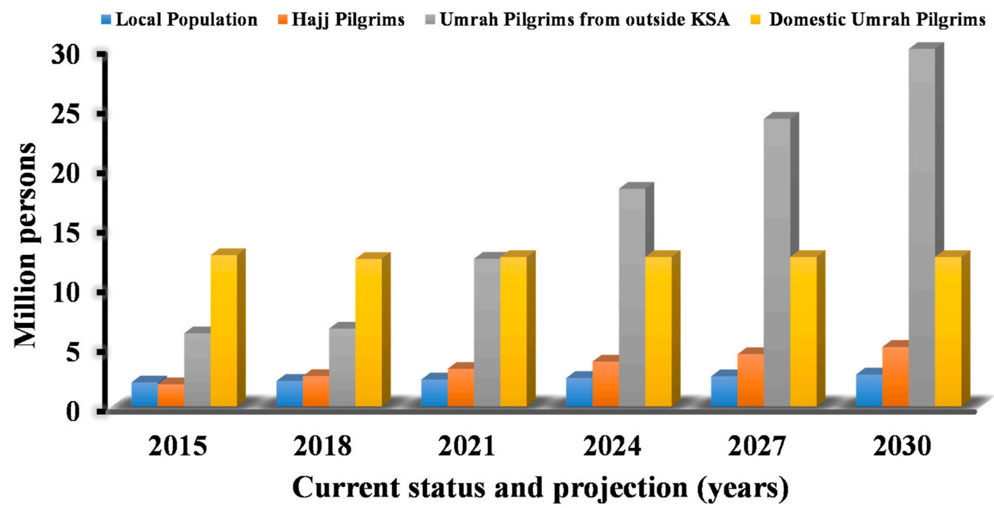

Fig. 3. The current and projected local population, Hajj, Umrah, and domestic pilgrims from 2015 to 2030.

the vision 2030, the government is trying to shift from its oil-based economy to various other measures, including an increment in the number of Hajj and Umrah pilgrims (Vision-2030, 2020). The number of international Hajj is projected to be 5M, whereas the Umrah pilgrims will be 30 M people in 2030 (Fig. 3). Consequently, the share of the pilgrims in the MSW generation was estimated to be 0.77–1.37 Mt during 2015–2030. The waste generation by domestic population was projected to be 1.04 to 1.78 from 2015 to 2030 as per projected increase in the domestic population and targeted numbers of pilgrims (Fig. 4).

3.2. Recycling food waste for compost production as an indicator of CE

Recycling is a scope 1-indicator of CE (Moraga et al., 2019). Its implementation in the kingdom's food waste management would result in considerable benefits to the environment and the local population (Waqas et al., 2018b). Makkah is the holy city of KSA, where many Muslim pilgrims around the world visit every year to perform religious rituals. Therefore, its waste generation compared to other cities is high (Nizami et al., 2017). The MSW of Makkah city consisted of ~50 % organic food waste (Shahzad et al., 2017b). The amount of OFW generation was 0.92 Mt in 2015, which is projected to be 1.35 Mt in the year 2030 (Fig. 3). The cumulative amount of OFW generated by the local population and Pilgrims will reach 1.60 Mt in 2030. If utilized for making compost, this increase in the OFW production would result in an increasing calculated amount of compost production with the time that will be ranged from 0.23 to 0.40 Mt in the years 2015–2030 (Table 1). Implementing recycling as an indicator of CE in food waste management could play an essential role in mitigating waste-associated pollution and becoming a source of industrial development and job creation for the local people.

Table 1
Economic analysis of compost production from food waste for the year 2015–2030.

Years	Food Waste	Compost	Selling value	[a]O & M cost	[b]Revenue
	Mt		MSAR		
2015	0.92	0.23	343.48	103.04	240.43
2018	0.97	0.24	361.90	108.57	253.33
2021	1.12	0.28	420.91	126.27	294.64
2024	1.28	0.32	479.51	143.85	335.66
2027	1.44	0.36	538.85	161.66	377.20
2030	1.60	0.40	598.96	179.69	419.27

[a] Operation and maintenance cost is considered 30 % of the revenue generated by compost selling.
[b] Revenue from composting operation.

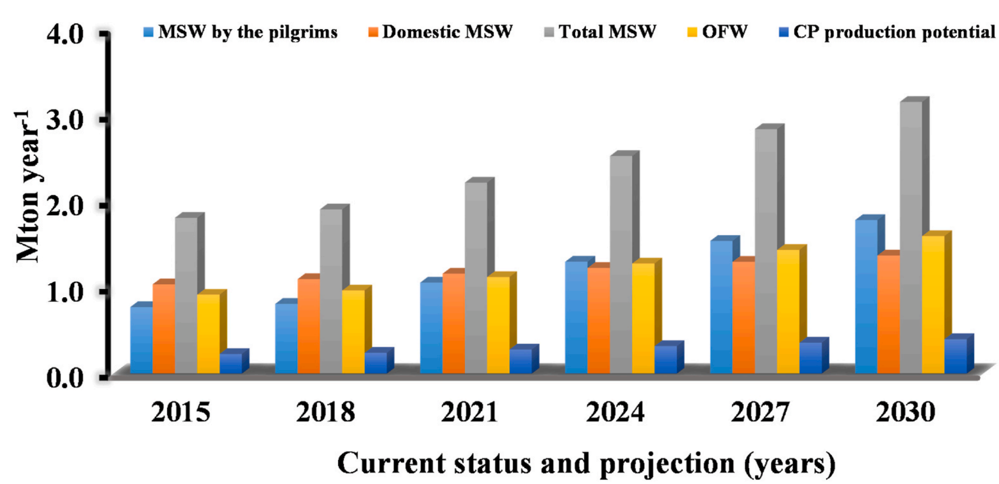

Fig. 4. Current and projected generation of total municipal solid waste (total MSW), the organic waste fraction (OFW) by the pilgrims, MSW produced by domestic population and pilgrims, as well as compost (CP) production from the OFW from 2015 to 2030.

