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Review

Wastewater reuse for livestock feed irrigation as a sustainable practice: A socio-environmental-economic review

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ABSTRACT

Rapid population growth will engender an intensification in agricultural activities which currently utilise most of global freshwater withdrawals, stressing not only the water sector, but also the energy sector due to the increase in demand for energy intensive commercial fertilisers. The global production of fertilisers, in addition to declining worldwide phosphorus reserves may find it difficult to sustain this rising demand at current capacities. As part of sustainable development, farmers will have to adopt alternative resources that balance the environment, economy and society. Wastewater reuse represents an opportunity for this challenge as it can alleviate the stress on scarce water resources and contribute to circular economies. In addition, it contains relatively high amounts of nutrients that can substitute for part of the fertilisation requirements. In the literature, reusing wastewater for agricultural purposes obtained relatively high acceptance rates amongst populations, especially for growing forage crops. This review gathers all the studies that have investigated the reuse of wastewater in growing animal feed. It details the findings based on the social, environmental, and eonomic dimensions of sustainability. This review provides a basis for future fertigation systems as it gathers all the tools required to make a comprehensive assessment of the practice. Interesting research directions include the need to investigate farmers' concern about consumers' attitude, which apparently obstructs them from adopting new technologies despite their improved harvests. In addition, it is worth investigating the overall environmental benefits associated with wastewater fertigation on the water-soil and on the water-energy nexus, in terms of global warming potential as reported carbon footprint savings in the literature are undervalued. Finally, there is a strong economic potential associated with the practice in terms of industrial symbiosis that requires further exploration.

Contents

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List of abbreviations

N	Nitrogen
TN	Total Nitrogen
P	Phosphorus
K	Potassium
TSS	Total Suspended Solids
TDS	Total Dissolved Solids
COD	Chemical Oxygen Demand
BOD	Biological Oxygen Demand
SO_4^{2-}	Sulfate
TWW	treated wastewater
WWTP	Wastewater Treatment Plants
GHG	Greenhouse Gas
USEPA	United States Environmental Protection Agency
SD	Socio-demographic factors
PSY	Psychological factors
WC	Water Characteristics
FC	Field Capacity
GWP	Global Warming Potential
TTHQ	Total Target Health Quotient
HRI	Human Health Risk Index
WF	Water Footprint
GIS	Geographic Information System
ET	Evapotranspiration

1. Introduction

As the world population is expected to increase by 2 billion by 2050, the global food system will have to cope with this rise by doubling production to sustain the demand and the improving living quality. Such intensification in agricultural systems and activities will stress fresh-water resources. Typically, local agriculture using irrigation enhances a country's food security and resilience to trade disruptions. Nevertheless, it can represent a threat to fresh-water resources, especially in water scarce countries due to the over abstraction of groundwater reserves. As of 2005, over 70% of global water withdrawals were intended for agricultural activities (FAO, 2016). That said, the growing demand for food products and the emerging competition on water resources threaten the sustainability and resilience of the agricultural sector, and have lead researchers to investigate new techniques to optimise water use within agricultural systems such as CO_2 fertilisation (Ghiat et al., 2021, 2020). Furthermore, the current global fertiliser production capacity cannot meet the growing demand, which has increased six fold in the last 50 years, and continues to expand in tandem with lands dedicated for cultivation (Chojnacka et al., 2020). For this reason, governments will have to adopt alternative sustainable water resources that meet social, economic and environmental objectives within sustainable development. The reuse of wastewater for agricultural activities represents an opportunity to alleviate the stress on water resources as well as on conventional fertilisation. Transitioning to treated wastewater fertigation represents a step towards achieving sustainable crop production, while alleviating the stress on not only the water sector, but also on the energy and food sectors as reuse represents an opportunity to reduce the demand on energy intensive commercial fertilisers and on conventional water supply, which can also have a high embodied energy, and to enhance crop yields. In fact, wastewater, whether diluted or treated has a higher nutrient concentration compared to conventional water resources. Produced water resources from different sectors are characterised with different chemical properties. Lahlou et al. (2020a) gathered the data for nitrogen (N), phosphorus (P), potassium (K), total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), biological oxygen demand (BOD) and sulfate (SO_4^{2-}) content in produced water from 12 different industries and from municipal wastewater treatment plants. These contaminants concentrations can vary even within the same sector depending various parameters such as the water use efficiency, yet these values indicate the potential nutrient content and contamination from these resources. Though it is not always possible to meet the fertilisation requirement using treated wastewater fertigation, the practice can at least substitute a portion of the demand for commercial fertiliser (Fonseca et al., 2007).

The existing reviews within this topic have addressed the reuse of wastewater for agricultural purposes from a feasibility perspective. For instance, Pedrero et al. (2020) reviewed the opportunities and challenges of sustaining olive oil production in the Mediterranean region using treated wastewater. As part of their review, the authors investigated olive trees fertigation using different sources of wastewater including municipal, agro-industrial and textile, and detailed findings related to the impact of fertigation on the overall quality of the soil and of the product. Poustie et al. (2020) reviewed food crop growth induced by irrigation using treated wastewater. The study focused on the findings about crops' and soil's exposition to nitrogen phosphorus, xenobiotics, and nanoparticles. Chauhan and Kumar (2020) presented

potential risks and recommendations for safe reuse. Similarly, Chojnacka et al. (2020) discussed the transition from traditional irrigation to reclaimed wastewater fertigation. The authors highlighted the benefits and potential challenges of the practice. Alternately, Hamilton et al. (2007) and Radingoana et al. (2020) reviewed the socio-environmental aspect of the reuse. The two studies reviewed the public attitudes related to reusing wastewater for irrigation. Radingoana et al. (2020) focused on greywater while Hamilton et al. (2007) tackled all sources of wastewater. They did not include the parameters that influence the acceptance. Incidentally, Hamilton et al. (2007) highlighted the environmental challenges that emerge from the reuse of wastewater considering a few parameters and did not include the global warming potential and water footprint. Evidently, no previous study has looked at the sustainable reuse of treated wastewater from a socio-environmental-economic perspective.

Livestock production is a large contributor to GWP and user of land especially in arid regions (Al-Ansari et al., 2015). In fact, over 33% of croplands are dedicated for growing animal fodder (Waitrose and Partners, 2018). It is also estimated that 26% of earth's ice-free land is dedicated for grazing (Waitrose and Partners, 2018). Green fodder is also an extensive consumer of water resources. In fact, 29% of the water used in agriculture is directed to livestock production, of which the largest share goes to animal feed cultivation (Al-Karaki and Al-Hashimi, 2012). It is determined that an average of 85 L of water is required to produce as little as 1 kg of fodder, as opposed to vegetables production which requires as little as 43 L of water per kg (Hoekstra and Mekonnen, 2002). Livestock feed production not only reduces regional water availability, but also extensively contributes to greenhouse gas (GHG) emissions as it requires large amounts of chemical fertilisers to sustain the global production which exceeds 1 billion tons per year (International Feed Industry Federation, 2018). As such, the objective of this study is to review all existing literature that has investigated animal feed irrigation using treated or raw wastewater. It congregates the different parameters and tools that need to be considered to assess the sustainability of the practice.

2. Methodology

This study gathers peer-reviewed journal papers in addition to conference proceedings and book chapters published in English that have addressed wastewater reuse for animal feed production. The studies considered are those that covered at least one of the three pillars of sustainability (social, environmental and economic). In the case of social studies, no study was solely dedicated to the reuse of wastewater to irrigate livestock feed, especially for articles that considered the public perception. For this reason, the keywords used to obtain social studies were general and were combined as follows: ((public opinion OR public perception OR attitude OR acceptance) AND (reclaimed OR recycled OR reuse OR treated) AND (water OR wastewater OR grey water). The studies that looked into the reuse for agricultural purposes were selected. As for the remaining papers, the following keyword combination was used: (wastewater AND (irrigation OR fertigation OR agriculture OR cultivation) AND (livestock feed OR animal feed OR fodder OR forage)). Scopus was the database used for the articles search. The selected documents included the above-mentioned keywords in their title, abstract or keywords. Table 1 illustrates the distribution of the documents based on the publisher and categories. A total number of 73 documents were gathered, of which the earliest was published in 1989 and the most recent in 2020. The most investigated forage crop in the gathered literature is rice followed by maize (Fig. 1). As for the type of wastewater, while most of the journal articles did not specify the level of treatment, the second majority looked at reusing raw wastewater. The sources of wastewater investigated as part of this review are sewage, abattoir, textile industry, pulp and paper industry, and winery wastewater. While the chemical composition of these resources can vary, Table 2 provides the approximate concentrations of N, P, K, TSS, TDS, COD, BOD and SO_4^{2-} according to Fourie et al. (2015) and Laurenson and Houlbrooke (2012), and to industries in the USA, which follow the USEPA's national pollutant discharge elimination standards system.

