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Sustainability assessment of vermifiltration technology for treating domestic sewage: A review

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ABSTRACT

With population surge and vigorous industrialization, scarcity of freshwater is intensifying day-by-day. Reutilization of treated wastewater has been regarded as the most promising effort to counteract this global issue. To meet the current need of sustainable development, researchers are emphasizing on practicing the green technologies to purify wastewater. In such regard, vermifiltration (VF), being a natural and eco-friendly technology, can be a wise selection for treating the domestic sewage. The present review includes a brief discussion on the performance of VF in remediating the domestic sewage. In addition, the life-cycle assessment (LCA) and life-cycle impact assessment (LCIA) of the VF technology have been explored and the results are compared with those of the conventional and non-conventional wastewater remediation technologies. It is found that VF is a standalone technology delivering enormous benefits, including negotiation of greenhouse gas (GHG) emissions, decentralized treatment facility, energy efficiency, value-added byproduct generation, contribution to circular bioeconomy, and preservation of local aesthetics. The main objective of this review work is to bring all the aspects related to VF of domestic sewage to the attention of the prolific researchers for establishing VF technology as a sustainable domestic sewage treatment alternative in near future, satisfying the zero-discharge concept.

1. Introduction

The unrestrained population growth, urbanization, and intense industrial activities have brought about the consumption of enormous quantity of freshwater and discharge of huge amount of wastewater containing hazardous contaminants such as organics, nutrients, pathogens, etc. [1,2]. According to the UN World Water Development Report 2020, a six-fold increase in the water utilization over the past century has been observed with an increasing rate of almost 1 % per year [3]. The presence of the abovementioned pollutants in the aquatic environment exhibits the concerns like eutrophication and depletion of dissolved oxygen (DO), thereby making the environment adverse for the aquatic lives to thrive. In extreme conditions, the human beings may also get affected as we share the food chain with the fishes [2,4]. The situation becomes even worse when the consumers are compelled to use the contaminated water or buy freshwater at high cost. Hence, to overcome the scarcity of clean water, the treatment and reuse of wastewater have become the compulsory choice for the competent authorities [2,5].

It has been reported that the domestic wastewater coming from various towns and cities has been the biggest source of water pollution in India [6]. Generally, 75–80 % of the freshwater supplied to the communities becomes wastewater [7]. As per the reports of the Status of Sewage Treatment Plants 2021, published by CPCB, in India, approximately 29,129 MLD swage has been produced by all the Class I cities and Class II towns together (estimated as per the population in 2001 census), which is expected to be 33,212 MLD at present, considering 30 % growth in urban population per decade. On the other hand, the existing wastewater treatment plants (WWTPs) facilitate the treatment capacity up to 7933 MLD which is just 23.88 % of the current domestic sewage generation. Meanwhile, the actual capacity utilization factor of the existing sewage treatment plants (STPs) is 0.722. Practically, only 13.5 % of the generated domestic sewage avails the centralized treatment facility and the remaining gets directly discharged into the waterbodies, deteriorating the water quality [8]. Moreover, the domestic sewage is enriched with nutrients, nitrogen (N) and phosphorus (P). Hence, in order to meet the stringent surface water discharge norms, to satisfy the accrescent need for the clean water, and from the perspective of nutrient recovery, the treatment of domestic sewage is of utmost importance [6,9].

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The conventional WWTPs, employed to overcome the water crisis, necessitate large material and energy input. Furthermore, the greenhouse gas (GHG) emissions from the WWTPs can potentially damage the environment [10]. In addition, as a byproduct of wastewater treatment, enormous quantity of sludge is produced in WWTPs, imposing additional monetary requirements, which, in turn, makes the WWTPs unsustainable [11]. The physical and chemical wastewater treatment methods are found to be costly as well as incompetent in removing the targeted pollutants from the wastewater, cutting down their acceptability as the sustainable wastewater remediation methods [12,13]. As a solution to the aforesaid problems, the biological wastewater treatment methods have gained the major attention of the researchers because of having several advantages over the aforementioned methods [14]. The anaerobic methods are energy-efficient and produce less sludge. However, it is a sluggish process and becomes unstable due to the slight deviation in the operating conditions. In addition, the anaerobic methods are not suitable for the low-strength wastewater such as domestic sewage. The anaerobically treated effluent is devoid of DO, restricting its disposal to the surface water. In addition, the gaseous emissions such as methane (CH_4) and carbon dioxide (CO_2) and the pungent smell produced during the anaerobic process hinder its environmental as well as social acceptability [1,7]. On the other hand, the aerobic methods, being more robust than the former, can be effectively implemented to overcome the concerns related to the anaerobic methods. However, high energy input and huge sludge production have been the perennial constraints for the commercialization of the aerobic wastewater treatment methods, especially in the underdeveloped and developing countries where the capital investment and skilled manpower are not available in abundance [2,5].

In the context of the developing and underdeveloped countries, the implementation of the sustainable wastewater treatment technology is of paramount importance. According to Bradley et al. [15], in order to achieve the sustainability, the technology has to be environmentally benign, economically feasible, and socially acceptable (Fig. 1). According to the American Society of Civil Engineers (ASCE), the sustainable water resource systems are designed and maintained to fulfill the objectives of the society without compromising the ecological, hydrological, and environmental integrity [15]. In short, sustainable development promotes the preservation of the social, economic, and environmental vitalities while satisfying the current needs.

The conventional WWTPs are reported to emit 3 % of the global GHG emissions [16,17]. Daelman et al. [18] investigated that 1 % of the chemical oxygen demand (COD) of the influent has been converted to

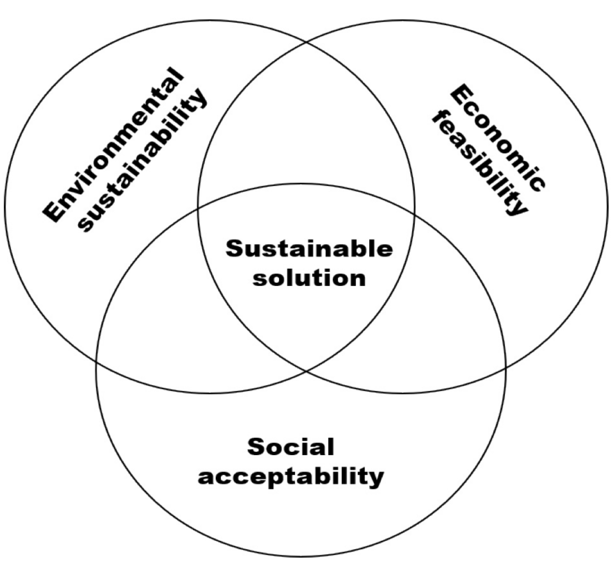

Fig. 1. Sustainability criteria for a wastewater treatment technology.

methane (CH_4) in the WWTPs, whereas Kampschreur et al. [19] have inspected that up to 14.6 % of the total nitrogen load of the influent has been released as nitrous oxide (N_2O) in the WWTPs. Such emissions become even intense when the activate sludge process (ASP) is used as the secondary treatment step in the WWTPs [20]. Moreover, the centralized treatment system necessitates the transportation of the wastewater and the produced sludge from the source of wastewater to the treatment site and from the wastewater treatment site to the sludge handling site, respectively [21]. In addition to the potential GHG emissions, huge monetary requirement for high energy consumption, and sludge handling make the centralized wastewater treatment systems unsustainable, especially for the small communities in rural areas. Implementation of decentralized onsite sanitation systems can be a potential solution for the above problem [22]. In fact, it is an automatic choice, especially where the central sanitation system has not reached. In addition, being easy to construct and operate, the decentralized systems have become more sustainable than the centralized systems and are expected to serve up to 500 million population by the year 2030 [23].

In this regard, the vermifiltration (VF) technology, being a natural, environmentally benevolent, cost-effective, and decentralized system, has gained the attention of the researchers, especially for remediating the domestic sewage [1,5,11]. The vermifilters are earthworm-based biofilters, facilitating the degradation of organics and eradication of nutrients through the combined action of the earthworms and microbes [5,11] (Fig. 2). Mostly, the VF technology has gained the popularity as the primary or secondary treatment alternative for treating the domestic sewage (Fig. 3). If the nutrient recovery from the domestic wastewater is intended, the vermifilters can also be potentially employed as the tertiary treatment step [3].

In order to evaluate the sustainability of VF technology for treating the domestic sewage, the life-cycle assessment (LCA) of VF technology has been explored. From the available data on the LCA studies on the VF technology treating domestic sewage, a comprehensive review on the inflow (raw materials and energy) and outflow (treated effluent, solid residue, and GHG emissions) of various forms of materials throughout all the stages of its lifecycle i.e., construction, operation, and dismantling has been portrayed in this review work. This not only helped to understand the environmental sustainability of the VF technology (in terms of GHG emissions, and sludge production), but also helped to understand the economic feasibility of the same (in terms of materials and energy consumption and value-added byproduct formation). To have an in-depth understanding of the actual environmental impacts caused by the VF technology while treating the domestic sewage, the concept of the life-cycle impact assessment (LCIA) has also been reconnoitered [24,25]. As already mentioned, since the VF technology has been mostly employed as the secondary treatment step, the results obtained from the LCA and LCIA studies on VF technology are compared with those of the ASP, the most frequently employed conventional secondary treatment step in the WWTPs, for assessing the sustainability of the VF technology. Apart from this, the VF technology has also been compared with the other non-conventional technologies such as constructed wetlands (CWs), aerated lagoons (ALs), and waste stabilization ponds (WSPs) regarding the materials and energy input and GHG emissions across all the stages of their life-cycle to reinforce the acceptability of the VF technology as the sustainable domestic wastewater treatment alternative.

