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Research article

# Potential reuse of domestic organic residues as soil organic amendment in the current waste management system in Australia, China, and The Netherlands

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ABSTRACT

Soil organic carbon (SOC) is essential for most soil functions. Changes in land use from natural land to cropland disrupt long-established SOC balances and reduce SOC levels. The intensive use of chemical fertilisers in modern agriculture accelerates the rate of SOC depletion. Domestic organic residues (DOR) are a valuable source of SOC replenishment with high carbon content. However, there is still a lack of knowledge and data regarding whether and to what extent DOR can contribute to replenishing SOC. This paper aims to unpack the potential of DOR as a SOC source. Total SOC demand and annual SOC loss are defined and calculated. The carbon flow within different DOR management systems is investigated in three countries (China, Australia, and The Netherlands). The results show that the total SOC demand is too large to be fulfilled by DOR in a short time. However, DOR still has a high potential as a source of SOC as it can mitigate the annual SOC loss by up to 100%. Achieving this 100% mitigation requires a shift to more circular management of DOR, in particular, more composting, and direct land application instead of landfilling and incineration (Australia and China), or a higher rate of source separation of DOR (The Netherlands). These findings form the basis for future research on DOR recycling as a SOC source.

## 1. Introduction

Soil organic carbon (SOC) depletion from agriculture and land use change contribute 10–20% to the yearly carbon increase in the atmosphere (Rahman, 2013; Watson and Schalatek, 2020), while the remaining carbon increase is attributed to energy-related emissions (European Commission, 2011). Globally, soil contains approximately 2500 gigatons (Gt) of carbon and is crucial as a carbon sink (Lal, 2008). In the past decades, the depletion of SOC has been recognized as a major problem that contributes to soil degradation and threatens food security (Haddix et al., 2020).

Naturally, the SOC content will remain stable if the land is left undisturbed by anthropogenic activities. However, this long-standing SOC balance is destabilised when natural land is converted to land used for human activities and intensified agricultural activities (Don et al., 2011; Wei et al., 2014). Since the beginning of human-induced land-use change, a total of 116 Gt SOC have been lost from the top 2 m of soil (Sanderman et al., 2018).

Extensive land cultivation and excessive use of chemical fertilisers have accelerated the depletion of SOC in croplands (Kumar Bhatt et al., 2019). Farmers prefer chemical fertilisers over organic fertilisers for practical or economic reasons (Brockmann et al., 2018). Chemical fertilisers are applied because they can supply essential nutrients, particularly nitrogen, phosphorus, and potassium (NPK) for plant growth. However, the fact that soil also requires 'nutrients', specifically organic carbon, is overlooked. Organic carbon is essential for several soil functions, including but not limited to water retention, nutrient recycling, biotic regulation, etc. (Adhikari and Hartemink, 2016; Kranz et al., 2020). The SOC level also affects soil quality (Magdoff and van Es, 2000) and thus form a threat to food security (Navarro-Pedreño et al., 2021).

Most products produced in soil end up in the food chain and are consumed by people. In the linear produce-consume-disposal approach (Lucertini and Musco, 2020), most consumed agricultural products are disposed of as domestic organic residues (DOR). They are then incinerated or landfilled instead of being returned to agricultural land. As DOR contains 40%–55% of carbon (Mu et al., 2020), recovering carbon

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from DOR and applying these in agriculture to amend SOC stocks could relieve (part of the) SOC demand.

DOR is the biodegradable portion of domestic residue, comprising kitchen and yard residue and organic elements in wastewater (Jayet and Petel, 2015). It represents a significant by-product of human activity, accounting for 32% to 58% of total residue produced in urban environments ( World Bank, 2018b). Due to the continuous increase in human population, it is estimated that the total generation of DOR will increase by 70% between 2016 and 2050 (World Bank, 2019). The increase in DOR is considered a threat to the sustainable development of human society due to the associated effects of global warming and other environmental effects (Jayet and Petel, 2015). China, for example, a country with a high percentage of landfilling, filled its largest dumpsite in 2019, 25 years ahead of the original plan (Jin, 2019).

According to the Landfill Directive (EU) 2018/850 by the European Union (European Union, 2018), as of 2030, landfilling bans will apply to all recyclable or otherwise recoverable waste in terms of materials or energy. Landfill and incineration are still the two main residue treatment methods used internationally. The main disadvantage of these processes is that they can result in inefficient resource utilisation (Agudelo-Vera et al., 2012): the resources contained in the residues, particularly the majority of the nutrients and carbon in DOR, are destroyed or wasted. Moreover, these processes can cause environmental problems leading to increased greenhouse gas emissions (Matsakas et al., 2017).