Table 1
Categories of reviewed papers and their database distribution.

Categories	Database classification[a]							Total articles
	El	MDPI	TF	IWAP	SL	Wi	Other	
Social	4	4	1	3	2	1	6	21
Environmental	8	–	5	2	5	1	6	27
Economic	–	–	–	2	–	1	5	8
Hybrid	4	1	–	2	3	1	6	17

[a] The classification of databases is as follows: El: Elsevier; MDPI: Multidisciplinary Digital Publishing Institute TF: Taylor and Francis; IWAP: International Water Association Publising; SL: Springer Link; Wi: Wiley; Other: ASABE, ASHS, AGU Publication ….

3. Social studies

3.1. Acceptance level

The most common researched area in studies that have investigated the social aspect of reusing treated wastewater for livestock feed irrigation focused on the public acceptance of the resource, which is considered as the major hurdle to the implementation of reuse schemes. As such, the factors influencing the public attitudes have been thoroughly investigated in the literature, including potential motivators and refrainers. Table 3 details the different studies, by region, which included livestock feed irrigation in their investigation. It summarises the categories of factors considered, and the different acceptance rates obtained. While some acceptance rates seem to be consistent in some regions such as China and UK, other regions report different levels of wastewater reuse approval. For the case of the Middle Eastern region, these differences could be due to the time period in which the studies were conducted. In fact, the acceptance shifted from a rate as low as 10% in 1991 to 87% in 2018 (Baawain et al., 2018; Shamim, 1991). It could also be due to the technological advancements, or again to the rising need for water resources, which drives the public to be more accepting to cost effective alternatives. Most studies focus on analysing the factors influencing the population acceptance. The latter can broadly be classified into three categories (Fielding et al., 2018): (1) socio-demographic factors encompassing age, level of education, etc; (2) psychological factors highlighting the most investigated parameter which is the health risk perception; and finally (3) water characteristics.

3.2. Prevalent factor

'Knowledge' has been reported to be one of the most prevalent factors influencing the acceptance of reusing treated wastewater (Saliba et al., 2018). In fact, Hui and Cain (2018) determined that acceptance is boosted when knowledge related to implemented recycled water schemes is provided, especially for non-potable uses. Abdulla and Ouki (2015) reported that public awareness can enhance the receptivity of people to use recycled water. Similarly, Baghapour et al. (2017) conveyed that knowledge related to the

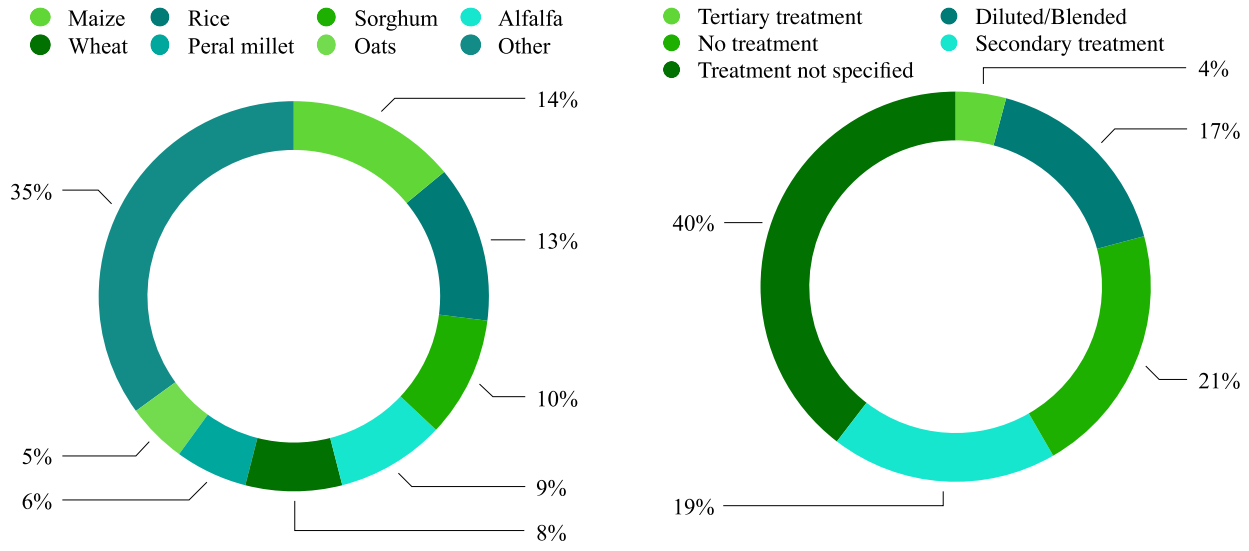

Fig. 1. Distribution of forage crops investigated and of the categories of wastewater treatment level in the gathered literature.

Table 2
N, P, K, TSS, TDS, COD, BOD and SO_4^{2-} concentration is produced water from different sectors.

Wastewater source	N	P	K	TSS	TDS	COD	BOD	SO_4^{2-}
	($mg.L^{-1}$)							
Abattoir	172	64	209	90	1329	585	268	236
Pulp and paper industry	5.6	0.6		121.7	508.3	103.2	18.4	508.3
Textile industry	6.9	4.7	2.2	20.4	1162.6	134.8	8.0	–
Winery	35	15	206	3000	–	1550	4500	–

chemical and microbiological quality of treated wastewater is a good predictor or acceptance. Goodwin et al. (2018) considered the extent to which respondents' attitude towards the reuse of wastewater can be influenced by message framing using informational video animation. The authors reported that presenting the participants with information regarding the treatment methods used in the purification process did not have any influence on the respondents. The same was observed for videos addressing the comparison of recycled water risk with other everyday risks. However, the message that engendered a higher acceptance rate was the quality compliance framed message. In fact, the respondents were presented with the different management practices that are employed throughout the wastewater treatment process, which aim to guarantee safe reuse for both people and the environment. The video played a role in attenuating the health risk perception and boosted the respondent's trust in the process and management (Goodwin et al., 2018). Similarly, Baawain et al. (2018) used a survey to investigate the population's concern in reusing treated wastewater. A total of 115 people from different parts of the capital of Oman, Muscat, were randomly picked for the survey. The authors reported that participants were willing to support any option that does not hinder human health and that is beneficial to the environment. These results confirm that when provided with information regarding the quality compliance the acceptance is enhanced. Alternately, another study that looked at the risk perception amongst the population confirmed that consumers do not consider health indicators such as cleanness of the store when choosing products (Antwi-Agyei et al., 2016). The authors reported that respondents prioritised other factors such as store proximity, cost, freshness and taste.

3.1. Farmers' attitudes

Farmer's perception has not been widely investigated, although they are the main stakeholder when it comes to the reuse for agricultural purposes. Sathaiah and Chandrasekaran (2020) assessed the socio-economic impact of reusing treated industrial wastewater for irrigation purposes in 5 different villages in Tamil Nadu, India. The authors reported that farmers' employment opportunities flourished in the villages where wastewater reuse was taking place compared to control villages that were still relying on groundwater for their agricultural activities. In fact, the man days accounted for 108 per year in the farms using treated wastewater, while in the control farms, the man days remained as low as 31 per year. Furthermore, many articles reported the potential of wastewater reuse in substituting fertilisation requirements which can engender an economic benefit as reported by Lahlou et al. (2020a). Nevertheless, the few studies that have considered farmers attitudes generally demonstrate a low motivation for reuse amongst farmers as compared to consumers. For instance, Saliba et al. (2018) conducted a study in Apulia, Italy, where it was concluded that 81% believe that treated wastewater does not deteriorate soil and crops' quality. The authors also reported that 47% of the farmers were motivated about using the resource for its high nutrient content, and 41% for its engendered reduced pumping cost. Therefore, one would expect the recycled water use acceptance to be higher than what was actually found. In fact, only 42% were willing to use it for irrigation. These results can be explained by what was found in the work of Jiménez et al. (2011). The authors reported that 86% of the farmers surveyed believe that consumers would not be willing to purchase their products if they had knowledge about the origin of

the water used for irrigation, even if the prices were lower compared to goods grown using conventional methods. With a focus on prices, a study conducted in Tunisia reported that the attractive pricing of treated wastewater was the motivator that led farmers to accept reuse (Dare and Mohtar, 2018). The same study reported that farmers in Palestine believe the reuse is unsafe. Nevertheless, due to their economic situation and to the scarcity of the resource, their health risk perception did not keep them from reusing the wastewater. The same was observed by Antwi-Agyei et al. (2016) who found that farmer's awareness of health risk associated with the water used does not influence their willingness to adopt safer alternatives. Rehman et al. (2013) considered the socioeconomic impact of using canal water, wastewater, and mixed water in urban and peri urban agricultural production in Faisalabad, Pakistan. The authors reported that farmers were interested in quantity rather than quality. Menegaki et al. (2007) conducted a social study in Crete, Greece, which considered the farmer's willingness to pay for treated wastewater and reported that most respondents are willing to pay no more than 0.15 €.m^{-3} for treated wastewater. This amount represents 55% of the freshwater charge. A more recent study conducted in the same region reported the same findings. The authors stated that amongst the respondents who are willing to pay for the resource, most are ready to spend up to 0.15 €.m^{-3} (Petousi et al., 2015). While the price farmers are willing to spend for the resource is the same as that reported by the previous study, the freshwater worth has dropped. In fact, the 0.15 €.m^{-3} represents about 88% of the agricultural water pricing in the research conducted in 2015. That being said, while the farmers are willing to spend relatively more compared to the previous years, they are not willing to disburse more money on treated wastewater than they would on their usual water resource.