Till date, many review works on evaluating the potential of the VF technology as an alternative of the conventional wastewater treatment technologies have been published by the various prolific researchers across the globe [2,5,11,26,27]. Singh et al. [5] have focused on the pollutant removal mechanisms, factors affecting the treatment performance, and the application of the VF technology in removing the key pollutants i.e., organics, nutrients, and solids from the wastewaters. Samal et al. [11] have emphasized on the potential of the macrophyte-assisted vermifilters in remediating the domestic as well as industrial wastewaters. Singh et al. [2] have highlighted the reusability of the

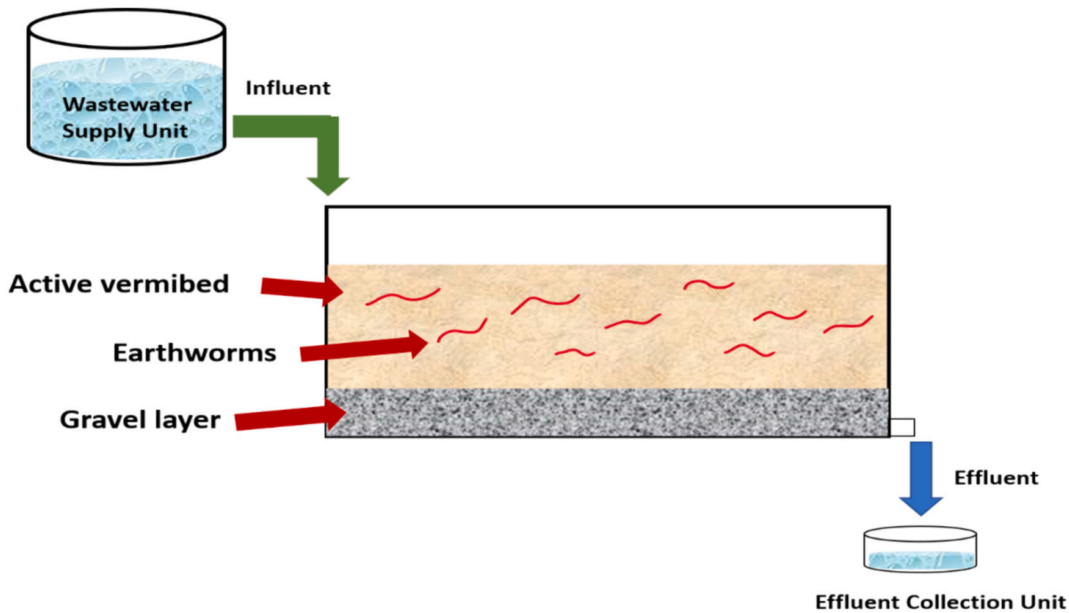

Fig. 2. Schematic diagram of a VF unit.

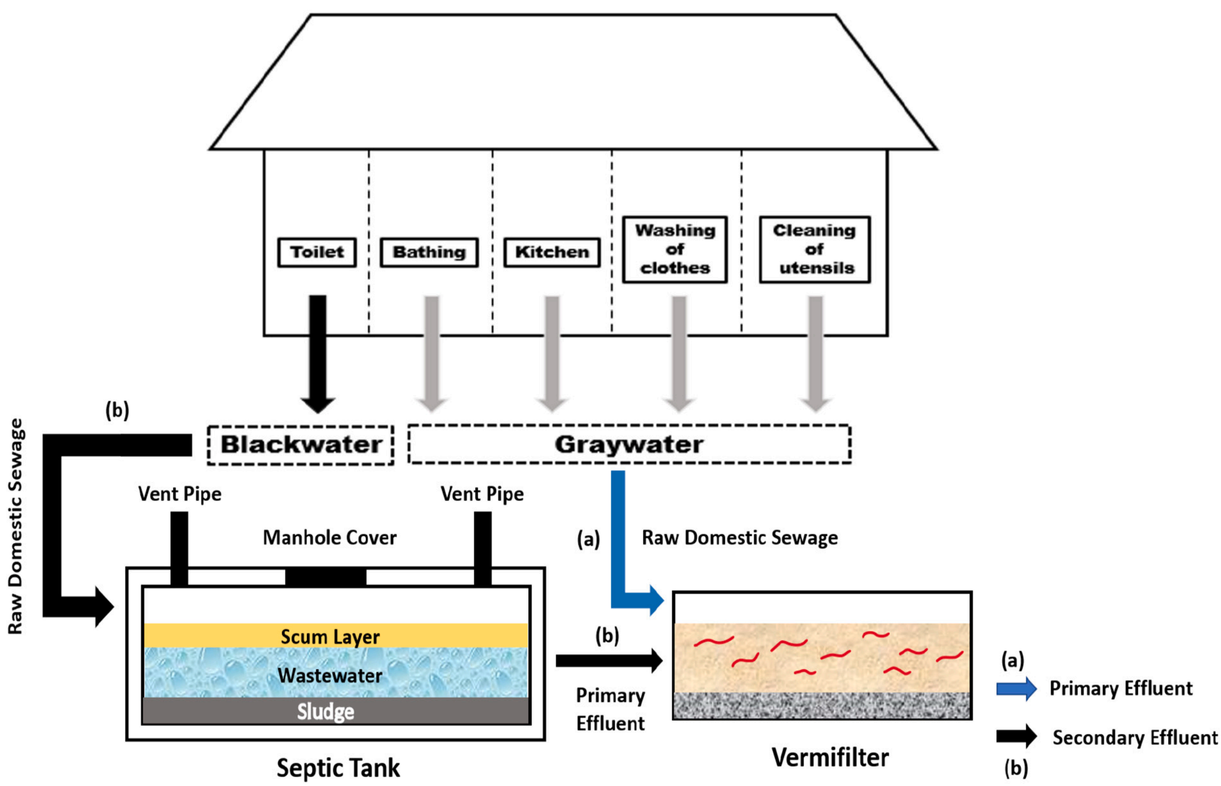

Fig. 3. Application of the VF technology for treating the domestic sewage. (a) primary treatment step and (b) secondary treatment step.

treated effluent from the VF of the wastewaters coming from both the domestic and industrial premises. Samal et al. [26] have enlighten the types and characteristics of the earthworms, their casting habits, and GHG emissions during the VF process while briefing about the pollutant removal mechanisms and the application of the VF technology for treating various wastewaters. Singh et al. [27] have particularly explored the nitrogen removal dynamics in the vermifilters while treating the domestic as well as the industrial wastewaters. Also from the available literature, it has been observed that very few researchers have published their review works on the sustainability, particularly on the environmental sustainability of VF technology for treating the wastewater [2,3,28,29]. Lourenco and Nunes [29] have evaluated the sustainability of the VF technology in terms of material and energy input and GHG emissions throughout all the stages of its life-cycle while treating the domestic sewage and compared the results with those of the CWs, small rate infiltration (SRI), and ASP. On the other hand, Abello-Passteni [28] has focused on the LCIA of the VF technology, ALs, and ASP while treating the raw domestic sewage from the small communities in Chile. However, to the best of our knowledge, no one has ever made an approach to assess the economic sustainability of the VF technology by performing the cost analysis and focusing on its linkage to the circular bioeconomy during the treatment of domestic sewage. Moreover, the assessment of the social acceptability of the VF technology during the course of treating the domestic sewage has also been overlooked by the researchers. Hence, in this review work, a genuine effort has been made to investigate the sustainability of the VF technology with respect to the three major bottom-lines of the sustainability i.e., environmental sustainability, economic affordability, and social acceptability during the course of treating the domestic sewage.

2. Types, operation, and sustainability of vermifilters

Predominantly, vermifilters are of three types: vertical subsurface flow vermifilters (VSSF-VFs), horizontal subsurface flow vermifilters (HSSF-VFs), and hybrid vermifilters (H-VFs). The design, operation, and sustainability of each of the aforementioned vermifilters are briefly discussed below.

2.1. VSSF-VFs

In VSSF-VF, the bed materials are stacked in layers vertically and the gravel is provided at the bottommost layer as a supporting media. The wastewater is allowed to flow vertically through the bed material from the top of the vermibed and treated effluent is collected at the bottom (Fig. 4a). The VSSF-VFs exhibits higher oxygenation capacity attributing to the better distribution of wastewater [30], which promotes enhanced biodegradation of the organics and nitrification process. Hence in addition to the burrowing activities of the earthworms, the configuration of the VSSF-VFs intensifies the natural aeration inside the system, which further cuts down the external energy requirement for mechanical aeration, thereby making the process cost-effective [5]. Since the wastewater flows vertically through the system, the vermibed materials get effectively utilized in the VSSF-VFs [1]. Moreover, the intensified aeration further aggravates the activity of the earthworms inside the VSSF-VFs. As a result, more casting is produced, which can be sold as organic fertilizer, cutting down the cost of the process [31]. On the other hand, the higher DO level inside the system ensures the complete degradation of the organics present in the wastewater, releasing carbon dioxide (CO_2) as the only gaseous emission, especially while treating the domestic wastewater with lower organic strength, which, in turn, promotes the environmental sustainability through negotiating the greenhouse gas (GHG) such as methane (CH_4) and nitrous oxide (N_2O) emissions [2,26]. Lastly, being a complete aerobic system, VSSF-VF does not produce any pungent smell during the treatment of wastewater, reinforcing the social acceptability [5].

2.2. HSSF-VFs

Unlike the VSSF-VFs, the bed materials are stacked in layers in horizontal direction and the gravel layer is provided just before the outlet. In HSSF-VFs, the wastewater is allowed to flow through the vermibed media horizontally and the treated effluent is collected at the outlet end, placed opposite to the inlet zone (Fig. 4b). According to the reports, the coexistence of the aerobic and anoxic/anaerobic conditions has been observed inside the HSSF-VFs, which allows higher denitrification along with the biodegradation of the organics and nitrification [30]. Unlike the conventional nitrification and denitrification system, in HSSF-VFs, the nitrification and denitrification take place simultaneously within a single unit, lessening the footprint requirement. Moreover, no external chemical such as methanol is required to be added as the external carbon source to trigger the growth of the denitrifiers in the HSSF-VFs, reducing the cost of the process [1,32]. Similar to the VSSF-