The DOR residues subjected to suitable treatment, e.g., anaerobic digestion and composting and their application to soil have been researched for decades. Lemming et al. (2019) reported that applying composted kitchen and yard residue increased soil phosphorus availability. Kurzemann et al. (2020) compared the application of composted DOR to chemical fertiliser on soil microbial biomass. They indicated that adding composted DOR can increase the quantity of soil microbial biomass. Ding et al. (2021) reported an improvement in soil quality, particularly in soil microorganisms, after the application of DOR compost. Chojnacka et al. (2019) observed that kitchen residue and sludge had more significant potential for NPK recovery and reuse than agricultural residues and animal by-products. Meanwhile, it is stated that DOR has a 5–9% substitution potential for annual chemical fertiliser usage. Alvarenga et al. (2017) reported a 0.8–2.5% increase in soil organic matter after two years of application of composted DOR. Overall, most current research has focused on utilising DOR as an NPK nutrient provider to enhance crop yield, as a biogas resource (Wainaina et al., 2020), or as a soil improver to increase soil water holding capacity (Meena et al., 2019) and soil health (Hamid et al., 2020). Glæsner et al. (2019) and Ulm et al. (2019) are among the few who have mentioned the increase of SOC through the application of DOR, while still focusing on phosphorus and nitrogen. The extent to which the annual DOR generation can meet the SOC demand is still unknown. This uncertainty will hinder the recycling of DOR effectively and efficiently.

This study aims to provide a quantitative analysis of the potential of DOR to meet the demand for SOC on cropland and to estimate the avoidable carbon losses associated with different linear DOR management options. To achieve this objective, different management options commonly used in organic waste management systems were investigated, including composting, anaerobic digestion and direct land application, which are widely used circular approaches. In addition, landfilling and incineration, which represent non-circular approaches, were investigated (World Bank, 2018b). These options were carefully selected based on their widespread use in several countries, allowing for a comprehensive comparative analysis and insights into the global potential of circular management of domestic organic residues. In addition, the selection of management options was based on their relevance to the research objective of replenishing cropland soils. As a result, certain streams, such as the direct application of DOR to mining land, were excluded as they were not consistent with the objective of cropland soil replenishment. The assessment was made to see to which extent the circularly managed DOR can match the SOC demand. This study hypothesises that the amount of carbon incinerated and landfilled can contribute significantly to the SOC demands of cropland soil. Australia, China, and The Netherlands were selected as case study countries considering their variations in the waste management system. The Netherlands has a relatively mature waste management system with a 99% separate collection rate of the DOR (Dijkgraaf and Gradus, 2014) and a 100% collection rate of all domestic residues (CBS, 2020), while Australia has a 49% DOR separately collected and 77% of all domestic residues (Pickin et al., 2020). The waste management system in China differs in the sense that the DOR collection rate is much lower (i.e., 53.9% in large cities (OTHB, 2022)). Besides this reason, countries with lower population densities, like Australia with 3.3/km$^2$ (China with 153/km$^2$ and The Netherlands with 508/km$^2$), are likely to have less pressure on local agricultural land (Matsunaga and Themelis, 2002); Asian countries, particularly China, are reported to produce ten to fifteen times less organic residue per person than European countries (UNEP, 2020). Additionally, The Netherlands is a biomass (food and feed) importing country. At the same time, Australia and China are biomass-exporting countries (FAO, 2019a), and a negative import-export balance is believed to lead to local SOC depletion due to intensive agriculture. All these factors may influence the DOC recycling potential as a soil amendment; it is, therefore, important to analyse and compare multiple case study areas as done in this study.

## 2. Methods

The research focused on three DOR flows, as previously defined by Jayet and Petel (2015), including domestic kitchen residue (KR), yard residue (YR), and wastewater treatment sludge (WWTS). Domestic kitchen and yard residues were combined (KYR) in this research as they are collected as a mixed fraction in Australia and The Netherlands. Given that most Chinese residents do not have a private yard, the DOR flow in China consists of KR and WWTS.

Cropland was chosen as the target for carbon replenishment in agriculture, considering the higher SOC loss per cubic meter of cropland soil compared to pasture land (Sanderman et al., 2018).

Australia, China, and The Netherlands were used as case study areas, and the temporal resolution was one year. The data collection process was to 1) quantify SOC demands, followed by an assessment of the current carbon fate in DOR related to waste management practices; 2) Comparison of the SOC demand to the DOR's current/potential carbon supply (Fig. 1).

### 2.1. SOC demand

Due to the lack of a standardised definition, the calculated SOC demand varies depending on the replenishment objective (Veeken et al., 2017). This research defined two types of SOC demand. One employed the highest SOC content achievable in worldwide soils under the identical pedoclimatic zones (PCZ) as a target for SOC replenishment. Another way was to mitigate the annual SOC loss from croplands.

#### 2.1.1. Total SOC demand

The difference in SOC content between the local cropland soil and the cropland soil with the highest SOC content under identical PCZ conditions determined the local cropland's total SOC demand. Several steps were taken to calculate the total SOC demand (as shown in Fig. 2).