Table 3
Acceptance level for reusing treated wastewater for agricultural purposes by region.

Region	Reference	Sample size	Type of study	SD	PSY	WC	Finding
UK	Goodwin et al. (2018)	N = 689	Survey		✓		92% of the respondents agree to reuse the resource for gardening. The acceptance drops to 60% for crop irrigation.
	Smith et al. (2015)	N = 309	Survey		✓		90% indicate their willingness to adopt it for non-potable uses.
Europe	Michetti et al. (2019)	N = 57	Survey	✓	✓		50% of the farmers have a positive attitude towards the reuse for crop irrigation.
	Saliba et al. (2018)	N = 183	Survey and interview	✓	✓	✓	37% acceptance amongst consumers and 35% amongst farmers for reusing the treated wastewater to grow animal feed
	Petousi et al. (2015)	N = 252	Survey		✓	✓	77% of the surveyed farmers accept to use the resource for olive trees irrigation.
	Menegaki et al. (2007)	N = 453	Survey	✓		✓	75% of farmers are willing to use secondary treated wastewater for olive trees irrigation Vs. 32% of consumers surveyed. 65% are willing to use tertiary treated wastewater for the same purpose Vs. 21% of consumers. 41.9% of the farmers are willing to use tertiary treated wastewater for tomato cultivation Vs. 41.5% of consumers.
USA	Hui and Cain (2018)	N = 1500	Survey	✓			65% accept reusing the water in dairy fields.
Latin America	Segura et al. (2018)	N = 255	Survey			✓	89% accept the reuse for ground level agricultural irrigation
	Jiménez et al. (2011)	N = 35	Survey		✓	✓	49% of the surveyed farmers use the treated wastewater. Almost all of them believe it is not polluted.
Middle east	Baawain et al. (2018)	N = 115	Survey			✓	87% of the respondent prefer to use the resource for non-edible crops. The acceptance drops to 51% for agricultural crops.
	Massoud et al. (2018)	N = 300	Survey	✓	✓	✓	80% of the respondents accept wastewater reuse for agricultural purposes.
	Maleksaeidi et al. (2018)	N = 74	Survey		✓	✓	59% of the farmers agree to use raw wastewater for irrigation.
	Dare et al. (2017); Dare and Mohtar (2018)	N = 20					
N = 7	Interviews	✓		✓	Low motivation amongst farmers in both of Palestine and Qatar.		
	Baghapour et al. (2017)	N = 562	Survey	✓	✓		65% of the respondents accept reuse for agricultural irrigation.
	Shamim (1991)	N = 100	Survey		✓		Over 90% of the respondents do not accept the reuse of treated wastewater in farming.
	Shamim (1988)	–	–	–	–	–	Low acceptance due to religious principles and health risk perception.
China	Zhu et al. (2018)	N = 2600	Survey	✓		✓	80% of the surveyed population accept the reuse for a gricultural irrigation.
	Gu et al. (2015)	N = 300	Survey	✓			77% agree to use the resource for agricultural irrigation.
	Chen et al. (2015)	N = 714	Survey		✓		82% of the respondents accept the reuse for crop irrigation.
Africa	Dare and Mohtar (2018)	N = 13	Interviews	✓		✓	Farmers had a high motivation to reuse wastewater
	Antwi-Agyei et al. (2016)	N = 490	Interview		✓		Respondents gave less importance to health indicators of food products and prioritized other factors such as cost and freshness.
	Abdulla and Ouki (2015)	–	Survey		✓		56% accept the reuse for food crops irrigation.

SD: Socio-demographic factors; PSY: Psychological factors; WC: Water characteristics.

Table 4
Climate change implication of reusing wastewater for fodder production.

Reference	Study	Fodder	Climate change parameter	Finding	GHG	
					Additional emissions	Savings
Lahlou et al. (2020)	Use of treated wastewater from 13 different industries.	Alfalfa	Emissions from water transportation and fertiliser substitution	–	–	26 kg-$CO_{2\text{-eq}}$ per ton of produced fodder.
Matheyarasu et al. (2016)	Use of abattoir wastewater to irrigate crops instead of land disposal.	Alfalfa, Mustard, Maize, Sunflower	Soil N_2O emissions	34% lower N emissions compared to land disposal. Slightly lower N emissions for Maize compared to Alfalfa.	–	For maize: 6.5 and 18.5 mg-N_2O per pot for 50% and 100%FC.
González-Méndez et al. (2015)	Assessment of 7-day cumulative N_2O and CO_2 emissions resulting from periodic wastewater irrigation.	Alfalfa, Rye grass, Maize	N_2O and CO_2 emissions from soil	Maize emits 5.7 times more N_2O compared to Alfalfa. Wastewater irrigated maize emitted more GHGs compared to rainfed maize.	For Maize: 60.9 mg $CO_2.m^{-2}.h^{-1}$ and 0.313 5 mg $N_2O.m^{-2}.h^{-1}$	–
Lal (2015)	Evaluation of 8 years irrigation using treated sewage effluent instead of groundwater.	Sorghum	Carbon stock occurrence and accumulation	79% increase in carbon stock occurrence. 11% increase in C accumulation.	–	5.2 ton of $CO_{2\text{-eq}}.ha^{-1}$
Maraseni et al. (2010)	Evaluation of GHG emissions of rice cultivation using wastewater in comparison with canal water.	Rice	Emissions from Farm machinery, fertilisation requirements (substitution was not considered), water treatment.	Treated wastewater irrigation emits 1.47 times more GHG emissions compared to canal fed irrigation.	398 kg-$CO_{2\text{-eq}}$ per ha	–
Fernández-Luqueño et al. (2010)	Evaluation of GHG emissions of Maize cultivation using wastewater.	Maize	N_2O, CO_2 and CH_4 emissions from soil	N_2O emissions rate was not affected by the utilization of wastewater on the contrary to CO_2 and CH_4 emissions.	4.87 μg of CO_2 and 128.3 87 μg of CH_4 per kg of soil per hour.	–

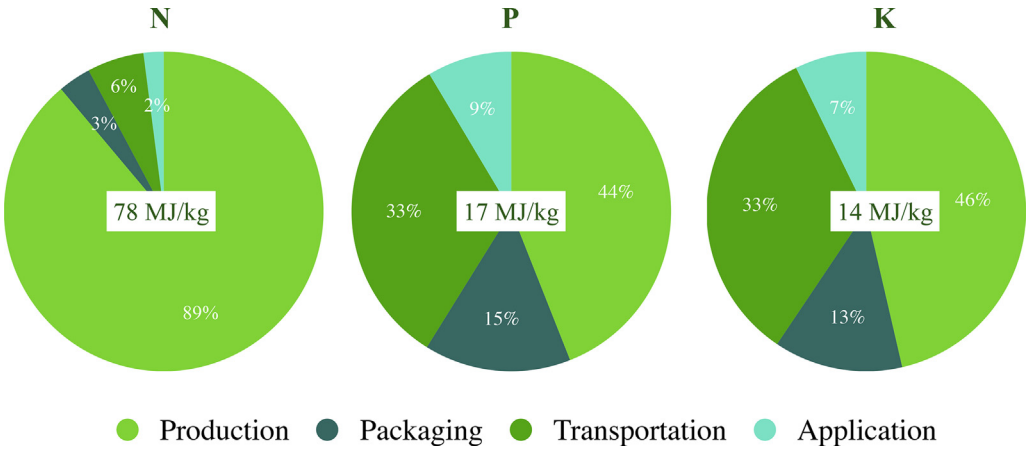

Fig. 2. Energy required to produce, package, transport and apply 1 kg of N, P and K fertilisers. Adapted from (Gellings and Parmenter, 2004).