3.3. Compost utilization/replacement potential of chemical fertilizers with the application of compost

The value-added product's utilization is the next phase to complete the CE goal (Kirchherr et al., 2017). In the kingdom, chemical fertilizers, i.e., urea, DAP, and SOP, are utilized in agriculture for crop production. The Ministry of Environment, Water, and Agriculture (MEWA) of KSA is trying to enhance the availability of cheap local organic fertilizers to improve organic production by 300 % (MEWA, 2018). As a result, the compost requirement is currently high in the kingdom (Alzaydi et al., 2013). The estimations reveal that 0.23 Mt of compost produced from OFW of Makkah city can replace 2.8, 0.7, and 0.9 kt of Urea, DAP, and SOP in 2015 (Fig. 5). The projected quantity of 0.40 Mt compost production in the year 2030 would lead to the replacement of 4.8, 1.2, and 1.7 kt of Urea, DAP, and SOP (Fig. 5).

In addition to N, P, and K replacement, compost can act as a supplementary C source for soil to improve its organic matter content, structure, water-holding, and cation exchange capacity (Ali et al., 2019). The same quantity of compost that replaced the Urea, DAP, and SOP would also enrich the soil with 28.9 kt C and substitute 119.4 kt of alternative C source fertilizers such as humic acid in 2015 (Table 2). There is an increasing trend of this replacement with time. In 2030, the projected quantity of compost (0.40 Mt) would replace 208.3 kt of alternative C source with C enrichment potential of 50.4 kt to the soil (Table 2).

The compost application to the soil will fulfill the nutrients demand and help to increase soil C content or organic matter, infiltration rate, water-holding capacity, sorptivity, and reduce cumulative evaporation (Al-Omran et al., 2019). These are much required characteristics of the soils under cultivation in the arid region of KSA, which are defined as poor organic matter, nutrient-deficient, and dry calcareous sandy soils (Bashour et al., 1983). The compost application in such soil is considered to counteract nutrient deficiencies and improve physicochemical and biological properties (Rashid et al., 2016). Its application will help mitigate the soil degradation problem in KSA (Benabderrahim et al., 2018). In addition to the short-term benefits of nutrient supply and increment in organic matter content, the compost also has residual effects on soil fertility and crop yield (Eghball et al., 2004). The buildup of organic matter in the soil by compost confers long-term nutrients release for approximately 6 years (Allievi et al., 1993). These long-term residual effects of compost are challenging to estimate in our calculation. If we take the long-term influence of compost into account, then the compost's substitution value would be much higher during the subsequent years (Jaza Folefack, 2009).

Table 2
Carbon enrichment potential and savings from the compost from the year 2015–2030.

Years	Compost	compost (DM)[a]	C enrichment[b]	Alternate source[c]
	kt			
2015	228.98	137.39	28.88	119.44
2018	241.27	144.76	30.43	125.84
2021	280.60	168.36	35.39	146.36
2024	319.68	191.81	40.32	166.74
2027	359.23	215.54	45.31	187.37
2030	399.31	239.58	50.36	208.27

[a] Moisture content in mature compost 40 %.
[b] Carbon content in mature compost 21.02% (Shah et al., 2017).
[c] Cost of alternate C source 562.5 SAR (Online web source).

3.4. Environmental benefits as indicators of CE: reduction in methane production from the food waste if dumped in landfills

CH_4 is a well-known greenhouse gas, and its GWP is 25 CO_2 eq. for a 100-year time scale (IPCC, 2007). It shows that this gas is 25 times more harmful in terms of global warming than CO_2 emission. Landfills are a significant source of CH_4 emissions around the globe. When solid waste is decomposed under anaerobic environmental conditions, especially in sanitary landfills, 40–60 % of this waste is converted into CH_4 production under deserted ecological conditions (Alzaydi, 1980). According to Khan and Kaneesamkandi (2013), landfills contribute to CH_4 emissions by ~76% in KSA. The estimation reveals that the compost production from OFW of Makkah city during 2015 could have reduced 0.043 Mt of CH_4 production associated with this waste dumping into the landfill. The projected CH_4 emission potential from landfills in 2030 will reach 0.08 Mt (Table 3). The kingdom's landfills are not scientifically designed to collect produced gases from the dumped waste. Such massive green house gas (GHG) production could have a global warming potential of 1.09 Mt from the food waste of Makkah city in 2015 and would be projected to increase up to 1.9 Mt in 2030 (Table 3) and therefore may serve as a significant source of environmental pollution and global warming in the future.

With the continuation of current waste management techniques, the threat of global warming potential will, even more, be enhanced in 2030

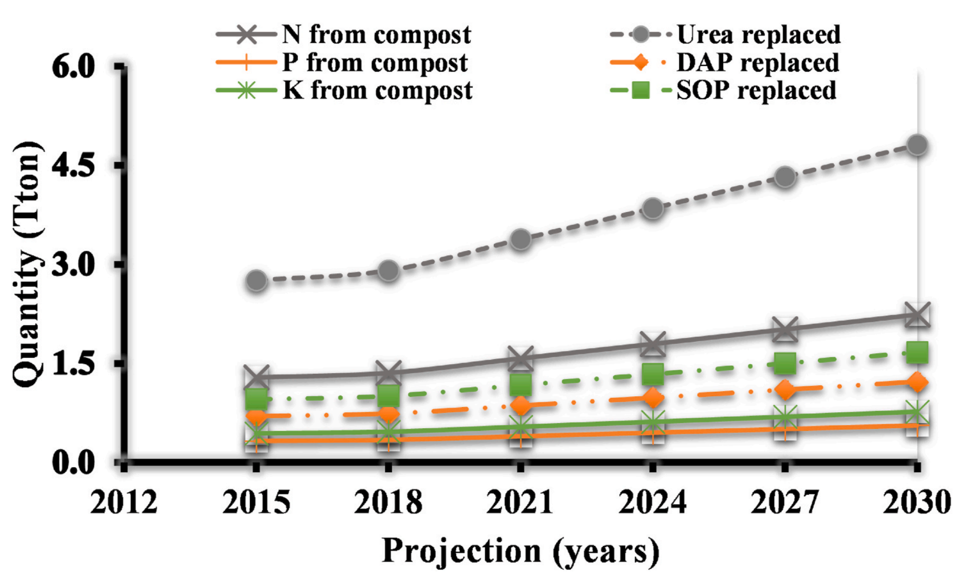

Fig. 5. Replacement of nitrogen (Urea), phosphorous (diammonium phosphate (DAP)), and potassium (sulphate of potash (SOP)) by the compost produced from the OFW from 2015 to 2030.