The PCZ was defined using the updated world map of the Koppen-Geiger climate classification (Peel et al., 2007) and the World Reference Base map of Soils of the World (IUSS Working Group WRB, 2015). The highest SOC for each PCZ was extracted from the SoilGrids250 m (Hengl et al., 2017). Only topsoil (0–30 cm depth of soil) from cropland was taken into consideration as this has the highest carbon demand per m$^2$ (Sanderman et al., 2018) and the most impact on crops. Furthermore, topsoil is thought to be the most impacted by human activities (Minasny

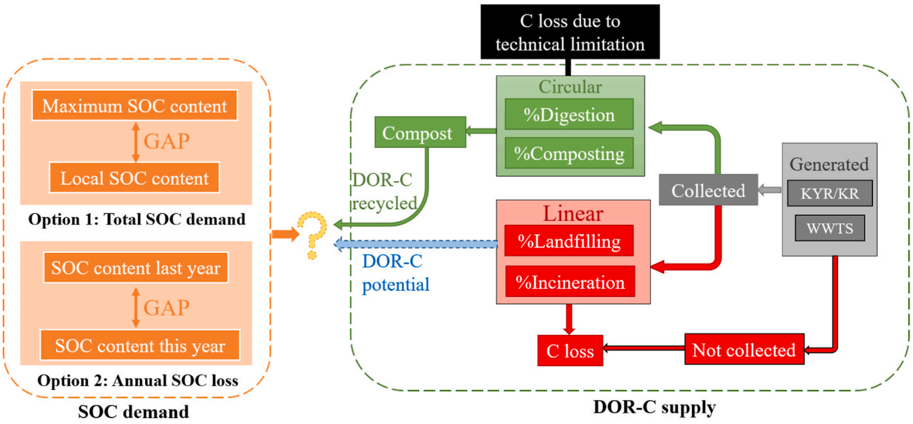

**Fig. 1.** Research design. SOC = soil organic carbon; KYR = domestic kitchen and yard residue; KR = domestic kitchen residue; WWTS=(activated) wastewater treatment sludge; DOR-C = carbon in domestic organic residue.

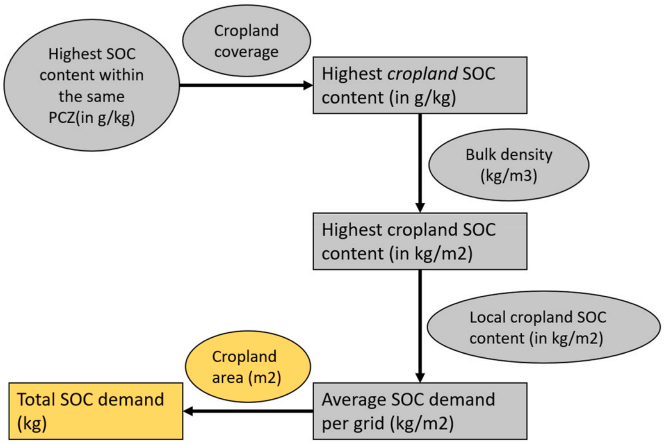

**Fig. 2.** Steps that were taken to calculate total SOC demand. The round boxes indicate the data is from another study. The square boxes indicate data derived from this paper. The grey boxes denote the calculation based on a single geo-grid (250 m * 250 m). The yellow boxes reflect the calculation based on the country border. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2017). ArcGIS (ESRI, 2018) was used to process these geospatial data.

Global datasets were refined to the national level (for example, the cropland coverage data and the current cropland SOC data). The land-use area was defined using crop coverage data acquired from the data-set GLOBAL-SHARE (Latham et al., 2014). The highest SOC contents within the defined PCZ are expressed in concentration (g/kg). Soil bulk density was derived from the SoilGrids250 m (Hengl et al., 2017) and used to convert the SOC content unit from concentration to kg/m$^2$. The statistics for the local cropland SOC content were adapted from the research by Zomer et al. (2017) and compared to the highest cropland SOC content. The visualised data about the highest SOC content in the case study countries (S-Fig. 1), cropland coverage in the countries (S-Fig. 2), cropland SOC content (S-Fig. 3), and the calculation formula with a more detailed explanation can be found in the supplementary material.

### 2.1.2. *Annual SOC loss*

The second definition of SOC demand aims to mitigate the annual SOC loss of croplands. There is considerable controversy about whether the cropland SOC is declining. Reijneveld et al. (2009) reported a net increase in cropland SOC from 1984 until 2004 in The Netherlands, while Sukkel et al. (2009) reported the opposite. Similarly, Zhang et al. (2017) and Song et al. (2005) observed a net drop in SOC from the 1980s to the 1990s in China, while Huang and Sun (2006) and Xie et al. (2007) state that there is a net increase. Lastly, in Australia, Metcalfe and Bui (2016) revealed a steady drop in cropland SOC stock, while Ren et al. (2020) claimed SOC accumulation. This article utilises FAO (2019b) data because it is a harmonised worldwide dataset collected and analysed using the same methodology.

### 2.1.3. *Soil data uncertainty*

The primary source of data uncertainty in this regard is mainly related to the input data uncertainties of the model in the referred studies. However, it is important to note that these uncertainties are beyond our control and were not directly addressed in this study.

## 2.2. *Carbon fate of DOR*

The DOR carbon flow was assessed by determining the amount generated in the areas under study, followed by analysing the carbon flows during treatment to the corresponding products with STAN (Cencic and Rechberger, 2008) for the material flow analysis.

Among all the DOR treatment approaches, only those with products considered to be beneficial to the cropland soil were considered, e.g., composting, anaerobic digestion, and direct application to cropland. This research focuses on avoidable carbon losses induced by management decisions (e.g., incineration/landfilling/mining land application, etc.) and residential behaviour (no source separation). Unavoidable carbon loss due to the technology limitations (e.g., $CO_2$ emission/$CH_4$ production, etc.) and losses via leachate formation or decomposition during composting and anaerobic digestion were calculated but not included in the scenarios as ‘carbon loss’.