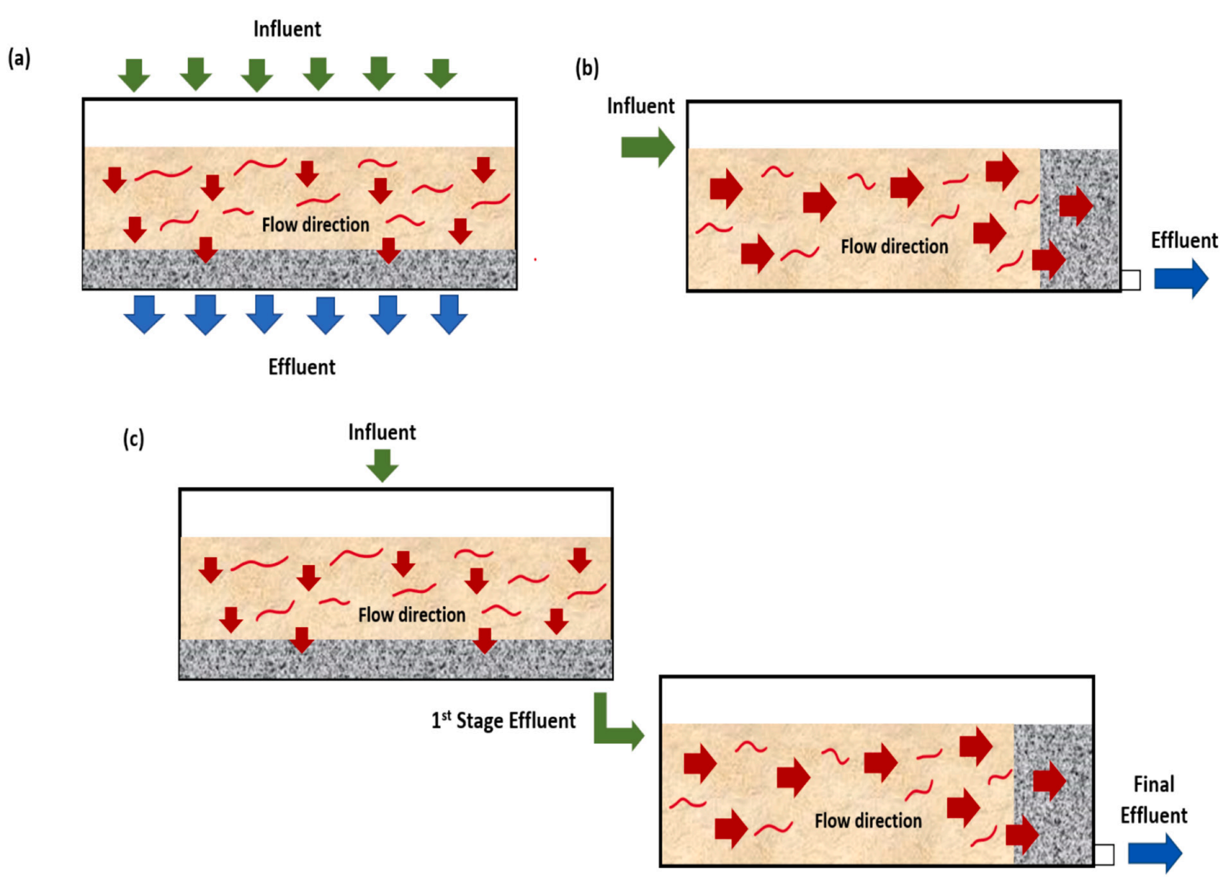

Fig. 4. Schematic diagrams of different types of vermifilter designs. (a) VSSF-VF, (b) HSSF-VF, and (c) H-VF.

VFs, the produced casting in the HSSF-VFs can be traded as the organic fertilizer. Moreover, the HSSF-VFs negotiate the emission of the potential GHGs and the generation of the pungent odor, thereby assuring the environmental sustainability and social acceptability, respectively [5,26].

2.3. H-VFs

H-VF allows two-stage filtration of the wastewater. Generally, a H-VF consists of a VSSF-VF followed by a HSSF-VF. First, the wastewater flows vertically through the VSSF-VF and the effluent coming out from the bottom of the VSSF-VF serves as the influent for the HSSF-VF, which flows horizontally through the HSSF-VF and finally, the effluent is collected on the other side of the HSSF-VF (Fig. 4c). As already discussed, in VSSF-VFs, the aerobic condition prevails, whereas in HSSF-VFs, the anaerobic condition becomes predominant [30]. Since, the wastewater has to travel through both the reactors, it experiences all the redox conditions during its passage through the H-VFs [33]. Basically, the H-VFs impart all the advantages associated with the VSSF-VFs and HSSF-VFs. Moreover, due to the improved redox conditions, the H-VFs ensure better removal of the organics and nutrients from the wastewater. Also, the effective length of travel of the wastewater gets increased in the H-VFs, leading to the enhanced interaction time between the wastewater, earthworms, bed materials, and microbes, which, in turn, aggravates the treatment efficacy of the VF technology through satisfying the criteria for the environmental and economic sustainability [1].

3. Pollutant removal mechanisms in VF technology

VF technology can substantially remove the organics, solids (both the suspended and dissolved solids), nutrients (mainly N and P), and pathogens from the domestic wastewater. The governing pollutant removal mechanisms in the vermifilter have been discussed in brief in the following subsections.

3.1. Organic and solid removal mechanism

In VF, the symbiotic action of the microbes and the earthworms captivates the purification of wastewater. The earthworms, incorporated into the vermibed, not only breakdown the pollutants present in the wastewater, but also devour the soil particles of the vermibed [1,31,34]. Apart from the earthworms and microbes, a large portion of pollutants has been removed by the vermibed media through adsorption and screening or trapping [2,35]. Generally, the vermibed consists of both the organic and inorganic materials. The organic materials such as vermicompost serve as the food to the earthworms and microbes and thereby helping the earthworms to grow and reproduce, which, in turn, improves the performance of the vermifilter [5,11]. On the other hand, the inorganic packing materials such as sand improve the hydraulic conductivity of the media, facilitating efficient wastewater treatment through the achievement of desired hydraulic retention time (HRT) [36]. During VF, the vermibed acts as the sorption medium or support matrix, enhancing the removal of nutrients in the vermifilter [37–39]. The earthworms through their burrowing activities, combination of ingestion, grinding, digestion, and excretion, convert the larger soil particles of the vermibed into finer fractions, increasing the specific surface area of the vermibed media, thereby escalating the sorption capacity of the support matrix. In addition, the earthworm's burrowing action also helps in improving the porosity of the vermibed media. Generally, the coarse pollutants such as suspended organics and suspended solids, present in the influent, get trapped on the pores of the bed media followed by their subsequent devouring by the earthworms and eventually, get released as the vermicasting with enlarged specific surface area. This vermicasting gets mixed with the bed materials and improves the sorption potential of the mixture [2,35]. Unlike the suspended pollutants, the dissolved pollutants in the influent percolate through the screening layer. Thereafter, a fraction of the dissolved pollutants gets absorbed by the suitable layer of the vermibed media and the remaining fraction gets degraded by the combined action of the earthworms and microbes [5] (Fig. 5).

As already mentioned, the earthworms perform a series of beneficial activities such as ingestion of larger particles, grinding of ingested particles in the gizzard, digestion of grinded particles in presence of gut microbes, and finally, excretion as vermicasting, enriched in microbes and nutrients [1]. Generally, the earthworms devour the large size particles into finer particles, favoring the microbial degradation of the pollutants [5]. Moreover, owing to the tunneling activity of the earthworms, natural aeration gets intensified within the system, triggering aerobic microbial degradation of the organics [40,41]. The introduction of earthworms promotes the growth of diversified microbial communities, improving organic oxidation potential of the vermifilter [42]. The earthworms release a slimy liquid, also known as mucus, containing various enzymes and microbes, which, in turn, facilitates the mineralization of the contaminants [43]. Mucus is also enriched in glucoproteins, amino acids, and glucosidic and proteic molecules, thereby upholding the optimum carbon to nitrogen (C/N) ratio for the microbial degradation [44,45]. In addition, the earthworms also possess pH neutralization potential by secreting calcium from their crop, thereby enhancing the bioavailability of the organics and solids for further degradation [46].

3.2. Nutrient removal mechanism

The domestic wastewater mainly contains ammonium N (NH_4^+-N) and organic N. Apart from N, domestic sewage also embraces significant amount of P. The N removal pathways in the vermifilter is very intricate, including ammonification or mineralization of the organic N, nitrification, and denitrification or adsorption by the bed materials, or microbial assimilation [1] (Fig. 6). The organic N, present in the domestic wastewater or released from the tissues of the dead earthworms, has been utilized by the heterotrophs such as *Bacillus*, *Proteus*, *Pseudomonas*, *Streptomyces*, etc. for their growth and reproduction and subsequently, the inorganic form of N i.e., NH_4^+-N gets released into the vermifilter [37,38]. Basically, the organics present in the domestic wastewater and the bed material and the nitrogenous substances excreted by the earthworms help in maintaining the adequate C/N ratio inside the vermibed, facilitating the growth of heterotrophs [47]. The NH_4^+-N, present in the domestic wastewater or produced due to the ammonification of organic N can be removed in two ways in the vermifilter: nitrification by the autotrophs and adsorption by the bed materials [35]. In vermifilter, the burrowing activity of the earthworms intensifies the air circulation inside the vermibed, which, in turn, helps in nitrification of NH_4^+-N. Nitrification is an aerobic process and is carried out by the autotrophs which grow when the availability of the organic carbon is less inside the vermifilter [1]. Generally, the nitrification takes place within the top few centimeters of the vermibed. Since NH_4^+-N carries positive surface charge and the bed materials are mostly negatively charged, NH_4^+-N gets adsorbed by the bed materials through electrostatic interactions (Fig. 6) [48,49]. On the other hand, since both the NO_3^--N and bed materials are negatively charged, the removal of NO_3^--N through adsorption is trivial. The hydrophobic interaction between the vermibed media and NO_3^--N governs the little adsorption of NO_3^--N onto the vermibed media [49]. Meanwhile, if macrophytes are present in the system, the NO_3^--N will be up taken as nutrient by the macrophytes. The most important N removal pathway in the vermifilter is denitrification [1]. Denitrification of the nitrified byproducts is carried out by the heterotrophs which become prevalent in the vermifilter when the organic carbon source is available in abundance inside the system [35]. During denitrification, the nitrified byproducts (mostly, nitrate N (NO_3^--N)) get directly converted into N_2 gas by the heterotrophs and subsequently, the produced N_2 gas gets released to the atmosphere. It has been