Table 3
The environmental savings from Carbon Credit (CC) and dumping fee.

Years	CH_4	GWP (CO_2 eq)[a]	Revenue from CC savings[b]	Dumping fee[c]	Environmental savings[d]
Mt			MSAR		
2015	0.043	1.09	93.68	524.25	617.92
2018	0.046	1.14	98.70	552.37	651.07
2021	0.053	1.33	114.80	642.43	757.22
2024	0.061	1.52	130.78	731.88	862.66
2027	0.068	1.70	146.96	822.45	969.41
2030	0.076	1.89	163.36	914.19	1077.55

[a] Based on global warming potential of 25 for methane.
[b] At the cost of US $ 23.20/t of CO_2.
[c] Savings based on Waste Diversion 572 SAR/t.
[d] Revenue from CC + tipping fee.

if wise and sustainable waste management techniques, such as the implementation of CE, will not be adopted. The release of other GHG emissions from the landfills to the atmosphere and discharge of concentrated leachate (with N, P, K, etc.), pollutants, pathogens into the soil and water bodies are causing severe environmental and public health concerns in the kingdom (Abdul Aziz et al., 2007). By adopting waste recycling technologies as a CE indicator (Moraga et al., 2019) with the compost production technique as a potential contender, the kingdom can reduce MSW-related GHG emissions, including CH_4. The problems associated with leachates, such as eutrophication of groundwater bodies and soil contamination in the areas of landfills, can also be reduced using compost production technology (Loni et al., 2013).

3.5. *Economic and environmental savings (CE indicator) through compost production from food waste*

Composting of organic waste is a well-established process. One can use mechanized, in-vessel, conventional static, a turned heap, and windrow composting methods to produce compost (i.e., organic fertilizer). The compost production is a lengthy process and may take 4–6 months to get matured compost. It has been reported that the process can be optimized, and maturing time can be reduced from 2 to 3 months by using biochar (Waqas et al., 2018a), natural zeolite (Waqas et al., 2019), lava meal (Shah et al., 2018), gypsum (Qu et al., 2020), etc. as additives and optimization of the moisture content and temperature. Windrow composting is the recommended method at municipalities which is a large-scale on-site production with minimum operational and maintenance costs (Vigneswaran et al., 2016). These composting systems consisted of linear rows where compost materials are piled. The material rows manually or mechanically turned to facilitate aeration and improve the mixing of composted material constituents. This mixing results in a faster decomposition rate and homogeneous finished compost than a static compost pile (Vigneswaran et al., 2016). This method is well established and adopted by many municipalities in western countries. The development of a composting facility to recycle the OFW in Makkah city will have multiple benefits, i) help solve the MSW problem, ii) create jobs for local people, and iii), a source of a significant amount of revenue generation. An economic analysis of developing a composting technology in Makkah city is provided here. The study includes the revenue generated from, i) waste diversion from landfill, ii) environmental savings through CC, iii) fertilizer selling, iv) and replacement of the equivalent quantity of N, P, K, and C nutrients which are being utilized in agriculture through Urea, DAP, SOP and humic acid from 2015 till 2030. The CE concept's implementation could save food waste dumping costs as tipping (waste transportation and dumping) fees due to the waste diversion from the landfill to the recycling facility. At present, the kingdom is spending a cost of 572 SAR/t for waste dumping into the landfill (Nizami et al., 2017). It was estimated that the kingdom could have saved an amount of 524 MSAR from waste dumping in the year 2015. There is an increasing trend in this saving amount with time, which has been projected to be 914 MSAR in 2030 (Table 3). In addition to gate or tipping fees with CE implementation, this waste diversion could have generated a revenue of 94 MSAR from CC in 2015, which is estimated to increase to 163 MSAR in 2030 (Table 3).

The total environmental saving of 617 MSAR could have been achieved in 2015, which is projected to be 1078 MSAR in the year 2030 (Table 3). Nizami et al. (2017) proposed anaerobic digestion to solve the food waste problem in Makkah city. This technology can generate a revenue of 244 million SAR from landfill diversion in the year 2014, and it can save 44 million SAR from carbon credit in that year. Anaerobic digestion in total can save an amount of 288 million SAR in the year 2014. Shahzad et al. (2017b) proposed biodiesel production from the slaughterhouse waste in the Makkah and estimated a net environmental savings of 302 million SAR in the year 2014. In contradictory to the anaerobic digestion or biodiesel production, the compost production technology can save 617 million SAR from the environment in the year 2015, which is approximately two times higher in terms of saving from the environment by any proposed technology to date. This increase in benefits is linked to the extension of the economic analysis to the application of the product (i.e. compost) which is the economic savings from nutrients (carbon and NPK) enrichment by organic compost and its replacement value of the mineral fertilizer. It showed this technology is much more beneficial for solving the food waste problem in Makkah city. Hence, by implementing CE with food waste management, the Kingdom can save vast amount from the environment.

The estimated amount of C, N, P, and K replacement savings from alternative organic fertilizer, urea, DAP, and SOP by compost is presented in Fig. 6. The estimations reveal that the C enrichment in the soil caused by the application of compost is equivalent to 67 MSAR, saved by replacing the alternate source, humus or humic acid, in the base year 2015, and this amount is projected to increase by 74.4 % (117 MSAR) in 2030, for the kingdom. Similarly, N, P, and K are the other significant nutrients supplied to the crop to fulfill their nutrient demand in Saudi Arabia, mainly from mineral fertilizers (Bank, 2020). If compost is produced locally from the food waste, the government could have saved 4.2 MSAR from the urea replacement in 2015, and this saving is expected to reach 7.4 MSAR in 2030 (Fig. 6). DAP and SOP replacement savings could have been 1.3 MSAR each in 2015 and projected to reach 1.9 MSAR each in 2030 (Fig. 6).