For Australia, KYR data and its treatment information were obtained from the report by Pickin et al. (2020). The WWTS data was abstracted from Vero (2019).

Data availability on amounts of KR in China was limited by the amount of reliably reported data available. Song et al. (2015) and Ding (2015) used the analysis data with a reported average KR generation of 16 kg/capita/year in China. WWTS generation and treatment in China were calculated based on the report by Wei et al. (2020). KR treatment information was obtained from Ye (2020) and Li et al. (2016).

The data for KYR and WWTS collection in The Netherlands were collected from Rijkswaterstaat (2018) and Statline (2018). Information about the treatment technologies applied was retrieved from Rijkswaterstaat (2020) and Broersma (2014).

The available data for Australia and China are the generated DOR, whereas, in The Netherlands, the data is available as the collected DOR. Considering that the DOR in The Netherlands is collected at a rate of 100% (CBS, 2020), the collected data was considered equivalent to its generated data.

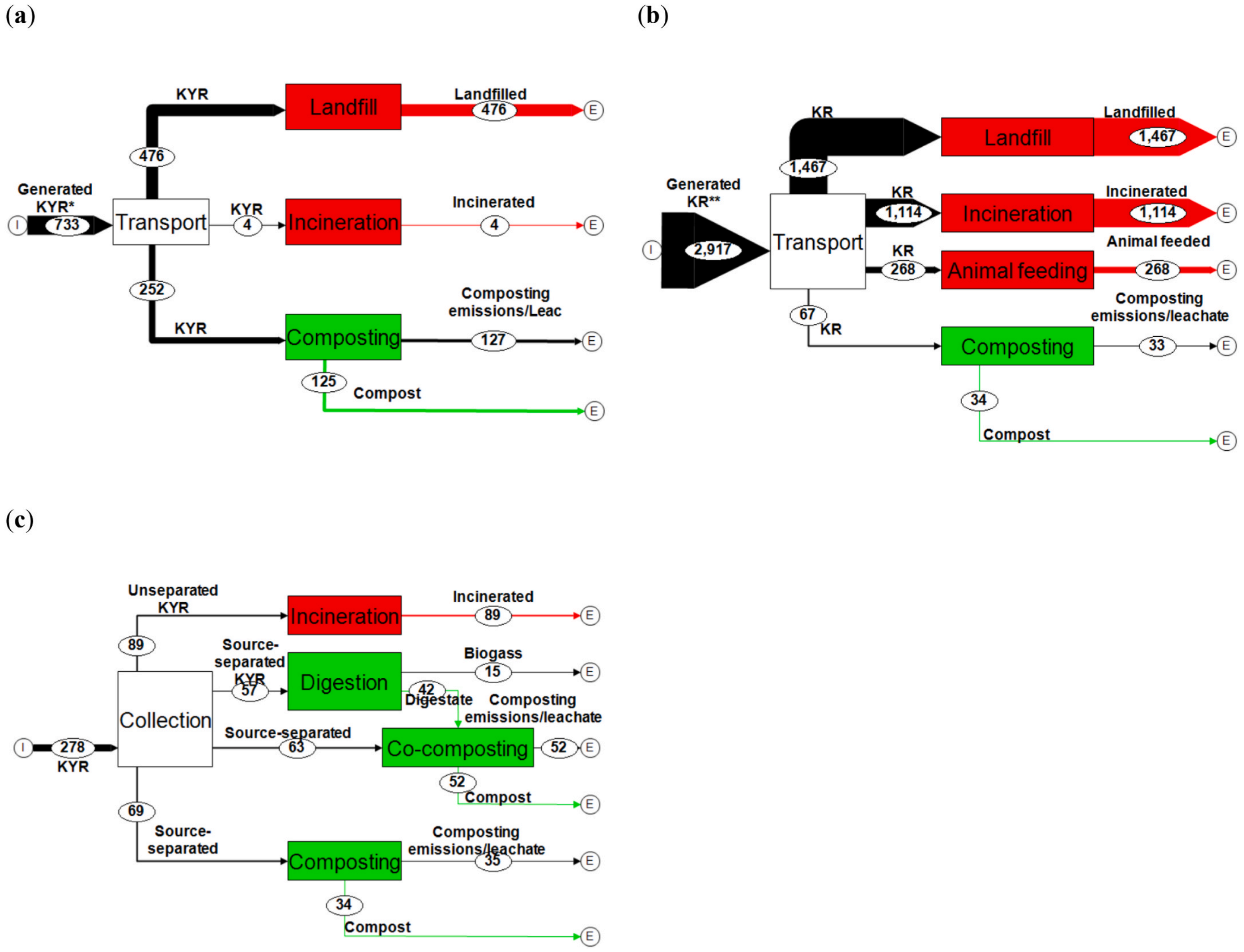

**Fig. 3.** Overview of the investigated household KYR treatment chain and relevant process flows in $1*10^6$ kg of carbon (C) within a country's boundary. I = import, E = export. The width of the flows illustrates the quantity of carbon that is transferred between processes. (**a**) Australia; (**b**) China; (**c**) The Netherlands. The * next to the inflow indicates that the source data is KYR generation data instead of collection data. The ** next to the inflow indicates that only data from the household kitchen are used.). The green colour of the export flow indicates carbon recycling. The red colour of the export flows indicates avoidable carbon loss. The black-coloured export flow indicates the unavoidable carbon loss (technology limitations). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The carbon content of the KYR and KR were assumed the same for the three countries and were adopted from the experimental data of Knoop et al. (2018), and the carbon content of WWTS was calculated using the molecular formula for biomass ($C_5H_7NO_2$) (Speece, 1983).