4. Environmental studies

4.1. Climate change

Amongst the journal articles that investigated the environmental impact associated with the reuse of either treated wastewater or raw wastewater for livestock feed irrigation, seven have analysed the practice in terms of climate change (Table 4). Lal et al. (2020, 2015) investigated and compared sorghum cultivation under different irrigation water qualities and various fertilisation levels, based on the level of carbon sequestration and on the reduced greenhouse gas emissions. After an irrigation period of eight years using treated sewage effluent, results determine that soil organic carbon stocks occurrence increased by 79% as compared to when the fodder was irrigated using groundwater. As for the C accumulation, it increased from 8.49 ton. ha^{-1} to 9.42 ton. ha^{-1}. Authors reported that irrigated fodder conserved 5.2 ton of $CO_{2\text{-eq}}.ha^{-1}$ compared to the base scenario. The carbon footprint savings resulting from using sewage water for fodder production instead of groundwater was sufficient to offset the carbon emissions from the treatment of 0.44 and 1.09 million L. day^{-1} of sewage water under 50% and 100% N–P fertilisation respectively, assuming an average $CO_{2\text{-eq}}$ release of 0.17 $g.L^{-1}$. The authors mentioned that the sewage water provided an addition of 108, 15, and 25 kg of N, P and K per hectare per year. These amounts can substitute for part of the fertilisation requirement and offset an additional amount of $CO_{2\text{-eq}}$, which can be significant as the energy required to produce, package, transport and apply commercial fertilisers is substantial (Fig. 2). While the latter research did not take these calculations into consideration, another study found that the chemical fertilisation substitution through treated wastewater fertigation can result in significant carbon footprint offsetting (Lahlou et al., 2020a). In fact, the latter study developed a water planning framework using the energy-water-food nexus approach to irrigate

alfalfa fields using treated wastewater generated from different sectors. Alfalfa water requirements averaged 724.7 mm. year^{-1}, and their allocation was conducted by blending the different sources of water in order to simultaneously meet alfalfa water and nutrient requirements while respecting irrigation water standards. The practice provided all N–P–K requirements to the fodder, which resulted in the offset of the carbon footprint from transportation as well as the offset of an average of 26 kg-$CO_{2\text{-eq}}$ for each ton of produced fodder. Nevertheless, this study did not consider the N losses through both of leaching and emissions, while it is important to consider these parameters since they can affect the overall assessment of the practice. In fact, 60% of total N_2O emissions originate from agricultural activities (Metz et al., 2007). It is also found that as much 1.38% of the nitrogen applied to soil can be lost through emission (Ito et al., 2018). For instance, Matheyarasu et al. (2016) investigated nitrous oxide emissions of four different fodder crops irrigated with secondary treated abattoir wastewater at 50% and 100% field capacity. Results indicate that cumulative emissions ranged between 17.6 and 18.2 mg N_2O for each cultivated pot for 50% field capacity (FC). These values are equivalent to 1.8% and 1.9% of N emitted from the total nitrogen provided by the treated wastewater, where the lowest and highest rates were for alfalfa and maize, respectively. These emissions were 34% lower compared to unplanted crops for the same FC. As for the experiments conducted at 100% FC, the lowest percentage of N emissions was observed for maize with a value of 1%, and the highest was for alfalfa with a value of 1.1%. This difference could be due to the different fertilisation requirements of the different crops, which is an important parameter to consider in order to obtain an enhanced nitrogen use efficiency (Millar et al., 2014). On average, maize requires 175 kg ha^{-1} of 14–23-14 N–P–K in addition to 50 kg ha^{-1} of urea (Dugué, 2009), while most studies show rates in excess of 80 kg-N.ha^{-1} are necessary to reach maximum productivity for alfalfa (Bélanger and Richards, 2019; Chen et al., 2017; Csathó, 2003; Raun et al., 1999).

The soil nutrient imbalance caused by excessive nutrient addition can generate increased $CO_{2\text{-eq}}$ emissions (Fares et al., 2017). González-Méndez et al. (2015) measured both N_2O and CO_2 emissions resulting from flood irrigation of ryegrass, alfalfa and maize using raw wastewater before, during and 1, 2, 3 and 7 days after the irrigation event, such that the total yearly irrigation water is 1850 mm. year^{-1} and the amount of water applied in each event averaged 190 mm. The authors determined that as soil moisture increased, the microbial activity was enhanced which resulted in an increase of emissions. The highest CO_2 emissions were observed for ryegrass with an average of 109.5 mg CO_2. m^{-2}. h^{-1} followed by Maize with an average of 77.5 mg CO_2. m^{-2}. h^{-1}. While Matheyarasu et al. (2016) reported that maize had lower N_2O emissions compared to alfalfa at high moisture content, González-Méndez et al. (2015) described the opposite, as the authors concluded that maize emitted 5.7 times more N_2O compared to alfalfa. None of the previous studies considered the treatment process of the wastewater in the global warming potential estimation of their reuse scheme. In fact, González-Méndez et al. (2015) did not account for the carbon footprint associated with the reuse of wastewater simply because they used raw wastewater. Conversely, the other studies did not consider the treatment process to be within their system boundaries as the wastewater will, in any instance, be treated (Lahlou et al., 2020a). Maraseni et al. (2010), on the other hand, did reflect the burden associated with the purification process of the water in their calculations, and found that using 27 million m^3 of treated wastewater results in 1.47 times more greenhouse gas emissions compared to using gravity fed canal irrigation. However, the authors did not quantify any of the carbon footprint offset from the nutrient substitution or from the carbon sequestration, in which as reported in different studies can be very significant. Furthermore, they did not assess the environmental burden that may be associated with leaving the wastewater untreated. The same can be said about the work of Fernández-Luqueño et al. (2010), which reported that maize grown using treated wastewater had 1.4 times higher GWP compared to maize grown using the urea. This is the only study that considered CH_4 emissions from the application of treated wastewater to cultivated soils in addition to CO_2 and N_2O fluxes. Results report a significant increase in methane emissions when treated wastewater was used instead of urea. Nevertheless, the authors did not consider the GHG emissions associated with the production, transportation and application of urea. Furthermore, they did not account for the carbon footprint offset from the fertilisation substitution.

For a more accurate estimation of the GWP, future studies must take into consideration the engendered emissions and the carbon footprint offset from various aspects; from the treatment and transportation to the application of the treated wastewater and its impact on soil emissions which are tightly related to soil microbiota. In fact, the latter remains unexplored, although it significantly contributes to soil fluxes of CO_2, CH_4 and N_2O. These aspects can be classified into two major categories: the water-energy nexus and the water-soil nexus (Fig. 3). The carbon footprint changes resulting from water energy change due to the substitution of conventional water resources with treated wastewater were not investigated as most studies fail to account for the embodied energy of conventional freshwater resources, which in some instances can be substantial compared to that embedded in treated wastewater. In fact, for the case of large depths to water, the energy required for pumping can reach up to 1.8 kWh.m^{-3} (Ronayne and Shugert, 2017). As for desalination, the energy demand ranges between 1 and 14 kWh.m^{-3} of produced water (Beltrán et al., 2004). Alternately, the energy requirements to treat wastewater to a tertiary treatment level are equivalent to 1.1 kWh.m^{-3} (Al-Obaidli et al., 2019). Since agriculture does not require highly purified wastewater, this value can be decreased further with minor plant modification that will allow simplified treatment with lower energy requirements and higher effluent nutrients concentration. The first major aspect of the water-soil nexus that is prompted by the application of the treated wastewater to agricultural land is the carbon footprint offset resulting from the substitution of conventional fertilizers. Studies need to consider the carbon footprint offset when treated wastewater substitutes for part or all of the nutrient requirements of a plant which can reduce conventional fertilisation demand. The final aspects to consider are those related to soil interaction with wastewater. This includes soil carbon sequestration which were previously quantified using organic carbon stocks occurrence and carbon accumulation. In addition, CO_2, CH_4, and N_2O emissions resulting from soil nutrient excess and from soil fluxes' complex interaction of soil type, degree and frequency of wetting, and water characteristic (C_{org}, N etc) need to be taken into account.

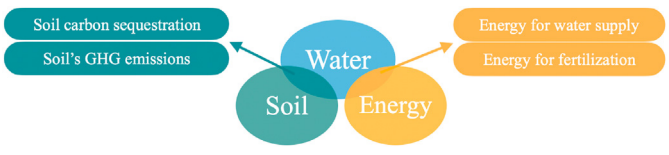

Fig. 3. Wastewater fertigation implications on the water-soil nexus and on the water-energy nexus in terms of global warming potential.