The total fertilizer replacement saving from Urea, DAP, SOP, and alternative C fertilizer with compost can add a saving revenue of 129 MSAR to the kingdom economy with the proposed CE concept in the year 2030 (Fig. 6).

The net revenue generation using CE indicators from the proposed composting technology is calculated by adding up the revenue generated by selling compost, fertilizer replacement, and environmental (tipping fee + carbon credits) savings (Figs. 7 and 8). It is estimated that sustainable compost production technology could have generated a net revenue worth of 932 MSAR in its base year 2015. With the installation of this compost production technology in Makkah city, the net revenue of 1626 MSAR can be added to the Kingdom's economy in 2030 (Figs. 7 and 8).

There is no additional and highly skilled labor required to recycle the food waste into compost. This technology can be implemented in any urban city, including Makkah. The compost production technology in Makkah city is technically, economically, and environmentally the most suitable technology for solving the food waste problem. It would be the first step towards the CE implementation (Fig. 8) in the region.

3.6. *Demand and utilization of compost in the kingdom of Saudi Arabia*

In Saudi Arabia, the rate of fertilizer used to fertilize crops is 177 kg nutrients (N, P, and K) ha^{-1} (Bank, 2020), and crop production is practiced in an area of 1,011,375 ha (MEWA, 2017). Consequently, the

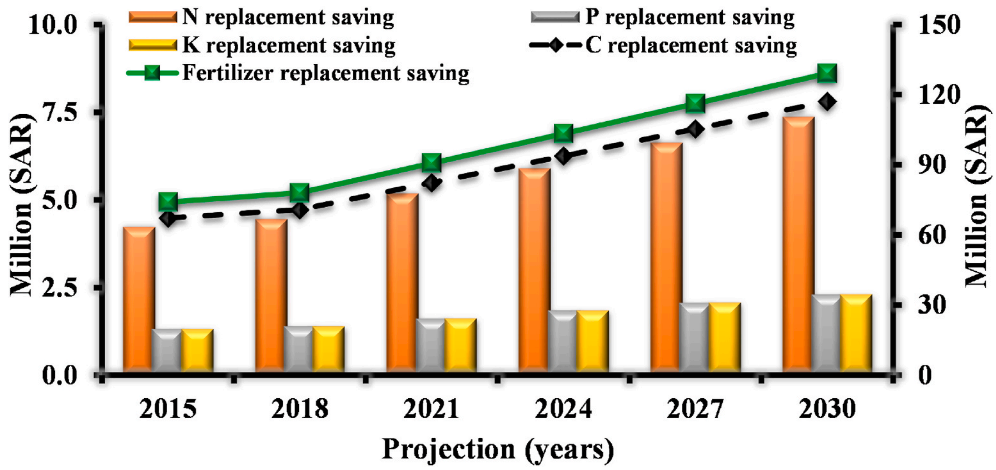

Fig. 6. Nitrogen (N), phosphorous (P), and potassium (K) saving values presented at the primary x-axis as well as Carbon (C) and cumulative fertilizer replacement (at secondary x-axis) savings by the use of the OFW compost from 2015 to 2030.

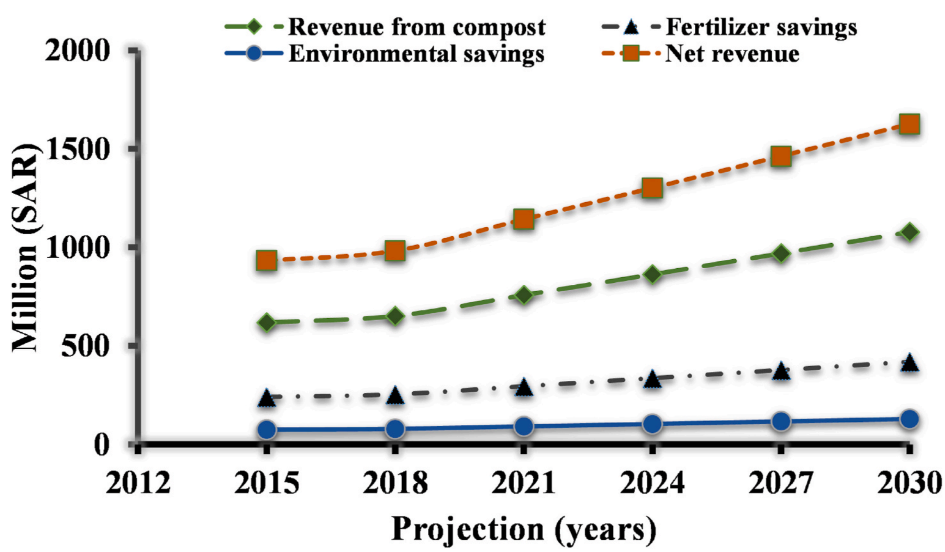

Fig. 7. Revenue generation from compost selling, fertilizer saving, and environmental savings from 2015 to 2030.

calculated amount of total fertilizer required to fertilize this area is 3.38 Mt of N, P, and K nutrients. In line with the goals set by the vision 2030, the Ministry of Environment, Water, and Agriculture is intended to increase organic agriculture production by 300 % (MEWA, 2018). In this production system, 100 % utilization of organic fertilizer (i.e., compost) is obligatory to produce crops organically. The ministry would like to enhance local organic fertilizer production and increase the area for organic agricultural practice. Currently, 18,635 ha area of the kingdom is under organic agriculture production or converted from conventional farming practices to an organic one, requiring 3636 t of N, P, and K nutrients in organic fertilizer (i.e., compost). The P (whose % presence is the lowest in the compost than all other significant nutrients) requirements for organic agriculture production is 1.5 Mt of compost, mostly imported from different countries (Hartmann et al., 2012). The estimation reveals that only 0.23 Mt of compost could have been produced in the base year (2015) from Makkah food waste, which could be increased to 1.6 Mt in 2030. Other nutrients such as C, N, and K are also an integral part of the compost, and their %ages are even higher than P in the compost. If the kingdom meets P nutrient requirements, then C, N, and K requirements will automatically be met by applying the same quantity of compost. Thus, the compost produced from the food waste of Makkah city can partially fulfill Saudi Arabian organic fertilizer demand. There is a need to explore the feasibility of implementing this technology for food waste produced in other major cities like Jeddah, Riyadh, and Dammam to meet organic fertilizer requirements in the Kingdom.