The supplementary material can provide a more detailed explanation of the calculation processes.

### 2.2.1. *Waste data uncertainty*

For waste production in China and Australia, data from papers or reports were used and for the Netherlands official statistics are available. In order to mitigate the impact of data uncertainty, between data in papers and reports, here data published in reputable journals were used when available. However, for detailed data, such as the nutrient content of local organic residue and recycling efficiency, we employ the composition of nutrients in organic residue and the efficiency of nutrient recycling in treatments from countries with similar contexts when data for our case countries are not available.

## 2.3. *Approaches toward a more circular management*

New scenarios were developed to replenish the total SOC demand or mitigate the annual SOC loss. The approaches were based on currently existing DOR circular management practices in all three countries, namely:

a. DOR-C recovery via composting.
b. Direct application of WWTS to cropland.

However, considering that a single approach may not fully restore the demand, a combination of both was also included in this study:

c. DOR-C recovery via composting and direct WWTS application on cropland.

In this approach, a strategic plan is to prioritise the composting of KYR/KR, mainly due to its larger volume compared to WWTS. Direct WWTS application was then introduced once the KYR/KR compost generated in the first phase was fully utilised. This sequential approach ensured the consistent use of available resources while effectively managing the DOR-C recovery process.

In all scenarios, legal and governmental constraints regarding the use of WWTS and its treated products as fertilisers were not considered.

## 3. Results and discussion

### 3.1. *Wasted and recycled DOR-C*

The KYR-C flows during different DOR treatments are depicted in Fig. 3.

Around 65% of the total generated KYR is landfilled in Australia (476 divided by 733 according to Fig. 3 (a)), 34% is composted (252 divided by 733), and the rest is transferred to incineration facilities for energy generation. China sends 50% of KR to landfills (1467 divided by 2917, according to Fig. 3 (b)), 38% to incineration (1114 divided by 2917), and only 2% to composting (67 divided by 2917). In The Netherlands, KYR is classified as source-separated and non-source-separated. All the source-separated KYR is managed circularly, while the non-source-separated KYR is mixed with other residuals and will ultimately be incinerated, the carbon is deemed completely lost in this research. The KYR disposed of in this manner accounts for 32% of the total household KYR (89 divided by 278, according to Fig. 3 (c)).

Most WWTS is directly applied to cropland in Australia and China, accounting for 67% and 29%, respectively (calculated according to the data shown in Fig. 4). The Netherlands incinerates 87% of its sludge.

Australia shows a high percentage of direct application of WWTS and its compost even though its heavy metal content exceeds the permitted level (Farrell et al., 2013; Garrido et al., 2005; Sullivan and Woods, 2000). This phenomenon may be explained by the state’s biosolids exemption enacted in 2014 (NEW-EPA, 2014). China has a relatively high threshold value (General Administration of Quality Supervision, 2018), which explains the country’s comparatively high rate of direct cropland application. On the other hand, The Netherlands has stricter regulations regarding WWTS and the application of its compost to crop production, according to Keurcompost (2018).