4.2. Ecotoxicity and human toxicity

Amongst the studies that explored the ecotoxicity resulting from fodder irrigation using wastewater, most considered the effect of heavy metals. Table 5 summarises the different studies that investigated the effect of wastewater irrigation on the accumulation of heavy metals in soils and their concentration in fodder. Different parameters influence heavy metal soil accumulation and plant uptake including the soil type, the plant species and moisture content. Samarah et al. (2020) used treated wastewater for the irrigation of barley and investigated the heavy metal content in the irrigated soil and the cultivated grains, although not in the fodder. After four months, where an average of 256 mm of treated wastewater irrigation was applied, the authors tested for zinc, cadmium and lead, and found that their concentrations in the grains did not change, while they increased in the 0–20 cm soil layer. Nevertheless, the values remained below the permissible limits. The study used drip irrigation in the field study, which could be the reason behind the low levels of heavy metals. In fact, a study that coonsidered the effect of wastewater fertigation on heavy metals accumulation using two different irrigation methods, found that the accumulation was lower when drip irrigation method was adopted compared to when flooding irrigation was used (Mojiri and Abdul Aziz, 2011). This could be due to the irrigation efficiency, which is higher for the drip method compared to the flood irrigation method. The latter requires a greater amount of water, and will therefore result in a higher accumulation of contaminants. Duy Pham et al. (2019) investigated the impact of 4.5 L. day^{-1} continuous irrigation using treated municipal wastewater on heavy metals accumulation in paddy soils and in rice. After five months into the experiment, heavy metals levels remained below the limits in both of the soil and the harvest. The same was observed in the work of Minhas et al. (2015), who tested the accumulation of heavy metals in both of sorghum and Egyptian clover after 8 years of irrigation using wastewater blended with groundwater. In some studies, authors considered the effect on heavy metals content in milk produced from livestock fed with wastewater irrigated fodder. In fact, Muklada et al. (2018) tested lead, nickel and cadmium concentration in secondary treated wastewater irrigated willow tree used as goat feed. The authors determined that the levels remained below the permissible limits in the trees. Furthermore, goat liver enzymes did not change, similarly the milk yield and milk quality were not affected. The same was observed in milk and blood of dairy cows fed with sewage wastewater irrigated fodder (Varadarajan et al., 1992).

While most of the studies reported no adverse effect, a few conveyed that reusing treated wastewater resulted in excessive levels of heavy metals in their harvest. Iqbal (2019) and Iqbal et al. (2020) monitored heavy metals concentration in different sites irrigated under different water qualities. In addition, they considered the concentration in milk produced from buffalo fed with wastewater irrigated fodder. The authors used the total target health quotient (TTHQ) and the human health risk index (HRI) as measures for the potential exposure to risks. The reported TTHQ exceeded 80 and 40 in the cultivated fodder and in the produced buffalo milk, respectively. As for the HRI, the values reported were higher than 1 for most heavy metals. This highlights human and animal population exposure to carcinogenic health risks in the sites where wastewater irrigation was adopted. Due to elevated heavy metals concentrations in buffalo milk. Another study determined the adverse effects of heavy metals concentration in milk produced from fed with industrial wastewater irrigated forage using the hazard index and the cancer risk (Castro–González et al., 2019, 2017). Pb was found to represent a serious health risk as it exceeded the international standard. As for As, though below permissible limits, it had a high hazard quotient for children with a value as high as 8. Cancer risk resulting from the elevated concentrations of Pb, Cr and As was as high as 0.004 which highlights the predisposition of children to cancer. Song et al. (2005) evaluated soil toxicity using the earthworm mortality test, which reached 32.5% after an exposure period of 8 weeks as compared to 0% in the control group, indicating the potential toxicity of the irrigated soil The studies that indicated health risks associated with heavy metals presence have assessed fodder cultivation using raw or diluted wastewater instead of treated wastewater. Thereafter, it appears that a minimum treatment is required to avoid any negative impact related to heavy metals accumulation.

Only few studies considered ecotoxicity caused by contaminants other than heavy metals. Carvalho et al. (2013) investigated the *Escherichia coli* and *Salmonella* levels in sunflower used as animal feed and found that the latter was below the limits. The same tests were conducted by Bevilacqua et al. (2014) on maize and tanner grass grown using secondary treated domestic wastewater. The authors reported high levels of the contaminants in the produced fodder, although animals did not manifest any sign of infection. Milk produced by goats fed with the fodder were conform with the standards in brazil and the European union standards. Compagni et al. (2020) used an integrated model to investigate the fate and induced risk of 13 contaminants of emerging concern in silage maize, rice, wheat and ryegrass irrigated with water channel where treated wastewater is discharged. The authors reported that the risk of ecotoxicity and human toxicity were both negligible for most contaminants. Nevertheless, sulfamethoxazole and 17a-ethinylestradiol were found to have a risk for consumers, however, the authors suggested that adopting a better irrigation system could lead to the reduction of the health risk associated with the contaminants.

4.3. Water use

It is important to consider the direct and indirect water requirement for the production of livestock feed. The assessment of the water use in what is known as the water footprint assessment, provides a representation for the expanding pressure on water resources in terms of green, blue, and grey water footprints. Water footprint assessment introduced by Hoekstra and Mekonnen (2002) began to gain momentum after the publication of the ISO 14046, which has since then been used in different studies (Müller Carneiro et al., 2019). In most published research, the focus is usually made on blue water as it has a high opportunity cost compared to green water (Hoekstra et al., 2012). Lately, more interest has been given to the grey water footprint as illustrates the extent to which wastewater can pollute the receiving water bodies. A study investigated the water footprint resulting from an actual WWTP which purifies 4000 m^3. day^{-1} of wastewater to a secondary treatment level and compared it with a no treatment scenario as well as to a tertiary treatment scenario where chemical phosphorus removal is adopted (Morera et al., 2016). The authors reported that the lowest grey water footprint was achieved under the tertiary treatment scenario. The latter was also responsible for the highest blue water footprint. Nevertheless, it only represented 9% of the total water footprint generated. That being said, the blue component of the water footprint can be neglected. Treating wastewater to appropriate levels alleviates the stress on receiving water bodies, although it results in an environmental burden. In fact, the GHG emissions from WWTP and the reuse of the resource within the energy water and food nexus cannot be neglected. A Canadian study considered the carbon footprint emissions from WWTP with different treatment units and reported that primary treatment can emit 0.005 kg-$CO_{2\text{-eq}}$.m^{-3} of treated wastewater (Monteith et al.,

2005). The emissions become 52 times higher (0.26 kg-$CO_{2\text{-eq}}.m^{-3}$) when conventional activated sludge with aerobic digestion are used to further treat the wastewater, and 160 times higher (0.8 kg-$CO_{2\text{-eq}}.m^{-3}$) when the treatment process is extended to include aeration and aerobic digestion. Another study found similar results as they reported that achieving tertiary treatment levels can emit as much as 0.89 kg-$CO_{2\text{-eq}}.m^{-3}$ (Falk et al., 2013). Certain agricultural activities such as growing forage crops do not require water of high purity levels as secondary treated wastewater is considered to be safe for reuse. In addition, cultivated lands can assimilate more pollutants and biogenic compounds compared to water bodies (FAO, 1992). That being said, reusing treated wastewater in agriculture can help reduce carbon emissions from WWTPs, as well as save large amounts of water resources through the reduction of greywater footprint (Fig. 4).

Water footprint assessment has not been extended to livestock feed irrigation as only three studies took it into consideration. A study combined geographic information system (GIS) and FAO crop model to assess water footprint associated with growing wheat using water from a river catchment where wastewater is discharged (Casella et al., 2019). The reported results show that combining the GIS and FAO method in WF assessment at basin scale is an interesting approach to assess the contribution of wastewater reuse as a solution to save water resources. This study considered the blue and green component of the water footprint only and did not include grey water footprint in their calculations. Another study investigated the water productivity and greenhouse gas emissions changes resulting from wastewater reuse (Maraseni et al., 2010). The authors reported an enhancement of water productivity that amounts to 21%, which will decrease the green water footprint of the practice. However, the reuse had an associated global warming potential that was 1.47 times higher compared to the base scenario where the wastewater is not part of the system boundaries. While some studies choose to include the wastewater treatment process in their computation, others do not since they consider that the wastewater must be treated anyways. Neither of the previous studies considered the grey water footprint associated with the treated wastewater, which could actually be a component that enhances the overall water footprint of the practice. Lahlou et al. (2020) found that using the treated wastewater as a fertilisation source in agricultural activities instead of being discharged to oceans or to uncultivated lands offsets a large grey water footprint. Nevertheless, the latter study considered the grey component resulting from few contaminants only. In fact, they only considered the total suspended solids, chemical oxygen demand, biological oxygen demand, total nitrogen and total phosphorus in their calculations.