Compost can also be used to substitute inorganic fertilizers for crop production, especially in low-input agriculture (Bedada et al., 2014). This organic fertilizer has a great potential to reduce farmer's dependence on commercial fertilizers (i.e., urea, DAP, SOP). The complete substitution of commercial fertilizer with organic ones resulted in lower net benefits than their partial substitution with compost. The partial substitution significantly enhanced crop yield, soil carbon sequestration, reduced GHG emissions, nutrients leaching, and runoff in China (Tang et al., 2019). Consequently, partial substitution of chemical fertilizer with compost will be more beneficial even in Saudi Arabian conditions, especially in areas where conventional agriculture is practiced, so there will also be a demand for compost in these regions. The production of compost from the food waste of various Saudi Arabian cities can replace the imported organic fertilizers and locally produced chemical fertilizers to meet the local fertilizer requirement.

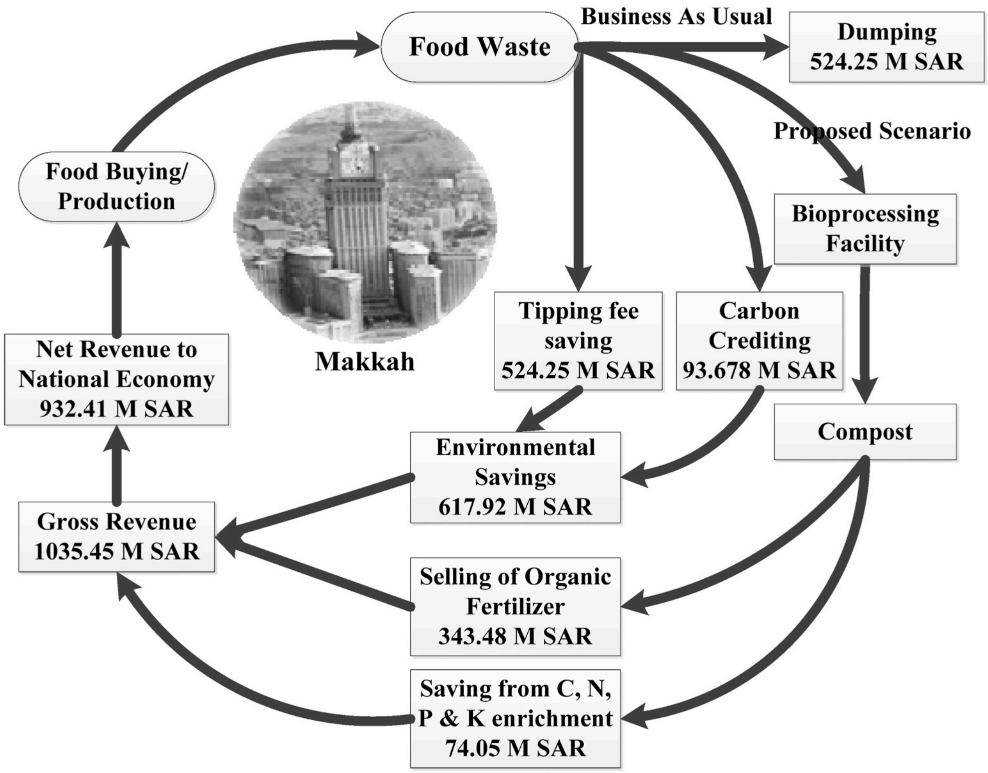

Fig. 8. The economic and environmental benefits of OFW recycling to produce compost as indicators of the circular economy for organic waste management in Makkah city.

4. Future outlooks

The proposed composting technology identified the great potential for sustainable recycling of the food waste of Makkah city. This will be the first step towards CE implementation in the Kingdom. Implementation of this technology will produce organic fertilizer, mainly imported to meet the demand for organic agriculture (Alzaydi et al., 2013). The proposed technology would significantly reduce the landfill sites occupied by waste dumping and help solve the socio-economic and environmental problems associated with food waste disposal. Despite the several positive observations, this study also has some limitations because of the challenges of covering all aspects of compost production in a single analysis. The current research only considered CH_4 emission from the landfill. It did not include other greenhouse gases (CO_2, N_2O, NO, and NO_2) emissions and eutrophication caused by the nutrient leaching from landfills (Bekchanov and Mirzabaev, 2018). Future studies should also focus on releasing the toxic ammonia (NH_3) and other GHG emissions from the waste dumping sites. These studies should also emphasize the positive impact of improved food waste management on the lakes' environmental quality and eutrophication problems associated with the current landfill sites (Loni et al., 2013). The development of the composting facility can reduce environmental pollution and improve overall air quality. In addition, there are GHG emissions related to the composting process, compost packaging, transportation, and application to the field. All these emission calculations and their relevant impacts will be part of future studies, including eco-economic evaluation of the compost production using life cycle assessment and life cycle cost methodologies. The future prognosis can also assess the climate change mitigation potential of composting technology and its utilization in the CE concept worldwide. A more detailed analysis can evaluate job creation's economic impact in the composting business on the overall national economy since the Kingdom is looking for an alternative business model to decrease its oil-based economy dependence. In the future, the current method used for assessing fertilizer replacement can further be improved by integrating nutrient release patterns from the compost with crop nutrient recoveries and yields. This detailed analysis will help understand the relationship between crop nutrient utilization efficiency and food production efficiency, which is the key to enhancing crop yields. The organic food demand is substantially increased worldwide, and the kingdom is keen to expand its organic food production in the coming years by 300 % (MEWA, 2018). Future-modeling studies can also focus on the revenue generated from the export of agricultural commodities utilizing compost production from food waste in the Kingdom and around the globe. It will further close the nutrients open loop in the current food waste management and give the economic picture of the recycled products circularity in the global agriculture sector.