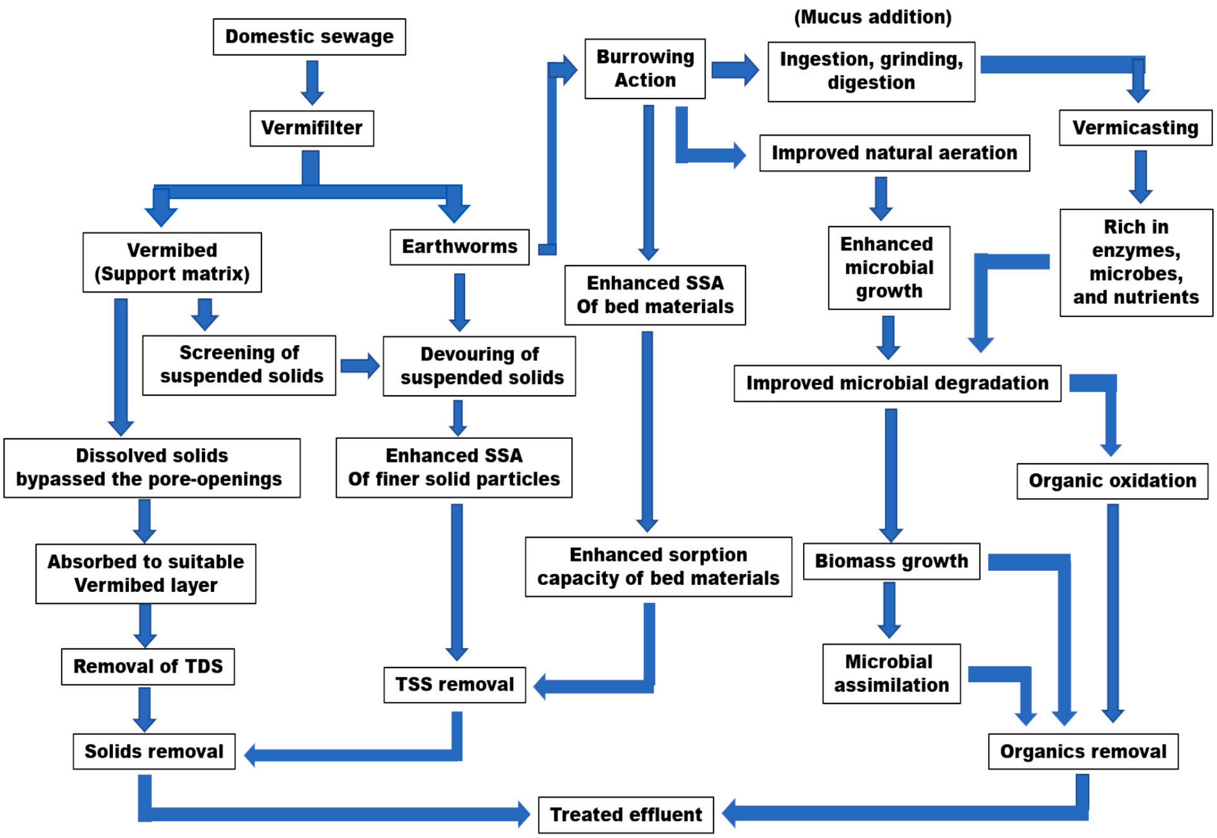

Fig. 5. Schematic diagram of the organic and solid removal mechanisms in vermifiltration (TSS: Total suspended solids; TDS: Total dissolved solids; SSA: Specific surface area).

reported that the anoxic/anaerobic condition triggers the denitrification process [30]. Thus, the denitrification mostly occurs at the bottom layers of the vermibed, the earthworm excluded zone, if sufficient organic carbon source is available for the growth of the heterotrophs [5]. Moreover, the mucus, released by the earthworms, embraces various gut microbes and enzymes, facilitating nitrification and denitrification processes [11].

The removal of P in the vermifilter is governed by the adsorption process [5] (Fig. 6). The enzyme-assisted microbial mechanism of the vermifilter does not facilitate the removal of P. Thus, the P removal potential of the vermifilters depends upon the adsorption capacity of the bedding material and the wastewater distribution time [50]. Apart from adsorption, a fraction of P also gets removed through the fixation of P as the phosphate (PO_4^{3-}) of different metallic cations [51]. However, attributing to the burrowing activities of the earthworms, the microbial and enzymatic activities inside the vermifilter get amplified, which, in turn, facilitate the mineralization of the bound form of P. As a result, the effluent total P (TP) concentration often gets escalated than its influent concentration [52].

3.3. Pathogen removal mechanism

Apart from the organics, nutrients, and solids, the vermifilters also have the potential to eliminate pathogens, especially from the domestic sewage [53]. Basically, the coelomic fluid, also known as mucus, secreted from the earthworm's body, portrays antibacterial properties and slays the unfamiliar microbes present in the domestic wastewater. Mucus only supports the survival of the gut microbes. It gets mixed with the bacterial cell and ceases their movement owing to its stickiness property [2] (Fig. 7). It further leads to the killing of the pathogens owing to the scarcity of food in their vicinity. Nevertheless, the earthworms also devour the pathogens and subsequently, the pathogens get destroyed in the earthworm's gut [40,41].

4. Application and performance of VF technology for treating domestic sewage

From the extensive literature, it has been observed that the VF technology has become one of the major alternatives of the conventional wastewater treatment methods for eradicating organics, nutrients, solids, and pathogens from the domestic wastewater [1,3,5,45,54]. A comprehensive overview on the performance of the VF technology in remediating the domestic sewage is portrayed in Table 1.

4.1. Organic removal

The vermifilters are reported to exhibit higher removal of organics than that of the geofilters [2,31]. The provision of sufficient HRT and optimum earthworm density further improves the performance of the vermifilter [74]. The earthworm species also plays a pivotal role in the performance of the vermifilters. For instance, Kumar et al. [61] reported that VF ensured 71.89 and 88.33 % removals of COD and biological oxygen demand (BOD_5), respectively from the real domestic sewage using riverbed material and vermicompost as the vermibed material in presence of *Eisenia fetida* earthworm species, whereas the presence of *Eudrilus eugeniae* yielded only up to 54.22 and 70 % removals of COD and BOD_5, respectively under the same operating conditions, indicating the superiority of *Eisenia fetida* over *Eudrilus eugeniae*. Even though, both *Eisenia fetida* and *Eudrilus eugeniae* belong to the epigeic species, the former earthworms have been reported to withstand the adverse operating conditions to the maximum extent. They can even operate under the water-logged condition. Compared to *Eudrilus eugeniae*, *Eisenia fetida* gets acclimatized very quickly to the surroundings. Moreover, these earthworms are the voracious eaters of the organics and produce huge

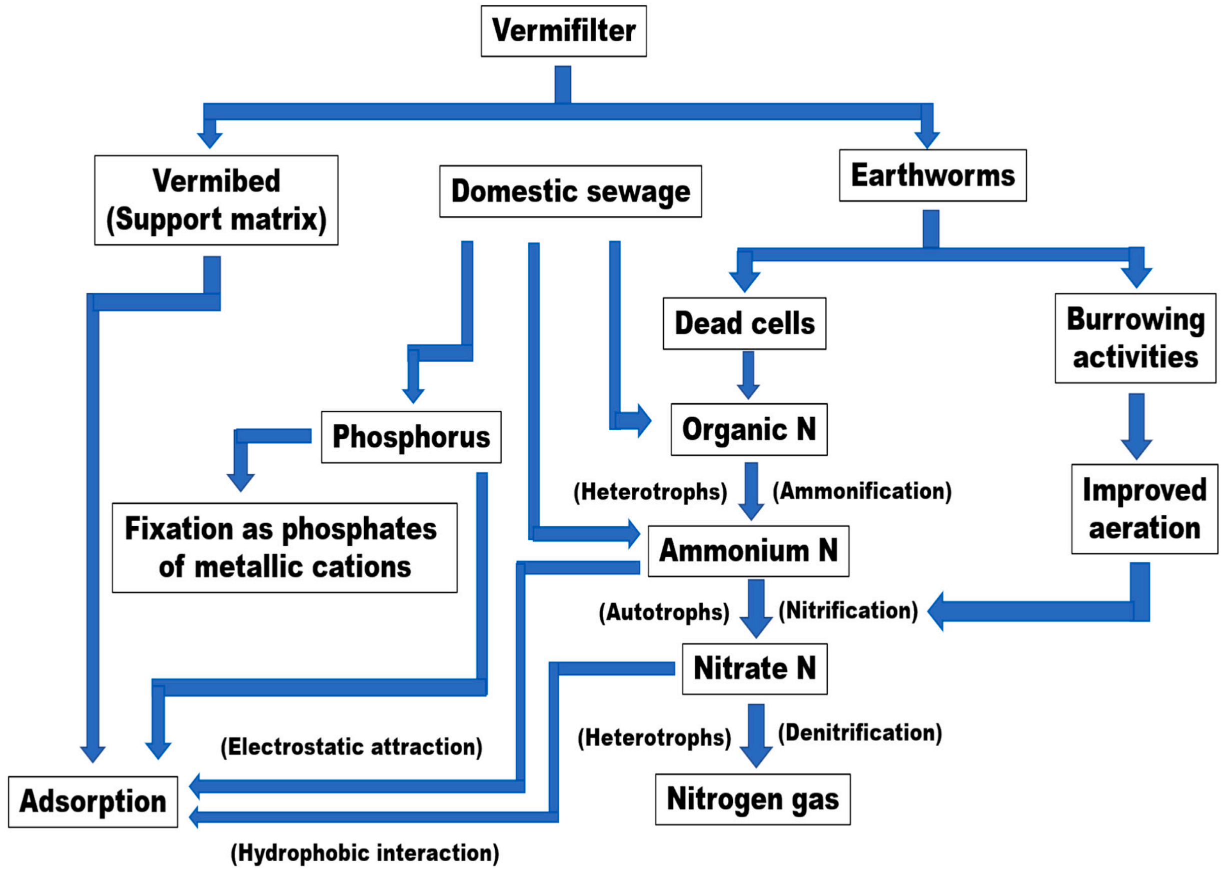

Fig. 6. Schematic diagram of the nutrient removal mechanisms in vermifiltration.