4.4. Nutrient removal

Livestock feed irrigation through reusing wastewater does not only contribute to the reduction of fertilisation requirements, but also to nutrient discharge into the environment. The latter results in various biogeochemical threats, which are manifested in the eutrophication of groundwater and surface water. Beyond eutrophication, so long as irrigation regulations and discharge criteria exist and are respected, and application matches nutrient requirements of crops and infiltration/water holding capacity of the soil, there is not a significant threat. Trinh et al. (2013a) estimated that the reuse of wastewater for growing livestock feed can reduce N and P discharge into the environment by as much as 27% and 17% respectively. In addition, the practice can be used as a tertiary treatment for nutrient removal. In fact, Muramatsu et al. (2015) used an experimental set up composed of a simulated paddy field and a storage tank to monitor the amount of total nitrogen forage rice can remove from the circulated municipal treated water used for irrigation. The authors compared the results with a control system where the conventional method to irrigate paddy fields was used, non-circulated surface irrigation. In addition, the authors compared the results of all their experiments to a similar case where the rice cultivated was intended for human consumption (Muramatsu et al., 2014). The results obtained demonstrate that total nitrogen removal reached an average of 99.7% for circulated top-to-top and bottom-to-top irrigation methods. As for the control system, the total nitrogen removal observed was lower albeit comparable to that of the circulated irrigation system with a value of 98.4%. This rate is three times higher than that reported for rice intended for human consumption, while fertilisation requirement for the latter is higher than that of fodder rice (Islam et al., 2017; Muramatsu et al., 2014). Nevertheless, the circulated method released almost twice as much N to the atmosphere compared to the control system where the water was not circulated which could be the reason behind the lower TN rates at the end of the experiment. That said, N releases into the atmosphere under wastewater irrigation regimes need to be further assessed. Muramatsu et al. (2014) results are not in agreement with those reported by Watanabe et al. (2017) who determined that only 73.6% of the TN supplied was removed in the conventional method compared to an average of 96.6% when the water was circulated (Fig. 5). Pham et al. (2018) and Tran et al. (2019) found an even lower TN removal for non-circulated surface irrigation with rates as low as 58% and 49.7%, respectively. These differences could be due to different factors, one of which is the organic fraction of N in the treated wastewater used. In Fact, at high concentrations, NH_3 can volatise. The reported %of NH_3 in the water streams used in both experiments are significantly different. Watanabe et al. (2017) reported high ammonia levels that reach up to 40% of TN compared to Muramatsu et al. (2015) who reported a fraction of 10%. In addition, the initial TN concentration in the different streams could have accentuated this phenomenon. Muramatsu et al. (2015) used treated wastewater with a concentration of almost 33 $mg.L^{-1}$ and Watanabe et al. (2017) reported a similar average concentration of about 30 $mg.L^{-1}$. These values are not significantly different, nevertheless they could have contributed to an extent to the TN removal rates.

5. Economic aspect

5.2. Circular economy

The reuse of wastewater for irrigation represents an opportunity to reduce costs associated with fertilisation requirements and increasing water demands particularly in water scarce regions. The high nutrient concentration in the resource can be reinjected in agricultural activities which have the potential to reduce the dependence on expensive and energy intensive commercial fertilisers. This will support the shift to a circular model where resources recovery and recycling are encouraged. This practice also represents an opportunity for industrial symbiosis. Lahlou et al. (2020a, 2020b) investigated the possibility to blend treated wastewater from different industries with the purpose of meeting water and nutrients demand of a crop simultaneously. Industries can cooperate to design wastewater treatment process that will achieve the right water composition in terms of nutrients, which can be directed to agriculture while respecting irrigation water standards. Various studies in the literature have considered the possibility to substitute chemical fertilisation through reusing wastewater. Tran et al. (2019) investigated the enhancement of forage rice nutritional quality under continuous irrigation using treated municipal wastewater. The authors also considered the opportunity to recycle

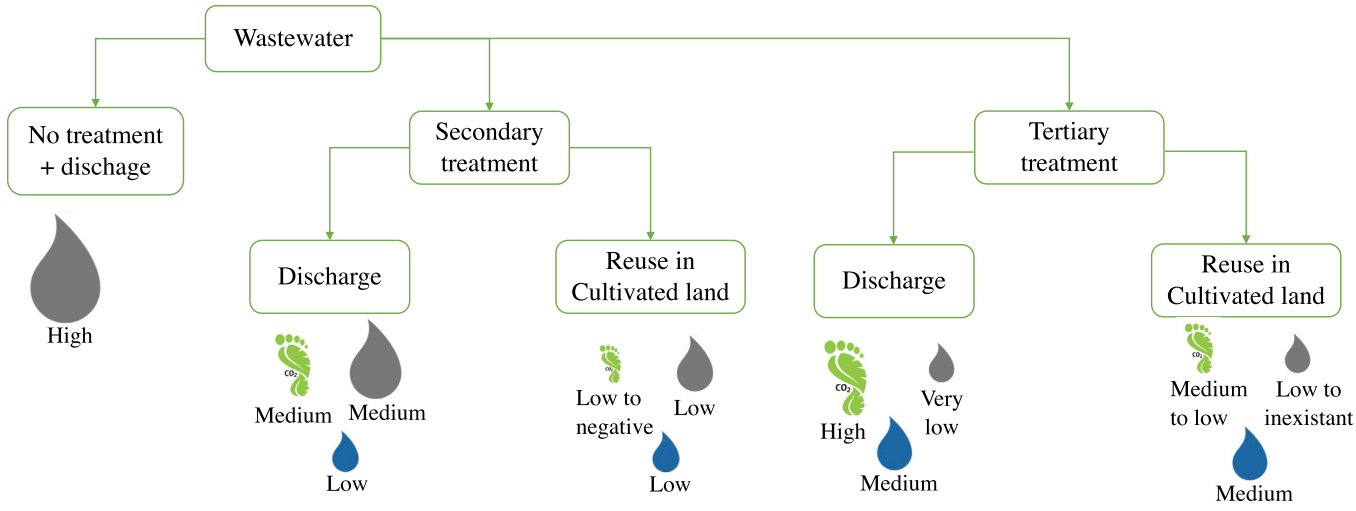

Fig. 4. Grey water, blue water and carbon footprint resulting from different treatment levels and reuse applications.

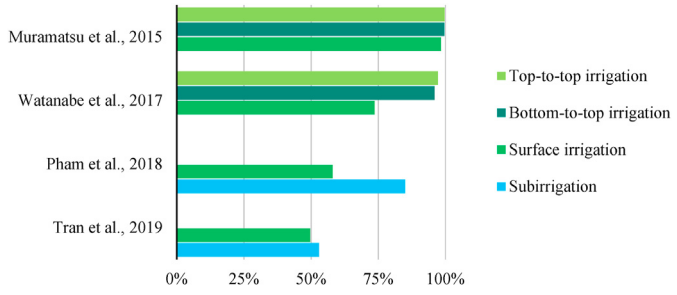

Fig. 5. Total Nitrogen removal from wastewater used in paddy rice cultivation under different irrigation techniques.

the nutrients for plant growth, thus, supporting the reduction in the fertilisation requirements. The authors determined that using the secondary treated wastewater with no fertilisation application resulted in yield equivalent to the conventional methods where fertilisation and tap water resources are employed. The protein content of the fodder was also found to be identical implying that the assimilation of nutrients from the TWW was as useful as those from chemical fertilisers. The reduced amount of fertiliser was not specified, neither the cost of it. Nevertheless, the savings can be estimated to be the same as those found by Duy Pham et al. (2019). The latter study used the same type of treated wastewater to grow the same type of fodder. The authors reported good crop quality under this practice compared the conventional method which consisted of using tap water in addition to a total amount of 1150 kg ha^{-1} of 14–14-14 N–P–K of commercial fertiliser, the price of which can go up to 6 USD. kg^{-1}.

Ta'any et al. (2013) reported the results of growing different types of fodder including pearl millet using treated wastewater. The authors shared information related to the N P K content of the resource used, although they did not quantify how much of the fertilisation requirement was substituted through this practice. Similarly, Fourie et al. (2015) investigated the impact of diluted winery wastewater irrigation on oats and pearl millet performance. The authors reported that for both plants, no K fertilisation was supplied, while it is documented that oats and pearl millet require 37 kg-K.ha^{-1} and 50 kg-K.ha^{-1} respectively (Attoe and Truog, 1950; Ausiku et al., 2020). Simmons et al. (2010) determined that more than 50% of the chemical fertilisation needs to grow wheat were substituted with the nutrients present in the wastewater. Finally, Minhas et al. (2006) examined the outcomes from an 8-year field study where sewage water was blended with groundwater to irrigate wheat, and reported that at least half of the N and P requirements were covered by the wastewater, which can reduce the production cost. Jiménez et al. (2011) reported that the overall farmers' revenues doubled as they started using wastewater generated from 24 wastewater treatment plants of which 17 use stabilization ponds and the rest adopt septic tanks and biological treatment unit. The nutrient content of the water resource substitutes for up to 85% and 100% of N and P requirements of the different cultivated crops in the area including fodder, respectively. The authors quantified that this type of reuse saves as much as 440 thousand USD. $year^{-1}$ only from the chemical fertilisation substitution. However, if the children morbidity rate for diarrhea is directly linked to the reuse of wastewater, due to the lower quality of water used in this particular study it is estimated that 110 thousand USD are lost each year due to the medical treatment engendered and to the human capital wasted. Nevertheless, pathogen related illnesses can be effectively managed through appropriate solids removal and disinfection processes during the treatment, while retaining nutrients.