5. Conclusions

This pioneering study provides the recycling potential of food waste to produce organic fertilizer (i.e., compost) and its economic and environmental assessment as indicators of circular economy in managing food waste. It discusses an integrated economic and ecological analysis of compost production from food waste and its substitution potential to replace its competitive chemical fertilizers (urea, DAP, and SOP) to save revenue. The analysis shows the recycling of food waste to the value-added product as an indicator of CE. Recycling and reusability of garbage will help reduce the operational and environmental issues associated with current waste management practices and add considerable revenue to the national economy. Implementing this technology in the year 2021 will convert 1.12 Mt of food waste into a total of 0.28 Mt of compost. This technology can save 757 and 91 MSAR from the environment (tipping fee and CC) and all fertilizer substitution and generate 295 MSAR from the fertilizer production. In total, this technology can add a net income of 1143 MSAR into the national economy in this specific year. As a result, it would help close the nutrients loop from the waste management issue and be the first step to convert the linear economic model of the kingdom to a CE model following the kingdom's goal of shifting from an oil-based economy into a sustainable economy as per the vision of 2030. Composting technology can add a net revenue of 1626 MSAR in the year 2030 to the Kingdom economy. In the year 2030, this technology's implementation only in Makkah city will not meet the kingdom's organic fertilizer requirement for organic agriculture. This concept of compost production from food waste should be extended to the other cities of the Kingdom to meet the local organic fertilizer demand. It will not only solve the Kingdom's food waste-associated problems, but it will also help to achieve the national goal of less dependence on oil-based income in the year 2030.

CRediT authorship contribution statement

Muhammad Imtiaz Rashid: Writing – review & editing, Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing. **Khurram Shahzad:** Writing – review & editing, Conceptualization, Methodology, Data curation and calculations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This project was funded by the Deanship of Scientific Research (DSR), King Abdulaziz University, Jeddah, Saudi Arabia, under grant no. (D-252-188-1440). The authors, therefore, gratefully acknowledge the DSR technical and financial support.