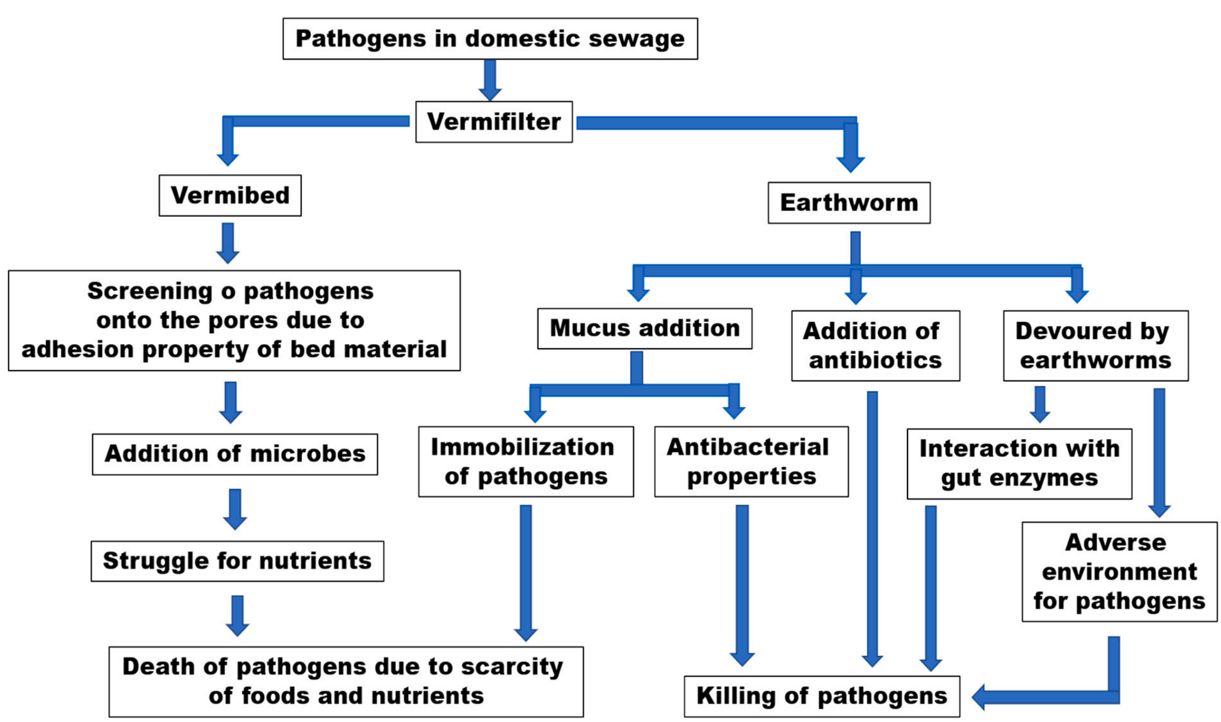

Fig. 7. Schematic diagram of the pathogen removal mechanisms in vermifiltration.

Table 1
Performance of VF technology treating domestic sewage.

Type of wastewater	Earthworm species	Location of wastewater source	Pretreatment facility	Active bed material	Depth of active vermibed (cm)	HLR ($m^3/m^2.d$)	HRT (h)	Performance (%)				Reference
								Organic removal	Nutrient removal	Solid removal	Pathogen removal (Log R)	
Concentrated greywater	*Eudrilus eugeniae* (200 worms)	–	Homogenization	Sawdust	40	0.016	–	BOD_5: 97.6, COD: 82.6	NH_4^+-N: 75, NO_3^--N: 62.2, PO_4^{3-}-P: 31.3	TSS: 99.4	–	Adugna et al. [55]
				Cow dung	20			BOD_5: 97.2, COD: 82.4	NH_4^+-N: 75, NO_3^--N: 45.9, PO_4^{3-}-P: 21.9	TSS: 98.9		
Synthetic domestic wastewater	*Eisenia fetida* (10,000 worms/m^3 active vermibed)	Environmental Engineering laboratory, IIT Roorkee, India	–	Mature vermigratings	20	1	7–8	$BOD_5 > 95$, COD: 74	–	–	TC: 3.15, FC: 2.88, TF: 3.46, *E. coli*: 2.03, Salmonella: 3.90, FS: 3.74, Actinomycetes: 1.09	Arora et al. [42]
Domestic sewage	*Eisenia fetida* (10,000 worms/m^3 active vermibed)			Kitchen waste underlain by vermigratings	Kitchen waste: 20, vermigratings: 15		–	$BOD_5 > 85.5$, COD: 77.8	NH_4^+-N: 90	TSS: 82.2	TC: 3.91, FC: 3.82, *E. coli*: 2.51, Salmonella: 2.20, TF: 0.80, Actinomycetes: 1.91	Arora et al. [53]
Institutional wastewater	*Eisenia fetida* (10,000 worms/m^3 active vermibed)	Dr. B. Lal Institute of Biotechnology, Jaipur, India	Thorough mixing	Mixture of vermigratings and cow dung	20		4–6	$BOD_5 > 98$, COD: 92	NO_3^--N and PO_4^{3-}-P increased in effluent	–	[b]TC: 0.20, [b]FC: 0.30, [b]FS: 0.23	Arora et al. [54]
Greywater	Indian blue worms (262 g/m^3 active vermibed)	–	–	Mixture of garden soil and sawdust (3:1 volumetric ratio)	20	0.28	–	BOD_5: 85.22–89.64, COD: 59.24–63.30	–	TSS: 86.47–90.28, TDS: 84.74–88.88	–	Bhise and Anaokar [56]
[a]Domestic sewage	*Eisenia fetida* (10,000 worms/m^3 active vermibed)	School of Infrastructure, IIT Bhubaneswar, India	Septic tank	Mixture of sand and vermicompost (VC) (3:2 volumetric ratio) (2-stage vermifilter; VSSF vermifilter followed by HSSF vermifilter)	20 each	3–7	5.49–12.82	COD: 67–77	NH_4^+-N: 74.4–98.2, TN: 73–87	–		Dey Chowdhury and Bhunia [1]
Domestic sewage	*Eisenia fetida* (5000–6000 worms/m^3 sewage)	Tehran, Iran		Mixture of fine grained coarse (40 %), windmill sandstone (20 %), and vermicompost (40 %)	20	2–4 m^3/d	–	COD: 64–83	NO_3^--N: 48–60	Turbidity: 83–92		Ghasemi et al. [57]
Domestic sewage sludge	*Eisenia fetida* (32 g/L)	China	Secondary sedimentation tank	Ceramic pallets (6–9 mm dia)	50	4		BOD_5: 48.41, COD: 38.39	–	TSS: 36.26, VSS: 40.94		Li et al. [58]
				Ceramic pallets (10–13 mm dia)	Ceramic pallets (10–13 mm			BOD_5: 61.06, COD: 53.01		TSS: 49.88, VSS: 56.26		

(*continued on next page*)

Table 1 (*continued*)

Type of wastewater	Earthworm species	Location of wastewater source	Pretreatment facility	Active bed material	Depth of active vermibed (cm)	HLR ($m^3/m^2.d$)	HRT (h)	Performance (%)				Reference
								Organic removal	Nutrient removal	Solid removal	Pathogen removal (Log R)	
				underlain by Ceramic pallets (6–9 mm dia)	dia): 100, Ceramic pallets (6–9 mm dia): 100 (total 200)							
Greywater	*Eudrilus eugeniae*	Uma apartment and Sahajanand apartment, Nagpur, India	–	Mixture of black cotton soil and cow dung (1:3 volumetric ratio)	12	–	2–3	BOD_5: 85–93, COD: 74–80		TSS: 70–80		Kharwade and Khedikar [59]
Synthetic domestic sewage	*Eisenia fetida* (10,000 worms/m^3 active vermibed)	Solid waste laboratory, IIT Roorkee, India		VC underlain by riverbed materials	VC: 5, riverbed materials: 20	2.5	–	BOD_5: 96, [b]COD: 87.89, TOC: 85	[b]NH_4^+-N: 86.5, NO_3^--N and TP increased in effluent	TSS: 90, TDS: 82		Kumar et al. [60]
Synthetic domestic sewage	*Eisenia fetida* (10,000 worms/m^3 active vermibed)			VC underlain by riverbed materials	VC: 10, other material: 5 for each	1.5		BOD_5: 81.2, COD: 72.3	NH_4^+-N: 75.7	TSS: 75, TDS: 53	[b]TC: 2.6, [b]FC: 2.22, [b]FS: 1.26, [b]*E. coli*: 1.81	Kumar et al. [52]
				VC underlain by wood coal				BOD_5: 74.5, COD: 64.6	[b]NH_4^+-N: 74.4	TSS: 64, TDS: 51	[b]TC: 2.4, [b]FC: 2.02, [b]FS: 1.06, [b]*E. coli*: 1.36	
				VC underlain by glass balls				BOD_5: 72.7, COD: 61.5	NH_4^+-N: 58.4	TSS: 59, TDS: 49.9	[b]TC: 2.2, [b]FC: 1.82, [b]FS: 0.87, [b]*E. coli*: 1.16	
				VC underlain by mud balls				BOD_5: 70.9, COD: 59.8	NH_4^+-N: 53.6	TSS: 55, TDS: 48.6	[b]TC: 2.3, [b]FC: 1.92, [b]FS: 0.96, [b]*E. coli*: 1.26	
Domestic sewage	*Eisenia fetida* (10,000 worms/m^3 active vermibed)			VC underlain by riverbed materials	VC: 5, riverbed material: 20	2.5		[b]BOD_5: 88.33, COD: 71.89, TOC: 80.71	[b]NH_4^+-N: 85.57, NO_3^--N and TP increased in effluent	TSS: 78, TDS: 75	[b]TC: 6.22, [b]FC: 4.83	Kumar et al. [61]
	Eudrilus eugeniae (10,000 worms/m^3 active vermibed)							[b]BOD_5: 70, COD: 54.22, TOC: 57.76	[b]NH_4^+-N: 73.77, NO_3^--N and TP increased in effluent	TSS: 67, TDS: 66	[b]TC: 4.11, [b]FC: 4.78	
Urban wastewater	*Eisenia fetida* (20 g/L)	–		VC obtained from municipal solid waste	14	0.89	6	BOD_5: 97.5–98.5, COD: 74.3	NH_4^+-N: 88.1–99.1	TSS: 96.6–98.2	–	Lourenco and Nunes [62]
Rural domestic sewage	*Eisenia fetida* (25,000 worms/m^3 active vermibed)	Quyang WWTP in Shanghai, China		Ceramsite	35	4	–	BOD_5: 83.7, COD: 58.2	NH_4^+-N: 76	TSS: 94.81		Liu et al. [63]
Rural domestic sewage	*Eisenia fetida* (8 g/L)	Suburb village, Shanghai, China	Screening followed by regulation tank		25	4.2		BOD_5: 67.6, COD: 78	NH_4^+-N: 92.1	TSS: 89.8		Liu et al. [64]
Urban greywater	*Eudrilus eugeniae* (200 worms)	Poor urban household in Ouagadougou, Burkina Faso	–	Sawdust	30	0.0955		BOD_5: 93–98, COD: 68–93	–	TSS: 88–96	*E. coli*: 1.4–3	Ndiaye et al. [65]
				Garden soil	10	–	1–2				–	