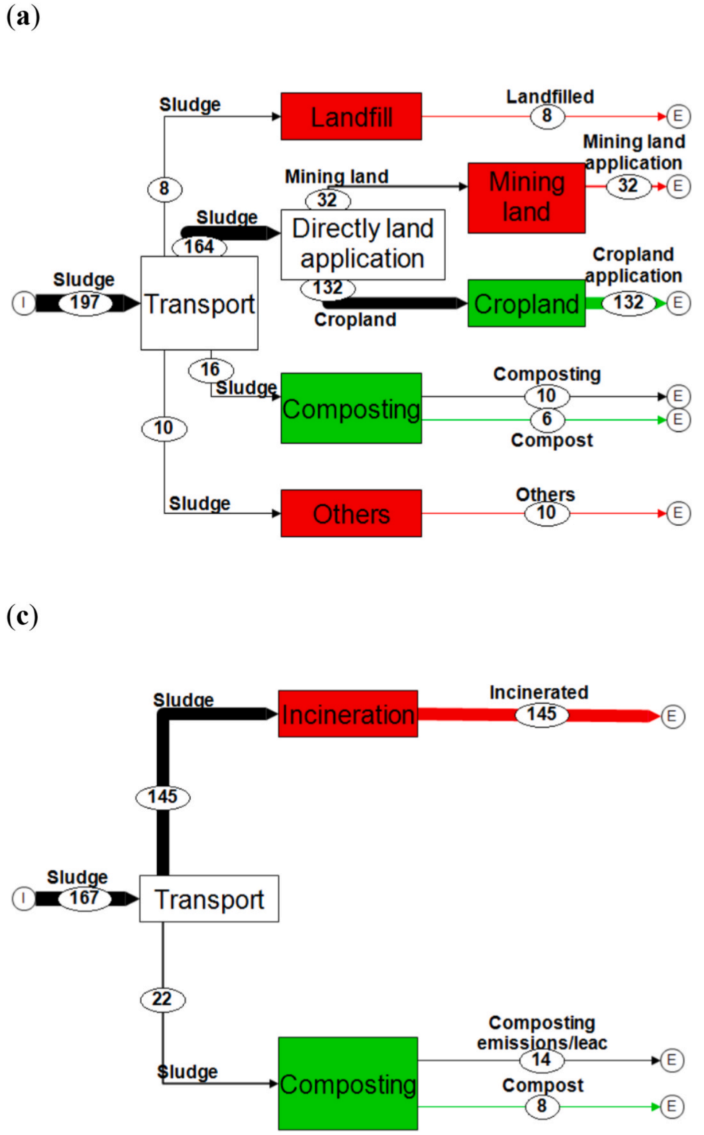

**Fig. 4.** Overview of the investigated sludge treatment chain and relevant process flows in $1*10^6$ kg of carbon (C) (I = import flow, E = export flow). (**a**) Australia; (**b**) China; (**c**) The Netherlands. Sludge that is sent to incineration, landfill, building material, mining land, and other destinations other than composting and direct cropland application is regarded as completely lost because it does not provide an acceptable SOC amendment/fertiliser product. The green colour of the export flow indicates carbon recycling. The red colour of the export flows indicates avoidable carbon loss. The black-coloured export flow indicates the unavoidable carbon loss (technology limitations). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The ratio of recycled/wasted DOR-C, including both KYR/KR-C and WWTS-C, is shown in Fig. 5.

In all three countries, more than fifty percent of DOR-C is wasted through linear management (Fig. 5). China has the highest waste rate of 88%. The recycling rates of DOR-C in Australia and The Netherlands are similar. However, due to the prohibition of the use of WWTS, all DOR-C recycled in The Netherlands (28%) is from KYR-C recycling, while for Australia, it is from both KYR-C recycling (14%) and WWTS-C recycling (14%). The technical loss in Australia (15%) is less than in The Netherlands (25%) as there is no technical loss from direct land application of sludge.

Several factors influence the recycling rate of DOR. For example, in the case of the Netherlands, which has a higher collection rate, a possible reason for the loss of DOM during the management process could be the lack of awareness and knowledge of effective separation techniques (known as KYR) and strict regulations regarding the reuse of sewage sludge on cropland (Keurcompost, 2020). On the other hand, in China, the limited availability of separation infrastructure in the majority of urban areas may be the main obstacle (Xu et al., 2023). It is therefore advisable to undertake further research to investigate the specific barriers to DOR recycling in different countries, thereby facilitating a more comprehensive understanding of waste management practices.

### 3.2. *DOR-C fate and the SOC demand*

The total SOC demand and the annual SOC loss were compared with the available amounts of DOR-C before and after the treatments to assess whether the carbon supply and demand could be matched. Information on the local population, territory and cropland area, and the calculated SOC, DOR-C are presented in Table 1.

For Australia and China, the yearly generated KYR-C have the potential to replenish less than 0.004% of the total SOC demand % and WWTS-C less than 0.001%; for The Netherlands, these figures were ten times higher but still low . Thus, there is a large gap between the total SOC demand and the DOR-C supply, and more than thousands of years will be needed to restore the total SOC demand. Meanwhile, compared with the annual SOC loss, the yearly generated DOR-C from Australia and China shows the potential to replenish the loss and even increase SOC. In The Netherlands, however, it is currently impossible to fully restore the annual SOC loss from cropland with DOR-C, but 97.35% of the annual SOC loss can be mitigated.

Over half of the DOR-C produced annually in the three countries is not recycled for soil application under the current DOR management system (Fig. 5). New scenarios with a more circular approach were calculated to mitigate the annual SOC loss (Table 2).

As has been shown in Table 2, Australia can fully restore the annual SOC loss by composting more KYR. If the use of WWTS is preferred,