References

Abad-Segura, E., González-Zamar, M.-D., Belmonte-Ureña, L.J., 2020. Effects of circular economy policies on the environment and sustainable growth: worldwide research. Sustainability 12 (14), 5792.
Abdul Aziz, H., Isa, M., Kadir, O., Nordin, N., Daud, W., Alsebaei, A., Abu-Rizaiza, A., 2007. Study of Baseline Data Regarding Solid Waste Management in the Holy City of Makkah during Hajj 1427, National Seminar on Hajj Best Practices through Advances in Science & Technology, Centre for Education. Training and Research in Renewable Energy and Energy Efficiency (CETREE), Universiti Sains Malaysia, p. 2007.
Al-Omran, A., Ibrahim, A., Alharbi, A., 2019. Evaluating the impact of combined application of biochar and compost on hydro-physical properties of loamy sand soil. Commun. Soil Sci. Plant Anal. 50 (19), 2442–2456.
Al-Wahaibi, A., Osman, A.I., Ala'a, H., Alqaisi, O., Baawain, M., Fawzy, S., Rooney, D.W., 2020. Techno-economic evaluation of biogas production from food waste via anaerobic digestion. Sci. Rep. 10 (1), 1–16.
Ali, A.M., Nawaz, A.M., Al-Turaif, H.A., Shahzad, K., 2020. The economic and environmental analysis of energy production from slaughterhouse waste in Saudi Arabia. Environ. Dev. Sustain.: A Multidisciplinary Approach to the Theory and Practice of Sustainable Development 1–18.
Ali, B., Shah, G.A., Traore, B., Shah, S.A.A., Al-Solaimani, S.G.M., Hussain, Q., Ali, N., Shahzad, K., Shahzad, T., Ahmad, A., Rashid, M.I, 2019. Manure storage operations mitigate nutrient losses and their products can sustain soil fertility and enhance wheat productivity. J. Environ. Manag. 241, 468–478.
Allievi, L., Marchesini, A., Salardi, C., Piano, V., Ferrari, A., 1993. Plant quality and soil residual fertility six years after a compost treatment. Bioresour. Technol. 43 (1), 85–89.
Alzaydi, A., Alsolaimani, S., Ramadan, M., 2013. Demand, practices and properties of compost in the western region of the Kingdom of Saudi Arabia. Australian Journal of Basic and Applied Sciences 7 (7).
Alzaydi, A.A., 1980. Methane Recovery and Utilization from Sanitary Landfills, Energy Resources and Conservation Related to Built Environment. Elsevier, pp. 531–537.
Ardente, F., Mathieux, F., 2014. Identification and assessment of product's measures to improve resource efficiency: the case-study of an Energy using Product. J. Clean. Prod. 83, 126–141.
Bank, W., 2020. Fertilizer consumption in Saudi Arabia. https://data.worldbank.org/indicator/AG.CON.FERT.ZS?locations=SA. Accessed 26/05 2020.
Barros, M.V., Salvador, R., de Francisco, A.C., Piekarski, C.M., 2020. Mapping of research lines on circular economy practices in agriculture: from waste to energy. Renew. Sustain. Energy Rev. 131, 109958.
Bashour, I.I., Al-Mashhady, A.S., Devi Prasad, J., Miller, T., Mazroa, M., 1983. Morphology and composition of some soils under cultivation in Saudi Arabia. Geoderma 29 (4), 327–340.
Baun, A., Jensen, S.D., Bjerg, P.L., Christensen, T.H., Nyholm, N., 2000. Toxicity of organic chemical pollution in groundwater downgradient of a landfill (Grindsted, Denmark). Environ. Sci. Technol. 34 (9), 1647–1652.
Bedada, W., Karltun, E., Lemenih, M., Tolera, M., 2014. Long-term addition of compost and NP fertilizer increases crop yield and improves soil quality in experiments on smallholder farms. Agriculture. Ecosystems & Environment 195, 193–201.
Bekchanov, M., Mirzabaev, A., 2018. Circular economy of composting in Sri Lanka: opportunities and challenges for reducing waste related pollution and improving soil health. J. Clean. Prod. 202, 1107–1119.
Benabderrahim, M.A., Elfalleh, W., Belayadi, H., Haddad, M., 2018. Effect of date palm waste compost on forage alfalfa growth, yield, seed yield and minerals uptake. Int. J. Recycl. Org. Waste Agric. 7 (1), 1–9.
Chen, Y.-T., 2016. A cost analysis of food waste composting in Taiwan. Sustainability 8 (11), 1210.
Ciccullo, F., Cagliano, R., Bartezzaghi, G., Perego, A., 2021. Implementing the circular economy paradigm in the agri-food supply chain: the role of food waste prevention technologies. Resources,. Conserv. Recycl. 164, 105114.
Ciriag, 2015. Circular economy: a critical literature review of concepts. Centre for the Life Cycle of Products Processes and Services, 1–75 (Montreal, France).
Dahiya, S., Kumar, A.N., Sravan, J.S., Chatterjee, S., Sarkar, O., Mohan, S.V., 2018. Food waste biorefinery: sustainable strategy for circular bioeconomy. Bioresour. Technol. 248, 2–12.
Donner, M., Gohier, R., de Vries, H., 2020. A new circular business model typology for creating value from agro-waste. Sci. Total Environ. 716, 137065.
DTNPF, 2020. Retail fertilizers prices. www.dtnpf.com/agriculture/web/ag/news/crops/article/2018/04/11/retail-fertilizer-prices-continue.
Eghball, B., Ginting, D., Gilley, J.E., 2004. Residual effects of manure and compost applications on corn production and soil properties. Agron. J. 96 (2), 442–447.
Flanagan, K., Clowes, A., Lipinski, B., Goodwin, L., Swannell, R., 2018. SDG Target 12.3 on food loss and waste: 2018 progress report. An annual update on behalf of Champions 12.
GAS, 2015. Umrah survey 2016. www.stats.gov.sa/en/5286.
Geng, Y., Sarkis, J., Ulgiati, S., Zhang, P., 2013. Measuring China's circular economy. Science 339 (6127), 1526–1527.
Graedel, T.E., Allwood, J., Birat, J.P., Buchert, M., Hagelüken, C., Reck, B.K., Sibley, S.F., Sonnemann, G., 2011. What do we know about metal recycling rates? J. Ind. Ecol. 15 (3), 355–366.
Hartmann, M., Khalil, S., Bernet, T., Ruhland, F., Al Ghamdi, A., 2012. Organic Agriculture in Saudi Arabia. Sector Study.
Huysman, S., Debaveye, S., Schaubroeck, T., De Meester, S., Ardente, F., Mathieux, F., Dewulf, J., 2015. The recyclability benefit rate of closed-loop and open-loop systems: a case study on plastic recycling in Flanders. Resources,. Conserv. Recycl. 101, 53–60.
IPCC, 2007. Global Warming Potentials (IPCC Second Assessment Report). Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change, pp. 95–212.
Jaza Folefack, A.J., 2009. The substitution of mineral fertilizers by compost from household waste in Cameroon: economic analysis with a partial equilibrium model. Waste Manag. Res. 27 (3), 207–223.
Kayikci, Y., Ozbiltekin, M., Kazancoglu, Y., 2019. Minimizing losses at red meat supply chain with circular and central slaughterhouse model. J. Enterprise Inf. Manag. 33 (4), 791–816.
Khan, M., Kaneesamkandi, Z., 2013. Biodegradable waste to biogas: renewable energy option for the Kingdom of Saudi Arabia. Int. J. Innovat. Appl. Stud. 4 (1), 101–113.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232.
Klemeš, J.J., Fan, Y.V., Jiang, P., 2020. Plastics: friends or foes? The circularity and plastic waste footprint. Energy Sources, Part A. Recovery, Utilization, and Environmental Effects 1–17.
Loni, O.A., Hussein, M.T., Alrehaili, A.M., 2013. Geo-environmental effect of landfill site, southeast of Riyadh, Saudi Arabia. Arabian Journal of Geosciences 6 (6), 2021–2033.
Lucchetti, M.G., Paolotti, L., Rocchi, L., Boggia, A., 2019. The role of environmental evaluation within circular economy: an application of life cycle assessment (LCA) method in the detergents sector. Environmental and Climate Technologies 23 (2), 238–257.
Maier, S., Szerencsits, M., Narodoslawsky, M., Ismail, I.M.I., Shahzad, K., 2017. Current potential of more sustainable biomass production using eco-efficient farming practices in Austria. J. Clean. Prod. 155, 23–27.
Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., Blengini, G.A., 2019. Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. J. Ind. Ecol. 23 (1), 62–76.
MEWA, 2017. Ministry of environment. Water & Agriculture (MEWA). https://www.mewa.gov.sa/ar/InformationCenter/Researchs/StaticticsData/Pages/default.aspx. Accessed 30/04/2020.
MEWA, 2018. Achievements of the ministry in the light of Saudi vision 2030. Accessed 30/04/2020.
MoHU, 2019. Hajj statistics 2019-1440. Ministry of hajj and Umrah, kingdom of Saudi Arabia, Makkah, p. 51.
Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., De Meester, S., Dewulf, J., 2019. Circular economy indicators: what do they measure? Resources. Conserv. Recycl. 146, 452–461.