5.3. Economic benefits

Sathaiah and Chandrasekaran (2020) observed that as farmers began using treated wastewater, the crop cultivation shifted from low water consuming fodder to high water consuming. Land value became three times higher for farms where treated wastewater was adopted compared to those which were still using ground water resources. The net income in the farms using treated wastewater was almost 71 times higher compared to the control farms with a net value as high as 133,018 Rs. They did not include the fertilisation reduction ,which on its own accounted for savings as high as 2510 Rs for FYM and 1998 for fertilisation. The growing cultivation of fodder increased the livestock production and income. Rehman et al. (2013) reported that farmers estimate of fertilisation costs are significantly lower when municipal wastewater is used for irrigation instead of canal water or when the two resources are blended. This represents an added value as most of the farmers in the region complain about the exorbitant chemical fertiliser prices. On the other hand, the chemical plant protection and manual weeding costs were higher. However, these costs represent a significantly low portion of the overall cost associated with the

Table 5
Heavy metals accumulation results in different studies.

Reference	Country	Type of water	Fodder	Tested on	Soil type	Irrigation	Contaminants measured	Finding
Samarah et al. (2020)	Jordan	Treated wastewater (source not specified)	Barley	Fodder	–	Drip irrigation	Cd, Fe, Zn, Pb	Below limit
Iqbal (2019); Iqbal et al. (2020)	Pakistan	Industrial and municipal wastewater (urban wastewater)	Maize, Mustard	Buffalo milk, fodder	–	–	Cd, Cr, Cu, Mn, Ni, Pb	Carcinogenic health risk
Duy Pham et al. (2019)	Japan	Treated municipal wastewater	Rice	Soil, fodder	–	Paddy irrigation	Fe, Mn, Cu, Zn, Cd, Ni, Pb, Cr, and As	Below limits
Tran et al. (2019)	Japan	Secondary treated municipal wastewater	Rice	Soil, fodder	–	Surface and sub irrigation	Cr, Cu, Zn, Cd, Pb, As	Below limits
Castro –González et al. (2019)	Mexico	Industrial wastewater discharged into river	Willow	Cow Milk	–	–	Zn, As, Pb, Cr, Cu, Ni	Carcinogenic health risk
Muklada et al. (2018)	Israel	Secondary treated wastewater	Willow	Fodder	–	–	Pb, Ni, Cd	Below limit
Ahmed and Slima (2018)	Egypt	Raw textile industry wastewater	Jew Mallow	Fodder	Clay loam	–	Cu, Cr, Zn, Cd, Pb, As, Mn, and Ni	Health risk
Pham et al. (2018)	Japan	Treated municipal wastewater	Rice	Soil, fodder	–	Paddy irrigation	Cu, Cr, Zn, Cd, Pb, As, Mn, Ni, Mo	Below limit
Mcheik et al. (2017)	Jordan	Secondary treated municipal wastewater	Vetch, Barley	Water	Sandy clay loam	Drip irrigation	Pb	Not detected
Mhaske et al. (2016)	India	Treated domestic wastewater	Maize	Soil, fodder	Unable to find paper		–	Below limit
Minhas et al. (2015)	India	Sewage water blended with groundwater	Sorghum	Water	Loam	Flood irrigation	Fe, Mn, Zn, Cu, Cd, Cr, Ni, and Pb	Below limit
Ta'any et al. (2013b)	Jordan	Treated wastewater (source not specified)	Tamarix sativa, alfalfa, pearl millet and Atriplex hallimus	Soil, fodder	Silty sand	Flood irrigation	Cu, Pb, Cr, Cd	Below limits
Trinh et al. (2013)	Vietnam	Domestic and industrial wastewater discharged into river	Rice	Water	–	Paddy irrigation	Pb, Hg, As, Mn, Cr	Below limits
Fitamo et al. (2011a)	Ethiopia	Wastewater discharged into river (industrial domestic and commercial)	Oats, Alfalfa, Rhodes, Desmodium, Setaria	Forage	Clay, Sandy loam	–	Cr, Ni, Co, Cu, Zn, Cd, Pb, Hg, Se, As	Significant accumulation
Mojiri and Abdul Aziz (2011)	Iran	Municipal wastewater	Wheat	Fodder	–	Flood irrigation and drip irrigation	Mn, Ni, Cd, Fe	Above limit
Al-Othman and Selim (2011)	Egypt	Secondary treated wastewater	Pearl millet	Fodder	Sandy loam soil	Flood irrigation	Zn, Cu, Cr, Cd, Pb, Ni	Below limit
Al-Karaki (2011)	Jordan	Tertiary treated sewage water	Barley	Fodder	–	Hydroponics	Pb, Ni, Cr, Cd	Below limit
Simmons et al. (2010)	Pakistan	Domestic wastewater	Wheat	Fodder	Sandy loam	–	Cd, Pb, Zn	Below limits
Asghar et al. (2008)	Australia	Pulp and paper mill treated wastewater	Maize, Sorghum, clover, wheat, oats, ryegrass, triticale	Water	–	–	As, Cd, Cr, Cu, Pb, Hb, Ni, Mn, Zn	Below limits
Song et al. (2005)	China	Domestic and industrial wastewater	Wheat	Soil	Loam, sandy loam, silt loam	–	Cd	Slight accumulation
Varadarajan et al. (1992)	India	Sewage watstewater	–	Cow Blood, Cow Milk	–	–	Fe, Pb, Zn	Below limit

activity. The use of the wastewater was followed by farmers revenue expansion. Ratnam (2004) reported the implications of using treated wastewater to irrigate fodder in a town in South Africa. The practice increased the water availability in the region which encouraged the farmers to expand their fodder production through enlarging the cultivated area. Given the enhanced harvest, livestock feed readiness was improved which augmented cheap milk production. This created small businesses and new job opportunities that revitalised the local economy. Finally, Joshua Amarnath & Gunasekaran (2017) conducted a feasibility study on the reuse of treated municipal wastewater for different applications including fodder irrigation. The authors believe that the reuse of the resource will enable the expansion of the cultivated lands which can engender increased revenues from fodder production.

5.4. Impact on forage properties

Reusing wastewater resources can increase revenues attributed to the enhanced yields and qualities that can be obtained through the practice (Table 6). Ines et al. (2017) determined that secondary treated wastewater can safely be used to grow Buffel grass achieving better heights and increased yields. This enhancement is likely due to the additional nutrients provided through the resource. In fact, the authors did not explicitly mention it, although they provided the N, P and K concentrations in the treated wastewater which were equal to 108, 26 and 60 mg.L^{-1} respectively. Mcheik et al. (2017) also used secondary treated wastewater and investigated its effect on vetch and barley production. The authors found that the highest yield was under 120% evapotranspiration (ET) irrigation compared to the other treatments which consisted of rain only, 80% ET and 100% ET. The irrigation method used in this study is drip irrigation and it has an average efficiency of 90% (World Bank, 2006), therefore the crop water requirement elevates to 111% ET. The increased yield could either be due to the water availability or to the increased N given to the plant as the water used had a N concentration of 40 mg/L, or to both. Similarly, Al-

Table 6
Impact of wastewater reuse on crop quality reported in the literature.

Reference	Country	Type of water	Fodder	Type of study	Finding
Ines et al. (2017)	Tunisia	Secondary treated municipal wastewater	Buffel grass	Field study	The practice improved plant growth. Soil and crop quality were not adversely affected by the treated wastewater.
Mcheik et al. (2017)	Jordan	Secondary treated municipal wastewater	Vetch and barley	Field study	The biomass and the grain yield of fodder were enhanced under Treated wastewater irrigation.
Al-Karaki (2011)	Jordan	Tertiary treated sewage water	Barley	Field study	Growing barley under hydroponic conditions using tertiary treated sewage water increased the yield compared to tap water.
Duy Pham et al. (2019)	Japan	Treated municipal wastewater	Rice	Lab experiment	TWW irrigation resulted in no adverse effect. TWW irrigation without fertilisation obtained the best rice quality.
Watanabe et al. (2017)	Japan	Municipal wastewater	Rice	Experimental set up	The practice resulted in an enhanced crop yield and quality
Parmar et al. (2017)	India	Primary Treated dairy wastewater	Sorghum	Field study	Treated wastewater had no adverse effect on the crop growth.
Fourie et al. (2015)	South Africa	Diluted winery wastewater	Pearl millet and oat	Field study	Improved dry matter production of oats and faster growth of pearl millets were witnessed when the diluted wastewater was used compared to river water. The fodder produced can cover the fertilisation expense and provides an additional revenue of R12200/ha/year.
Al-Othman and Selim (2011)	Egypt	Secondary treated municipal wastewater	Pearl millet	Field study	Crops irrigated with the secondary treated wastewater have the same quality as those irrigated with canal water, if not better.
Grzegorczyk et al. (2019, 2020)	Poland	Potato starch and brewery wastewater	Medow sward	Field study	The resulting crop had low quality due to excess of K content and deficiency in Mg.
Simmons et al. (2010)	Pakistan	Domestic wastewater	Wheat	Field study	Quality of the fodder was similar to that irrigated with canal water.