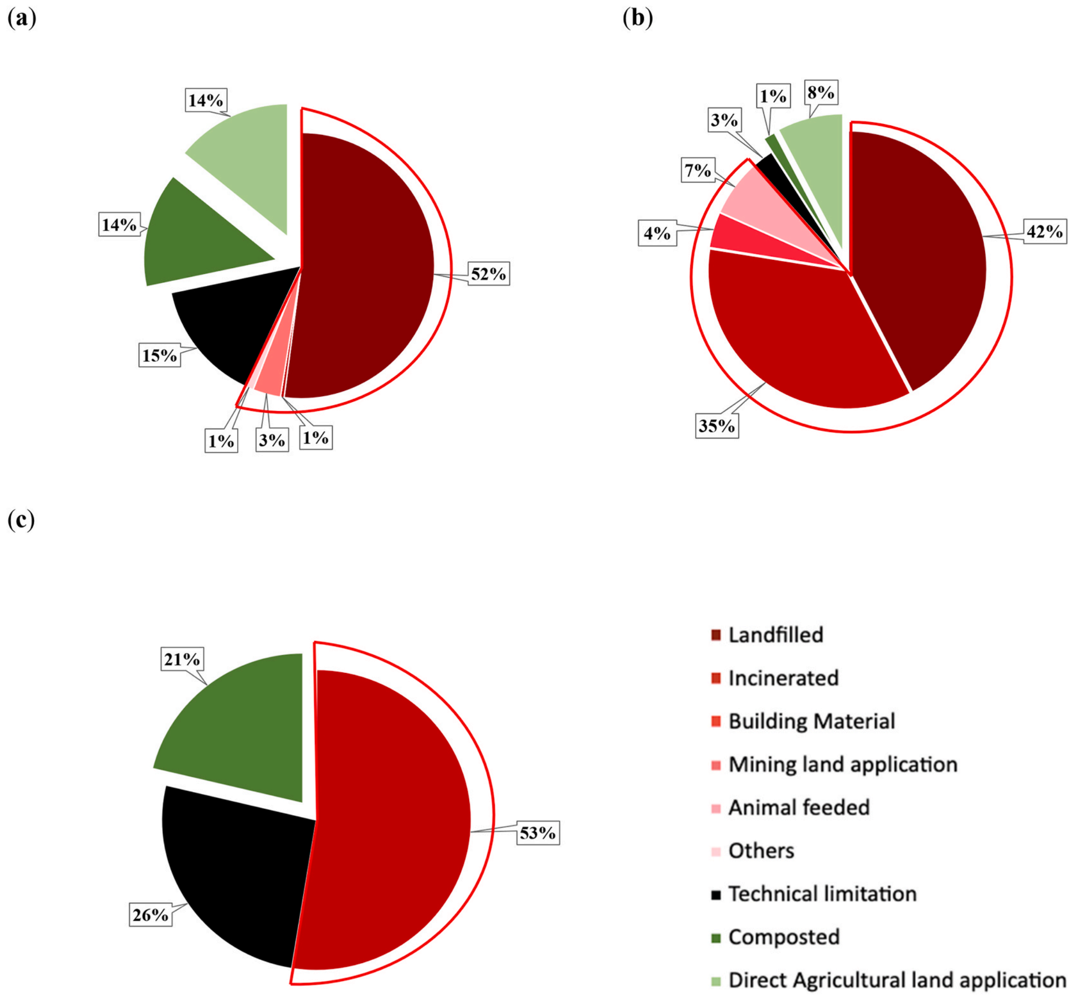

**Fig. 5.** Overview of the DOR-C fate in three countries. (**a**) Australia; (**b**) China; (**c**) The Netherlands. Intermediate processes such as anaerobic digestion have been excluded. DOR-C recovered is indicated by the detached portion of the pie chart. The region highlighted with red lines indicates the DOR-C wasted. Losses due to technical limitations, such as biogas generation or composting emissions, are indicated in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 1**
Local information and calculated total SOC demand, annual SOC loss, DOR-C supply potential before and after the treatments, and the matching between the SOC demand and DOR-C supply.

| | Australia | China | The Netherlands |
|---|---|---|---|
| Population[a] (million) | 25.50 | 1439.32 | 17.13 |
| Territory[b] ($m^2$) | 7.74 E+12 | 9.60 E+12 | 4.15 E+10 |
| Cropland[c] ($m^2$) | 3.13 E+11 | 1.36 E+12 | 1.06 E+10 |
| Inhabitants/cropland[d] ($\#/m^2$) | 8.1E-5 | 1.06E-3 | 1.62E-3 |
| DOR/inhabitants[d] (kg/#/y) | 284.63 | 21.42 | 160.07 |
| Total SOC demand[d] (kg) | 2.32 E+13 | 1.07 E+14 | 9.75 E+11 |
| Annual SOC loss[e] (kg/y) | 5.25 E+8 | 4.36 E+8 | 4.57 E+8 |
| KYR-C generated[d] (kg/y) | 7.32 E+8 | 2.92 E+9 | 2.78 E+8 |
| Total SOC demand replenish potential by KYR[d] (%) | 0.0032 | 0.0027 | 0.029 |
| Annual SOC loss mitigation potential by KYR[d] (%) | 139.43 | 669.03 | 60.81 |
| WWTS-C generated[d] (kg/y) | 1.97 E+8 | 1.04 E+9 | 1.67 E+8 |
| Total SOC demand replenishment potential by WWTS[d] (%) | 0.00085 | 0.00097 | 0.017 |
| Annual SOC loss mitigation potential by WWTS[d] (%) | 37.52 | 239.22 | 36.54 |
| Recycled DOR-C[d] (kg/y) | 2.63 E+8 | 3.61 E+8 | 9.40 E+7 |
| Actual mitigation rate of annual SOC loss[d] (%) | 50.09 | 82.80 | 20.57 |

[a] data from World Population Review (2020).
[b] data from World Bank (2018a)
[c] data from OECD (2018).
[d] data from this study.
[e] data from FAO (2019b).