Mu'azu, N.D., Blaisi, N.I., Naji, A.A., Abdel-Magid, I.M., AlQahtany, A., 2018. Food waste management current practices and sustainable future approaches: a Saudi Arabian perspectives. J. Mater. Cycles Waste Manag. 1–13.
Närvänen, E., Mattila, M., Mesiranta, N., 2021. Institutional work in food waste reduction: start-ups' role in moving towards a circular economy. Ind. Market. Manag. 93, 605–616.
Nizami, A., Shahzad, K., Rehan, M., Ouda, O., Khan, M., Ismail, I., Almeelbi, T., Basahi, J., Demirbas, A., 2017. Developing waste biorefinery in Makkah: a way forward to convert urban waste into renewable energy. Appl. Energy 186, 189–196.
Noor, Z.Z., Yusuf, R.O., Abba, A.H., Hassan, M.A.A., Din, M.F.M., 2013. An overview for energy recovery from municipal solid wastes (MSW) in Malaysia scenario. Renew. Sustain. Energy Rev. 20, 378–384.
Oliveira, d., Martins, M., Lago, A., Dal'Magro, G.P., 2021. Food loss and waste in the context of the circular economy: a systematic review. J. Clean. Prod. 294.
Population-city, 2014. Population of Makkah. http://population.city/saudi-arabia/makkah/. (Accessed 12 February 2020).
Potting, J., Hanemaaijer, A., Delahaye, R., Ganzevles, J., Hoekstra, R., Lijzen, J., 2018. Circular Economy: what We Want to Know and Can Measure-System and Baseline Assessment for Monitoring the Progress of the Circular Economy in the Netherlands. PBL Netherlands Environmental Assessment Agency. Hage, The Netherlands.
Qu, J., Zhang, L., Zhang, X., Gao, L., Tian, Y., 2020. Biochar combined with gypsum reduces both nitrogen and carbon losses during agricultural waste composting and enhances overall compost quality by regulating microbial activities and functions. Bioresour. Technol. 314, 123781.
Rashid, M.I., Mujawar, L.H., Shahzad, T., Almeelbi, T., Ismail, I.M.I., Oves, M., 2016. Bacteria and fungi can contribute to nutrients bioavailability and aggregate formation in degraded soils. Microbiol. Res. 183, 26–41.
Salmenperä, H., Pitkänen, K., Kautto, P., Saikku, L., 2021. Critical factors for enhancing the circular economy in waste management. J. Clean. Prod. 280, 124339.
Sehnem, S., Ndubisi, N.O., Preschlak, D., Bernardy, R.J., Santos Junior, S., 2020. Circular economy in the wine chain production: maturity, challenges, and lessons from an emerging economy perspective. Prod. Plann. Contr. 31 (11–12), 1014–1034.
Shah, G.A., Shah, G.M., Rashid, M.I., Groot, J.C., Traore, B., Lantinga, E.A., 2018. Bedding additives reduce ammonia emission and improve crop N uptake after soil application of solid cattle manure. J. Environ. Manag. 209, 195–204.
Shah, G.M., Tufail, N., Bakhat, H.F., Imran, M., Murtaza, B., Farooq, A.B.U., Saeed, F., Waqar, A., Rashid, M.I., 2017. Anaerobic degradation of municipal organic waste among others composting techniques improves N cycling through waste-soil-plant continuum. J. Soil Sci. Plant Nutr. 17 (2), 529–542.
Shahzad, K., Narodoslawsky, M., Sagir, M., Ali, N., Ali, S., Rashid, M.I., Ismail, I.M.I., Koller, M., 2017a. Techno-economic feasibility of waste biorefinery: using slaughtering waste streams as starting material for biopolyester production. Waste Manag. 67, 73–85.
Shahzad, K., Nizami, A., Sagir, M., Rehan, M., Maier, S., Khan, M., Ouda, O., Ismail, I., BaFail, A., 2017b. Biodiesel production potential from fat fraction of municipal waste in Makkah. PloS One 12 (2), e0171297.
Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., Azapagic, A., 2020. Assessing the economic and environmental sustainability of household food waste management in the UK: current situation and future scenarios. Sci. Total Environ. 710, 135580.
Stahel, W.R., 2016. The circular economy. Nature News 531 (7595), 435.
Tang, Q., Ti, C., Xia, L., Xia, Y., Wei, Z., Yan, X., 2019. Ecosystem services of partial organic substitution for chemical fertilizer in a peri-urban zone in China. J. Clean. Prod. 224, 779–788.
Teigiserova, D.A., Hamelin, L., Thomsen, M., 2019. Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing. Resources. Conserv. Recycl. 149, 413–426.
Teigiserova, D.A., Hamelin, L., Thomsen, M., 2020. Towards transparent valorization of food surplus, waste and loss: clarifying definitions, food waste hierarchy, and role in the circular economy. Sci. Total Environ. 706, 136033.
Vigneswaran, S., Kandasamy, J., Johir, M., 2016. Sustainable operation of composting in solid waste management. Procedia Environmental Sciences 35, 408–415.
Vision-2030, 2020. Saudi arabia's vision for 2030. https://vision2030.gov.sa/en. Accessed 28 December 2020.
Waqas, M., Nizami, A., Aburiazaiza, A., Barakat, M., Asam, Z., Khattak, B., Rashid, M.I., 2019. Untapped potential of zeolites in optimization of food waste composting. J. Environ. Manag. 241, 99–112.
Waqas, M., Nizami, A., Aburiazaiza, A., Barakat, M., Ismail, I., Rashid, M.shiudI, 2018a. Optimization of food waste compost with the use of biochar. J. Environ. Manag. 216, 70–81.
Waqas, M., Nizami, A.S., Aburiazaiza, A.S., Barakat, M.A., Rashid, M.I., Ismail, I.M.I., 2018b. Optimizing the process of food waste compost and valorizing its applications: a case study of Saudi Arabia. J. Clean. Prod. 176, 426–438.
Zhang, A., Venkatesh, V., Liu, Y., Wan, M., Qu, T., Huisingh, D., 2019. Barriers to smart waste management for a circular economy in China. J. Clean. Prod. 240, 118198.