(*continued on next page*)

Table 1 (*continued*)

Type of wastewater	Earthworm species	Location of wastewater source	Pretreatment facility	Active bed material	Depth of active vermibed (cm)	HLR ($m^3/m^2.d$)	HRT (h)	Performance (%)				Reference
								Organic removal	Nutrient removal	Solid removal	Pathogen removal (Log R)	
Untreated municipal sewage	Mixture of *Eisenia fetida*, *Eudrilus eugeniae*, and *Perionyx excavatus* (20,000 worms/m^3 active vermibed)	Oxley WWTP in South Brisbane, Australia						BOD_5: 98.1–99.4, COD: 45–55		TSS: 90–95, TDS: 90–92, turbidity: 98		Sinha et al. [31]
Domestic sewage	*Eisenia fetida* (21,000 worms/m^2)	Shanghai, China		Ceramsite underlain by quartz sand	Ceramsite: 20, quartz sand: 10	2.4–6.7	–	BOD_5: 55–66, COD: 48–65	NH_4^+-N: 35–68, TN: 7.5–14	TSS: 57–77		Xing et al. [66]
				Two layers of quartz sand	Total 30 (20 underlain by 10)			BOD_5: 52–60, COD: 47–56	NH_4^+-N: 20–62, TN: 10–15	TSS: 60–78		
Rural domestic sewage	*Eisenia fetida* (12.5 g/L vermibed)	Changzhou village, Jiangsu province, China		Soil (3-stage tower vermifilter)	30 each	1		COD >81.3	NH_4^+-N: 98, TN: 0–96.4, TP: 98.4	–		Wang et al. [45]
Synthetic domestic sewage	*Eisenia fetida* (4.5–16.5 g/L vermibed)	–		Mixture of padding soil and rice straw (4:4 volumetric ratio)	35	0.2		COD: 67.8–76.6	NH_4^+-N: 71.5–77.9, TN: 62.7–65.9, TP: 80.3–82.3			Wag et al. [67]
Synthetic domestic sewage	*Eisenia fetida* (70 worms)	National Institute of Environmental Sciences, Ministry of Environmental Protection, Nanjing, China	Manual agitation	Mixture of soil and sawdust (4:4 volumetric ratio)	40, 60, 80	0.2		[b]COD: 86.2–91.3	[b]NH_4^+-N: 65.3–71.3, TN: 39.8–62.9, TP: 89.7–91.6			Wang et al. [68]
Domestic sewage	*Eisenia fetida* (8000 worms/m^2)	Quyang WWTP in Shanghai, 30China	–	Granular materials	160	2–3	6–9	BOD_5: 91–98, COD: 81–86	–	TSS: 97–98		Xing et al. [69]
Municipal wastewater	*Eisenia fetida* (32 g/L)	Municipal WWTP, Shanghai, China	Aerated grit chamber	Ceramsite	30	2	–	BOD_5: 81.3, COD: 83.5	NH_4^+-N: 55.6, TN: 32.4, TP: 38.6	TSS: 93.7		Wang et al. [70]
Domestic sewage sludge	*Eisenia fetida* (40 g/L)	Domestic WWTP, Quyang, Shanghai, China	Aeration tank	Ceramsite pallets	100	4		COD: 67.6–78	NH_4^+-N: 92.1	–		Li et al. [71]
Human feces	*Eisenia fetida* (2 kg/m^2)	Series of bucket toilets at Centre for Alternative Technology, Powys, Wales, United Kingdom	–	Mixture of coir, wood chips, and VC (1:1:1 volumetric ratio)	10	0.012–0.03		COD: 88–90	–		Thermotolerant coliform: 3	Furlong et al. [72]
Human feces	*Eisenia fetida* (4 kg/m^2)		Homogenization			0.012		COD: 74.9–88.8			[b]Thermotolerant coliform: 2.61–2.74	Furlong et al. [73]
				Mixture of coir and wood chips (1:1 volumetric ratio)	10			COD: 74.9–89.7			[b]Thermotolerant coliform: 2.61–3.16	

Note: HLR: Hydraulic loading rate; HRT: Hydraulic retention time; Log R: Log removal; BOD: Biological oxygen demand; COD: Chemical oxygen demand; TOC: Total organic carbon; NH_4^+-N: Ammonium nitrogen; NO_3^--N: Nitrate nitrogen; TN: Total nitrogen; PO_4^{3-}-P: Phosphate phosphorus; TP: Total phosphorus; TSS: Total suspended solids; TDS: Total dissolved solids; TC: Total coliform; FC: Fecal coliform; TF: Total fungi; FS: Fecal streptococci.

[a] The real domestic sewage was subjected to two-stage macrophyte-assisted vermifiltration, employing *Canna indica* macrophyte species.

[b] Calculated by the authors from the reported influent and effluent concentration of the pollutants.

quantity of vermicasting, which, in turn, enhances the organic removal efficiency of the VF process [5,26]. On the other hand, under the same operating conditions, Kumar et al. [60] obtained the COD and BOD_5 removals up to 87.89 and 96 %, respectively during the treatment of synthetic domestic sewage, employing *Eisenia fetida* earthworm species (Table 1). The difference in the organic removal, in presence of the same earthworm species and similar conditions, could be due to the higher complexity of the real domestic sewage as compared to the synthetic domestic sewage [11]. As discussed before, the synergistic action between the earthworms and microbes governs the higher removal of organics in the vermifilter. The earthworms devour the coarse organics into finer particles, thereby enhancing their bioavailability for the microbial degradation [5]. The burrowing activity of earthworms helps in keeping the system aerobic, triggering the growth of favorable microbes [75]. The mucus also accommodates digestive enzymes, captivating the degradation of the organics [76].

Xing et al. [69] observed that the vermifilters treating the real domestic sewage, in presence of *Eisenia fetida*, resulted in 81–86 % abatement of COD, whereas the removal of BOD_5 was up to 91–98 %. It signifies the higher inclination of the earthworms towards the biodegradable organics compared to the nonbiodegradable organics [53]. Similar observations were also postulated by Arora et al. [53] and Sinha et al. [31]. The VF technology has also been employed to remediate the human feces (Table 1). Furlong et al. [72] reported that the application of the VF technology to remediate human feces ensured substantial COD removal up to 88–90 %, indicating high concentration of the biodegradable organic matters in human feces.

It can also be observed from Table 1 that almost all the studies have been conducted employing *Eisenia fetida* and *Eudrilus eugeniae* earthworms. Both of them are epigeic earthworms. Generally, for VF process, the epigeic earthworms are employed by the researchers because of their ability of rapid acclimatization with the surroundings, higher reproducibility, early attainment of the matured phase, withstanding the fluctuations in the operating condition to a great extent, and displaying endurance and resistance to handling. Moreover, due to the decompacting nature of the epigeic earthworms, the bioavailability of the nutrients in the produced vermicasting gets increased for plant uptake [26]. The other two types of earthworms i.e., endogenic and anecic are not as advantageous as epigeic earthworms. Thus, the epigeic earthworms are mostly preferred by the researchers. Among all the epigeic earthworms, *Eisenia fetida* can operate under the water-logged condition and can handle the fluctuations to the highest extent. That is why, *Eisenia fetida* earthworms become popular among the researchers. However, in one study, by Sinha et al. [31], *Perionyx excavatus* earthworms were used while treating raw municipal sewage (Table 1), which also come under epigeic earthworms.

4.2. Nutrient removal

Nitrogen (N) is the most common nutrient present in the domestic wastewater. Predominantly, N is available in the form of ammonium N (NH_4^+-N) and organic N in domestic sewage [1,2]. In vermifilters, the removal of N from the domestic wastewater is attributed to a series of mechanisms such as mineralization or ammonification of organic N, nitrification, and denitrification, or adsorption by the bed materials, or microbial assimilation [1,2,5,35]. Nitrification, carried out by the autotrophs, is a very slow process because the autotrophs are slow growers [1,5]. The nitrification of NH_4^+-N is an aerobic process. Thus, the burrowing activity of the earthworms has a positive impact on the nitrification potential of the vermifilter (Fig. 6). To ensure substantial nitrification inside the vermifilter, requisite HRT and DO have to be maintained inside the vermibed. This indicates that the nitrification mostly takes place within the top few centimeters of the vermibed [11]. At greater bed depth, with the reduction in DO availability, anoxic condition prevails, promoting higher denitrification, if sufficient organic carbon source is available [45,77]. In addition, the mucus secreted by the earthworms contains various enzymes and microbes, assisting the mineralization of the organic N, which, in turn, enhances its bioavailability [44]. Furthermore, the vermicasting, rich in microbes, also facilitates the nitrification of NH_4^+-N when the domestic sewage comes in contact with the vermicasting [53]. Apart from the microbes and earthworms, the bed materials, by acting as an adsorption media, also helps in removing the nutrients from the domestic wastewater. Generally, the vermibed materials having negative surface charge exhibit the better adsorption potential for the positive-charged NH_4^+-N as compared to the negatively charged NO_3^--N [78].

Dey Chowdhury and Bhunia [1] have investigated the potential of a macrophyte-assisted vermifilter (MAVF) to eradicate N from real domestic sewage employing *Canna indica* macrophytes. They reported that the HLR had a negative impact on the nitrification of NH_4^+-N with 74.4 and 98.2 % conversion of NH_4^+-N at HLRs 7 and 3 m^3/m^2.d, respectively. It signifies that at low HLR, the domestic sewage got sufficient interaction time with the microbes, bed materials, and earthworms, triggering the nitrification of NH_4^+-N. They also found that the removal of the total N (TN) was the maximum (87 %) when sufficient organic carbon was available, justifying denitrification as the principal N removal pathway in the vermifilter. Similar trend of the N transformation dynamics in the vermifilters was also reported by Xing et al. [66]. In addition, Liu et al. [64] and Li et al. [71] have also reported high nitrification potential of the VF technology (Table 1).