**Table 2**
The potential of different DOR management improvement approaches (a, b, and c, all with units in kg/y) and their respectively achieved SOC demand replenishment percentage.

| | Australia | China | The Netherlands |
|---|---|---|---|
| Further carbon Needed (kg/y) | 2.62 E+8 | 7.5 E+7 | 3.63 E+8 |
| a. More composting | 5.32 E+8 (KYR composting) | 1.62 E+8 (KR composting) | 1.45 E+8 (WWTS composting) + 8.9 E+7 (KYR composting) |
| Replenish Percentage (%) | 100 | 100 | 26.54 |
| b. More direct land application | 5.00 E+7 (WWTS) | 7.50 E+7 (WWTS) | 1.45 E+8 (WWTS) |
| Replenish Percentage (%) | 19.08 | 100 | 39.94 |
| c. DOR-C recovery via composting and direct WWTS application on cropland | 5.00 E+7 (WWTS) plus 4.30 E+8 (KYR composting)c | Not needed | 1.45 E+8 (WWTS) plus 8.9 E+7 (KYR composting) |
| Replenish Percentage (%) | 100 | – | 52.03 |

combining KYR composting with direct land application of WWTS can achieve the replenishment target. Both approaches to more circular management in China can fully replenish its annual SOC loss. The approach with The Netherlands's highest annual SOC loss mitigation rate is the combination of WWTS direct land application and KYR composting, which can lead to an additional 52.03% annual SOC loss mitigation. One of the steps needed to produce more KYR compost is to increase the KYR source separation rate in The Netherlands. The collection and separation rates for Australia and China are not yet accurate. Therefore, further research is suggested to build a DOR management dataset in both countries to develop improvement strategies more appropriate to the local situation.

The scenarios did not consider the potential risks, such as the presence of heavy metals, associated with the direct application of WWTS on cropland. Kelessidis and Stasinakis (2012), among others, have highlighted the soil contamination risks by heavy metals from WWTS application. In addition to heavy metals, organic micropollutants, micro/nano plastics, pathogens and other contaminants may also be present in WWTS. The fate of these contaminants during treatment as well as their fate after soil application of treated organic residues has been under investigation in different contexts (Chen et al., 2020; Mohajerani and Karabatak, 2020; Wei et al., 2017). Further research is recommended to investigate the approaches that can minimise the risk of DOR reuse on cropland soil.

### 3.3. *Data uncertainties and limitations*

Although the impact of data uncertainty was avoided to the greatest extent, possible bias in the results due to different data sources does exist; when a country's total output is divided by its population, the output per unit of population varies significantly between countries. For instance, Australia's KYR generation number is 222, China's is 16, and the Netherlands' is 87 (all in kilo tonne per million people). China's KR generation is extremely low in comparison, which could be explained as follows: 1) garden residue and the residue generated at restaurants are excluded, as is a portion of organic residue. 2) Europe generates 10 to 15 times the amount of organic residue per person as Asia countries (UNEP, 2020). 3) the wide existence of informal waste collectors. Similarly, for WWTS generation, the production could be calculated for Australia (56), China (6), and the Netherlands (73) (all in kilo tonne per million people). In theory, the excreta should be more or less similar. The extremely low value in China might be a result of the country's incomplete coverage of wastewater treatment plants and the involvement of the informal waste management sector. If this is the case, China's potential for DOR-C supply will be higher than what is described in this research. These uncertainties and data source limitations will not alter the conclusions drawn from this research, which is that the DOR has a high potential to mitigate the SOC loss in the countries included in our study.”

## 4. Conclusions

This study aimed to gain insight into the potential of using DOR-C as a supplement to SOC. To date, no studies have linked the two, mainly because the need for SOC is not yet clearly defined, and there is a lack of statistical data on the fate of DOR-C. This paper addresses these issues. Total SOC demand is defined and calculated, DOR-C production and flows are tracked, and the two are compared. The results show that the gap between the total SOC demand and annual DOR-C supply is thousands of times more significant, which means that supplementing the total SOC demand cannot be done in one go. Meanwhile, up to 100% of the annual SOC loss can be mitigated with DOR-C only if a change to a more circular system is made. More specifically, shifting from DOR incineration or landfilling towards more composting and direct land application in China and Australia can achieve the goal of mitigating SOC loss. In The Netherlands, on the other hand, a need to improve source-separation efficiency is recognized.

Regarding sustainable waste management, the study's findings suggest that incorporating DOR into agricultural practices could offer a potential solution for recycling organic waste materials and diverting them from landfills. This could reduce the environmental impact associated with waste disposal and contribute to a circular economy approach.

Furthermore, the study's emphasis on the potential of DOR to enhance SOC levels in soil can possibly contribute to mitigating climate change by reducing greenhouse gas emissions and promoting sustainable land use practices. Besides, increased SOC levels can enhance soil fertility, improve soil water retention capacity, increase soil nutrient availability, enhance crop yields, and reduce reliance on synthetic fertilizers. This can have positive implications for food security, environmental and economic sustainability, and the overall efficiency of agricultural systems.

By exploring these broader implications, the study can provide valuable insights for policymakers, waste management professionals, and agricultural stakeholders. It can also serve as a basis for further research and encourage the adoption of sustainable practices that promote a more circular and productive agricultural sector.

To conclude, this study has demonstrated the importance and potential of returning DOR-C to replenish the soil. This study also provides a novel approach to defining total SOC demand, which provides an idea for future soil carbon research.

## Author statement

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## Declaration of competing interest

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## Data availability

I have shared my data and calculation steps in supplementary material

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## Appendix A. Supplementary data

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