Karaki (2011) investigated barley quality and yield grown in a hydroponic system under tertiary treated sewage wastewater which had more or less the same N concentration, and reported a yield increase as well. In fact, the latter compared barley performance under tertiary treated wastewater, tap water, and a blend of the two resources. The forage yield under the treated wastewater was 42% and 16% higher compared to tap water and blended water, respectively. The mineral nutrient and crude protein contents in the produced barley were enhanced. Furthermore, the crop water productivity was improved under treated wastewater cultivation. In fact, the authors measured an approximate 15% reduction in the total water required to grow 1 ton of fodder. The authors reported that the enhanced performance is due to the higher N content in the treated wastewater compared to the tap water. The authors did not report how much N the fodder requires for optimum growth, although they did report the concentration of nutrients. The treated wastewater contains three times more N compared to tap water in the form of nitrate, and almost the same concentrations of P and K.

Fodder rice was a recurrent forage used to assess the impact of wastewater irrigation. Duy Pham et al. (2019) used treated municipal wastewater irrigation to grow fodder rice and compared the results with the conventional method which consisted of using tap water + fertilisation. The best plant attributes in terms of dry shoot mass, yield and protein level were higher under treated wastewater irrigation even without the application of additional fertilisers. This suggests that the resource provides all nutrient requirements for the optimum growth of fodder rice. The same was observed by Watanabe et al. (2017) who noticed an increase of yield as they used more treated wastewater for the irrigation of fodder rice. However, the practice can cause an increase in soil salinity which negatively influences rice yield (Biggs and Jiang, 2009). In fact, the authors suggested that switching to para grass, which has a higher salinity tolerance, could be a solution to the decreasing yields. That said, in order to be able to reuse the wastewater resources for livestock feed irrigation while minimising its potential adverse effects, the cultivated crop must be selected based on the water quality. For instance, sorghum has a higher tolerance to poor soil quality compared to other cereals (Slakie et al., 2013). A study that used poorly treated dairy wastewater to grow sorghum confirms the latter. The authors reported a reduction of yield of 20% compared to using tube well water with an application of farm yard manure of 5 t ha^{-1} (Parmar et al., 2017). As gypsum was added at a rate of 1 t ha^{-1} the yield reduction changed to 3% only. Fourie et al. (2015) explored the impact of diluted winery wastewater irrigation on oats and pearl millet performance and nutrient content. Winery wastewater is characterised with high concentration of K in mineral form, which enables the immediate availability of the nutrient for plants uptake. The results reported that oats irrigated using the diluted wastewater had an enhanced performance compared those grown using river water. Furthermore, the high N and K content in the diluted wastewater improved the dry matter yield. As for the cultivated pearl millet, the authors reported that the irrigation regime had no adverse effect neither on the performance of the fodder nor on the total dry matter produced. Al-Othman and Selim (2011) also investigated pearl millet. In this study, the authors aimed to highlight the economic benefits engendered from the utilisation of secondary treated wastewater in irrigation. The experiment consisted of a three-year experiment where secondary treated wastewater was used to grow fodder in sandy loam soils under the Egyptian climate. The authors reported an enhanced pearl millet dry matter yield under treated wastewater irrigation compared to canal water, which they attributed to the increased nutrient availability from the effluent, especially K. Actually, all pearl millet K requirements were provided through the practice. This nutrient, when readily available, is found to put the plant into the reproductive phase sooner than usual especially in the initial growing phases (Fourie et al., 2015). The forage quality was better compared to the fodder grown under canal water, which did not alter livestock performance (Al-Othman and Selim, 2011). Other works claim that in the long term, this practice can reduce the quality of the produced fodder. This can be confirmed by Grzegorczyk et al. (2019, 2020) who determined the quality of meadow fodder grown using brewery wastewater irrigation for 15 years. The authors reported that the meadow did not meet high quality fodder criteria. Nevertheless, this low performance can be attributed to the fact that meadow requires a yearly K application rate of 67 kg ha^{-1} at most while the wastewater used in this study had high concentrations (Brummer and Davis, 2014). Sometimes the higher concentration result in better nutrient content in the produced fodder, as was stated by Simmons et al. (2010) who reported the quality and yield of fodder produced in a peri-urban village in Pakistan where untreated wastewater has been used for

at least 25 years for growing wheat straw fodder. The authors stated that irrigation using treated wastewater was associated with in an increase of N and P content in the soils, which resulted in better N content in the produced wheat straw. Furthermore, under the wastewater irrigation regime, the same product quality and yield were obtained as that under canal water irrigation.

6. Insightful suggestions

The social studies that have been conducted thus far have focused on reporting the acceptance level from the public whilst investigating the factors that alter the approval of the public, rather than understanding the reason behind this influence to better plan for awareness campaigns. For instance, whilst farmer's attitudes were investigated, the reason behind their differing opinion on wastewater reuse has not been considerably examined. The same applies for the case of females, which were reported to be less likely to accept wastewater reuse compared to males. This trend may be explained by maternal altruism, which alludes to the fact that females with children may question adopting new technologies for their children and themselves, i.e. wastewater reuse. This is a research direction that is worthy of further investigation. For instance, maternal altruism can be applied to farmers who have the responsibility of delivering good quality food to their consumers, and therefore may require additional assurances and consideration prior to adopting recycled water. As such, a farmer's altruism might be the reason they tend to reject the idea of using recycled water, although they may be satisfied with the quality and benefit on the crop yield. Regarding environmental analysis, there is a gap in the literature regarding the investigation of the environmental implications engendered by the practice. Most reported studies have considered just one aspect of an LCA of wastewater fertigation. In addition, assessments conducted were not comprehensive as they did consider the implications of fertigation on the soil-water and energy-water nexus. For instance, no study has looked at all the aspects involved in the global warming potential of wastewater reuse in growing crops from cradle to grave. In addition, the impact of wastewater fertigation on soil microbiota and their impact on soil's GHG fluxes remains unexplored. For the case of human and ecotoxicity impacts, there is a need for comparative studies between growing multiple crops in different soils using wastewater with varying chemical composition and different irrigation techniques and regimes, and their impact on soil properties, crop quality and crop yield. In addition, the water footprint of the practice needs to be assessed using the three WF components for better resource optimisation and pollution prevention. For better WF and CF optimisation, future studies must look at how the wastewater treatment processes of different industries can be modified to produce effluent with the required chemical properties at lower energy requirements and reduced costs. In addition, the opportunity for industrial symbiosis can be further investigated by examining the possibility of blending different sources of wastewater to obtain the perfect nutrient ratio.

7. Conclusion

Reusing wastewater in growing animal feed represents an opportunity to alleviate stress on the water and energy sectors while enhancing food production thanks to the increased yields obtained from the practice. This wastewater reuse application is one of the few that engenders a relatively high acceptance amongst the population, as more people are willing to use the resource in growing non-food crops compared to growing food crops or to other applications such as dish washing. This review presents the existing studies that investigated the practice from a social, environmental or economic perspective and details the different parameters considered thus far as well as those that need further investigation. The general conclusions drawn from the 73 peer reviewed journal articles are:

- Knowledge is the most prevalent factor that influences the acceptance level of reusing treated wastewater. If awareness campaigns are to be organised, it is necessary to provide the public with information regarding the quality compliance of WWTP and standards of reuse to be able to engender a higher acceptance rate amongst the population.
- The attitude of farmers is important as they are the main stakeholders in agriculture. Thereafter, awareness campaigns need to focus on involving farmers as much as consumers.
- There is a lack of comprehensive LCA studies that assess the practice.
- Future studies must consider all the different components and parameters that result in greenhouse gas emissions, sequestration and offsetting to be able to have a comprehensive assessment of the carbon footprint relative to the practice. The current assessment is confined to a single parameter which does not reflect the global warming potential of the practice.
- There is a lack of studies that have holistically considered all factors relating to environmental burdens and included all sources and offsets of GHGs (distribution, soil fluxes, fertiliser offset); and made strong comparisons to the same environmental burdens under surface or groundwater irrigation.
- The irrigation methods used in growing forage crops and the soil type and texture have been reported to influence the accumulation of contaminants of emerging concern, thereafter, to influence the ecotoxicity and the human toxicity of the practice. Nevertheless, some studies failed to report these parameters. In addition, there is a lack of comparative studies between different types of forage crops and soils using different sources of wastewater in terms of resistance to contaminants and increased yields.
- The impact of different sources of wastewater on soil biota has not been considered in the existing articles.
- None of the studies that considered the water footprint assessed all three components, noting that it has been reported that under different scenarios, their values can significantly vary.
- As livestock feed does not require highly purified wastewater, technology modification can be introduced in WWTP, which will reduce the cost of treatment and enhance the economic benefit associated with reusing wastewater to grow forage crops.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at

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