It is clearly evident from the data amalgamated in Table 1 that many researchers have obtained higher effluent NO_3^--N concentration than its influent concentration during the course of VF of domestic sewage [60,61]. As mentioned before, the nitrification of NH_4^+-N requires high HRT. Thus, after nitrification, the wastewater might not get the sufficient time for denitrification. As a consequence, the NO_3^--N concentration was increased in the effluent [1,35]. The mucus, secreted by the earthworms, is also rich in organic nitrogenous compounds, enhancing the concentration of the organic N in the domestic sewage, which initially got nitrified followed by the denitrification of the nitrified compounds [5,35]. Thus, during VF of domestic sewage, due to the insufficiency of interaction time, the produced NO_3^--N might not get denitrified, thereby accumulating in the effluent.

Apart from N, phosphorus (P) is another nutrient causing concerns for the competent authority. Generally, the removal of total P (TP) is mainly governed by adsorption, a physical process [51]. P predominantly gets adsorbed by the bed materials. Wang et al. [67] have reported up to 80.3–82.3 % removal of TP using the mixture of padding soil and rice straw (volumetric ratio: 4:4) as vermibed material (Table 1).

Few researchers have found that the effluent TP concentration was higher than its influent concentration [60,61]. The activities of the earthworms have been found to liberate P from its bound form, pilling up the TP concentration in the effluent [79].

4.3. Solid removal

The solids present in the domestic wastewater can be predominantly classified into two types: total suspended solids (TSSs) and total dissolved solids (TDSs) [7]. As depicted in Fig. 5, the large TSSs, present in the domestic sewage, get trapped onto the pores of the bed media and devoured by the earthworms into finer particles with enhanced specific surface area, which, in turn, facilitates the adsorption of solids onto the bed materials [80]. On the other hand, the TDSs get bypassed through the screening layer and subsequently absorbed by the suitable layer of the bed materials [2]. In addition, the biodegradable fraction of both the TSSs, adsorbed onto the pores of the bed materials, and TDSs get putrefied by the combined action of the earthworms and microbes [2,5,11]. For instance, Adugna et al. [55] investigated the potential of the vermifilters in removing TSSs while treating the concentrated greywater. They achieved a hopping TSS removal up to 99.4 %, using sawdust as the bed material. Similarly, Liu et al. [63] obtained the TSS removal up to 94.81 % during VF of rural domestic sewage using ceramsite as bed material (Table 1).

The type of vermibed media employed also affects the solid removal performance of the vermifilters. For instance, Kumar et al. [52] have compared the potential of four different vermibed materials with respect to the solid removal from the synthetic domestic wastewater (Table 1). They found that the application of the riverbed materials as vermibed ensured the maximum removal of solids (both TSSs (75 %) and TDSs (53 %)). This could be due to the better adsorptive properties and higher specific surface area of the riverbed materials as well as the better activity of the earthworms inside the riverbed materials as compared to the wood coal, glass balls, and mud balls.

HLR is found to have negative impact on the solid removal performance of the vermifilters. For instance, Xing et al. [66] have varied the HLR from 2.4 to 6.7 m^3/m^2.d to evaluate the impact of HLR on the TSS removal performance of the vermifilter during the treatment of real domestic sewage (Table 1). It has been observed that the removal of TSS was the least (57 %) when the HLR was 6.7 m^3/m^2.d, whereas the TSS removal was the highest (77 %) when the HLR was maintained at 2.4 m^3/m^2.d. This could be attributed to the fact that high HLR created turbulence inside the vermibed, causing washing of solids, which ultimately cut down the solid removal efficiency of the vermifilters [81].

4.4. Pathogen removal

In order to meet the stringent disposal norms and reusability criteria, the destruction of the water-borne pathogens from the domestic wastewater has become a prime concern [2]. As portrayed in Fig. 7, the removal of pathogens takes places in various ways during VF. The mucus, released by the earthworms, possesses antibacterial and sticky properties. Owing to the antibacterial properties, the foreign microbes (non-indigenous microbes), present in the domestic wastewater, get destroyed [82]. Again, the stickiness of the mucus restricts the movement of the non-indigenous pathogens, thereby captivating the killing of the pathogens due to unavailability of substrate in their vicinity [83]. Some pathogens are also removed by the adhesive properties of the bed materials during filtration of domestic sewage [60] (Fig. 7). For instance, Kumar et al. [52] investigated the potential of four different bed materials in removing the pathogens from synthetic domestic sewage (Table 1). They found that the vermifilter with vermicompost and riverbed materials as the vermibed media ensured the maximum removal of total coliform (TC) (Log R: 2.6), fecal coliform (FC) (Log R: 2.22), fecal streptococci (FS) (Log R: 1.26), and *E. coli* (Log R: 1.81) (Table 1). This difference could be attributed to the difference in earthworm activities inside the bed materials and also the difference in the adhesive properties and size of the pore-openings of different bed materials. Similarly, Arora et al. [53] also ensured substantial removal of TC (Log R: 3.91), FC (Log R: 3.82), and *E. coli* (2.51) during the VF of domestic sewage. Furlong et al. [72] have employed VF technology for treating human feces and achieved the Log R of the thermotolerant coliforms as 3.

In light of the above discussion, it can be stated that the VF has become a promising alternative of the conventional treatment methods when it comes to the remediation of the wastewater generated from the domestic premises.

5. Sustainability of VF technology

As mentioned earlier, a particular technology can be labelled as a sustainable technology if it satisfies the following three broader aspects i.e., the technology has to be environmentally sustainable, economically viable, and socially acceptable [84]. Various other factors coming under the aforementioned broader aspects are portrayed in Fig. 8.

From Fig. 8, it is clearly evident that the carrying capacity of the receiving ecosystem of a technology also has a monumental impact on its sustainability. Meanwhile, the surrounding components involve

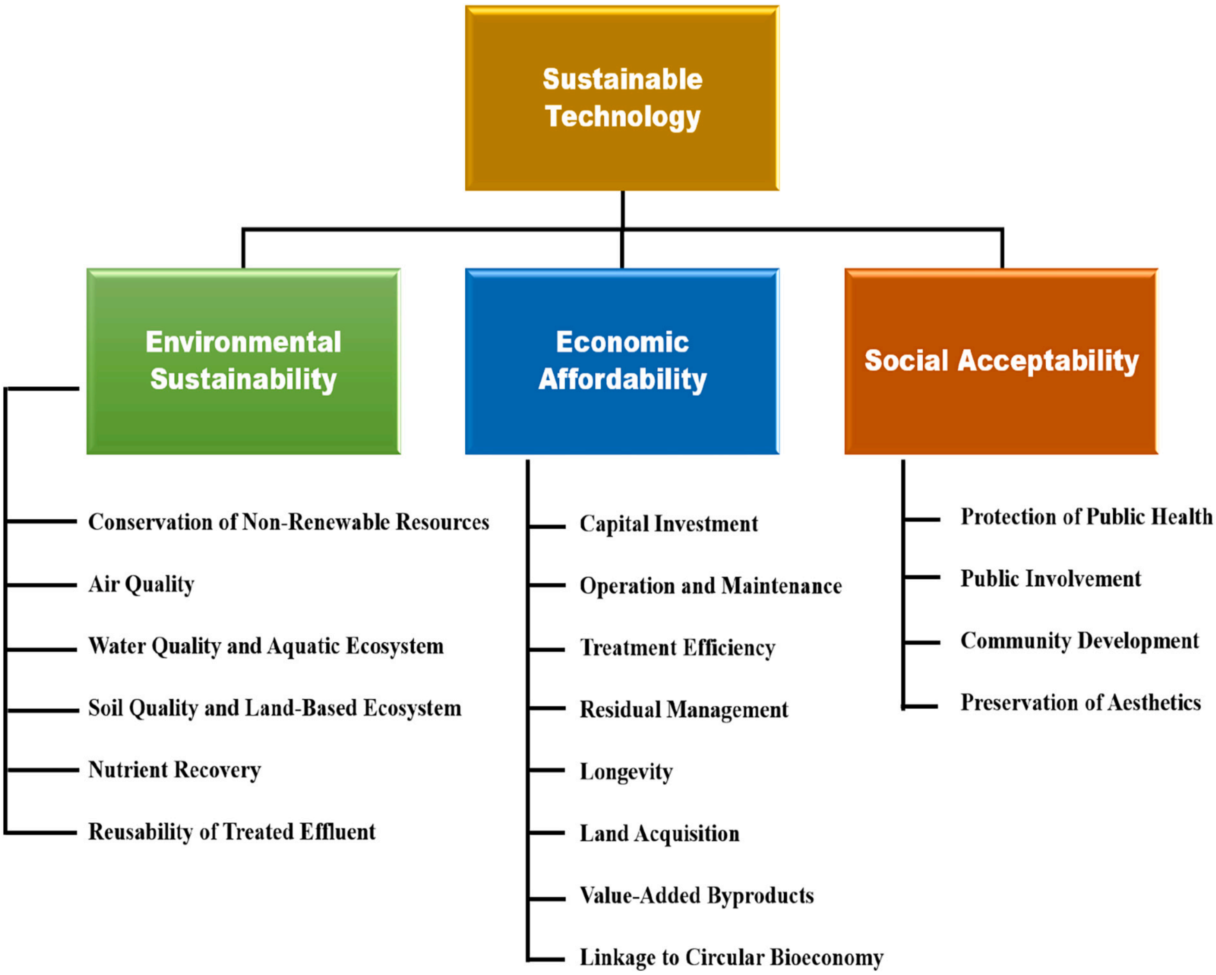

Fig. 8. Different criteria for the sustainability of a wastewater treatment method.

water, soil, and air quality, preservation of aquatic and land-based ecosystems, conservation of the non-renewable resources, and nutrient recovery [85] (Fig. 8). The factors like initial investment, operational and maintenance cost, management of the solid residues, and the economic value of the byproducts must be taken into account for evaluating the economic sustainability of the wastewater treatment technology under consideration [15,84].

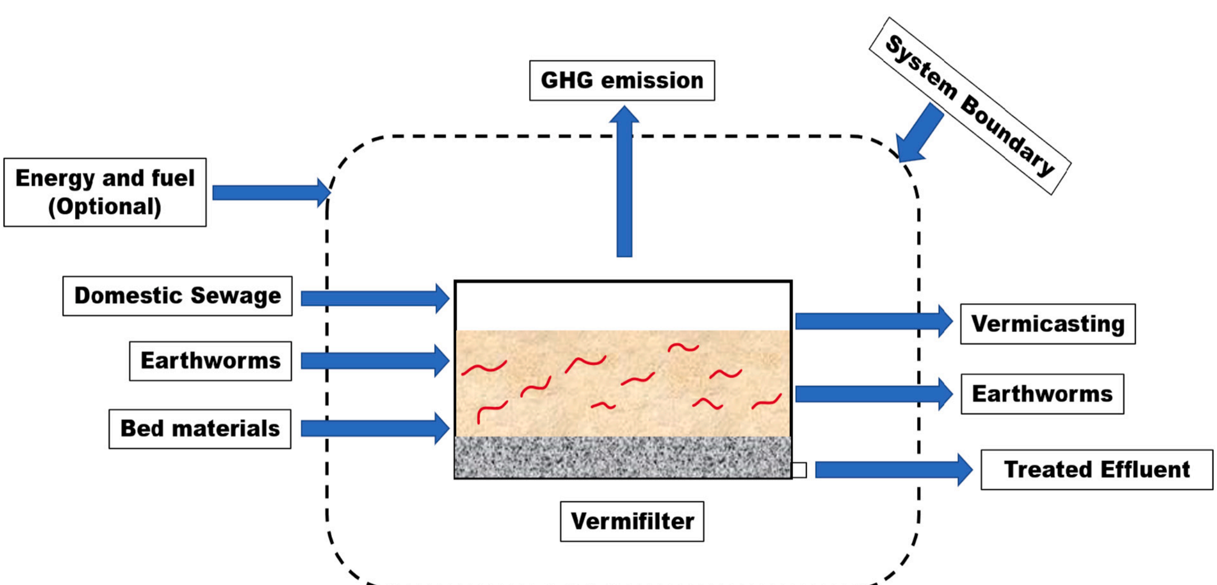

Fig. 9. System boundary for the LCA of VF technology treating domestic sewage (GHG: Greenhouse gas).

5.1. Environmental sustainability of VF technology

The environmental sustainability of the VF technology during the remediation of domestic sewage has been evaluated in reference with the factors depicted in Fig. 8. Especially, the LCA as well as the LCIA of the VF technology, reported in the literature, has been explored and compared with those of the ASP, CWs, ALs, and WSPs to strengthen the environmental feasibility of the VF technology.

5.1.1. Overview of the LCA studies on VF technology

In order to carry out the LCA studies on the VF technology, the researchers have adopted gate-to-gate approach to establish the system boundary [29]. Generally, the gate-to-gate approach is popular for unit processes. Here, the life-cycle inventory (LCI) includes the details of all the inputs and outputs throughout all the stages of its life-cycle, including the assessment of raw materials, influent domestic sewage, energy consumption, treated effluent, solid residues, and gaseous emissions across the construction, operation, and dismantling phases of the VF technology (Fig. 9). According to the literature, two standardized functional units, namely one population equivalent (PE^{-1}) [86] and one cubic meter of influent wastewater [87] are available for performing the LCA of the various processes. A system boundary, considering the gate-to-gate approach, for carrying out the LCA of the VF technology has been represented in Fig. 9. Mainly, the environmental sustainability of the VF technology treating the domestic sewage has been evaluated with reference to the criteria portrayed in Fig. 8 through the exploration of the LCA and LCIA studies on the VF technology, available in the literature.

5.1.1.1. Conservation of the fossil fuels. Abello-Passteni [28] has made an approach to investigate the consumption of natural non-renewable resources, especially the fossil fuels, including coal and diesel during the treatment of domestic wastewater employing ASP, VF, and ALs in Chile. He has considered 1 kg of BOD_5 removed as the functional unit. It has been observed that the consumption of fossil fuels varied between 0.0001 and 0.03 kg/kg of BOD_5 removed for ALs and the same for the ASP was 0.0001–0.04 kg/kg of BOD_5 removed, whereas the VF technology did not consume any fossil fuel across all the stages of its life-cycle. As already discussed, in VF technology, unlike ASP and ALs, the burrowing activity of the earthworms keeps the system naturally aerobic, eliminating the requirement of external energy for mechanical aeration. If pumping of wastewater is not required, i.e., the gravitational flow of wastewater is allowed through the vermifilter, no external energy is required during the VF process, cutting down the requirement of fossil fuels [31]. Since in this study, the major part of the total energy consumed by different technologies, including ALs and ASP was supplied utilizing the non-conventional and renewable sources like hydroelectricity, solar energy, and wind energy, the requirement of the fossil fuels was comparatively less in both the aforementioned processes. However, in one of the WWTPs where ASP has been employed as the secondary treatment step, up to 57.6 % of the total energy was supplied using diesel as fuel.

Another group of researches, Lourenco and Nunes [29], have also performed the LCA of two commonly used decentralized wastewater treatment alternatives such as CWs and VF while treating the domestic sewage in Southern Europe and compared the results with those of the ASP. They have considered one PE as the functional unit. It has been found that the total fossil fuel consumption during the construction phase was 0.638 kg/PE for ASP, whereas zero consumption of fossil fuel was reported in construction phase when ASP was replaced with VF technology. The electricity consumption during the operational phase was up to 1.16×10^6 MJ/PE for ASP, whereas when ASP was replaced with VF technology, it was reduced to 4520 MJ/PE. The same for the CWs was 3940 MJ/PE. Here, the electricity during the operational phase was generated from the fossil fuels, especially diesel. Singh et al. [88] inspected that the energy consumption for treating 1 MLD municipal wastewater was 65.7 MJ/year for ASP. Such a high energy consumption during the operational phase of the ASP was mostly attributed to the electricity consumed by the mechanical aerators for external aeration. They also found that the energy consumption for treating 1 MLD municipal wastewater for the upflow anaerobic sludge blanket reactor (UASBR) was 43.8 MJ/year. This could be due to the maintenance of the wastewater flow in upward direction at a particular velocity [7]. Meanwhile, the requisite energy has been supplied by burning the fossil fuels, reflecting the depletion of the fossil fuels.

In light of the above discussion, it can be stated that the VF technology negotiates the consumption of fossil fuels, a non-renewable source of energy, thereby promoting the conservation of natural non-renewable resources.

5.1.1.2. GHG emissions. Emission of GHGs is another factor governing the environmental sustainability of the VF technology treating the domestic sewage. Mainly, the emissions during the operational phase have been taken into consideration. Mostly, the vermifilters have not been reported to release GHGs while remediating the domestic sewage. This could be because the gaseous emission (only CO_2 due to complete aerobic degradation of the organics) during the VF of domestic sewage was so nominal that it could be neglected [5,11]. As mentioned earlier, the burrowing activity of the earthworms results in the abundance of DO inside the vermibed [1]. Being a low-strength wastewater, complete aerobic degradation of the organics present in the domestic sewage takes place with the help of natural aeration, reducing the production of methane (CH_4). In fact, Luth et al. [76] have stated that the vermifilters act as the sink for CH_4. Aditionally, owing to the low-strength of the domestic sewage, the generation of the CO_2 is also less. At the same time, attributing to the natural aeration, the engagement of external aerators has also been eliminated, cutting down the need for burning the fossil fuels for keeping the aerators running. It further eliminates the emission of the GHGs, which, in turn, lessens the environmental cost of the VF process [89]. In addition, owing to the abundance of DO, complete nitrification of NH_4^+-N to NO_3^--N takes place, which subsequently gets denitrified to nitrogen gas (N_2), eliminating the emission of nitrous oxide (N_2O), another potential GHG. Generally, from the VF of the low-strength wastewater such as domestic wastewater, CO_2 is released as the major atmospheric emission. According to IPCC [90], the global warming potential (GWP) of CO_2, CH_4, and N_2O are 1, 25, and 298, respectively. However, the GWP of CO_2 is not considered as it is considered to be biogenic in origin [91]. CH_4, and N_2O are considered to be the major threats to the air quality.

On the other hand, Singh et al. [88] have investigated the emission of GHGs from various municipal WWTPs across India. They observed that the WWTPs employing anaerobic deep lagoons, WSPs, UASBR, and ASP with the capacities 321, 279, 2326, and 979 MLD, respectively have recorded the GHG emissions up to 118,700, 31,858, 1,317,375, and 71,696 t $CO_{2\text{-eq}}$/year, respectively, highlighting the poor environmental sustainability of the WWTPs. These emissions included the emission during the treatment of municipal wastewater as well as the emission due to the burning of fossil fuels for generating electricity. Daelman et al. [18] found that out of the total CH_4 production in the WWTPs, 80 % CH_4 has been produced during ASP. Similarly, Campos et al. [20] have reported that up to 90 % of the total N_2O emissions from the WWTPs has been released during ASP. On the other hand, Johansson et al. [92] and Mander et al. [93] investigated the GHG emission potential of the CWs and reported that the emission of CH_4 was up to 1.8 mg/m^2.h for free water surface CWs (FWS-CWs) and 6.4 mg/m^2.h for horizontal subsurface flow CWs (HSSF-CWs), whereas the N_2O emission was ranging between 0.031 mg/m^2.h for FWS-CWs and 0.42 mg/m^2.h for HSSF-CWs. Another group of researchers, Hernandez-Paniagua et al. [94], have made an effort to quantify the amount of GHGs emitted from the WSPs. They mentioned that the WSPs have resulted in the production of CH_4 up to 25 mg/m^2.h.

Unlike domestic sewage, if the vermifilters are fed to the high-strength wastewaters such as industrial wastewaters, substantial amount of GHGs can also be released from the VF process. For instance, Luth et al. [76] have stated that the emission of CO_2, CH_4, and N_2O was up to 4.4 mg/d, 2.8–20.3 g/d, and 2–438 mg/d, respectively during the VF of pig slurry.

From the above discussion, it is clearly evident that the VF technology promotes the environmental sustainability by protecting the air quality, especially while treating the domestic sewage. More detailed understanding on the environmental sustainability of the VF technology can be achieved during the LCIA of the VF technology.

5.1.1.3. Generation of organic fertilizer. As already mentioned, during VF of wastewater, the earthworms consume all the produced sludge and excrete in the form of vermicasting [5,11]. Hence, as the solid residue, the vermicastings are produced during the course of VF of domestic sewage (Fig. 9). Liu et al. [64] have carried out the VF of the rural domestic sewage in China for a duration of 17 months. They have found a minimal sludge production of 0.08 kg SS/ kg of COD removed. The produced sludge was mostly vermicastings. Such negligible sludge production could be attributed to the activities of the earthworms inside the vermifilter [64]. In fact, Singh et al. [5] have mentioned that there was no sludge production during the VF of domestic wastewater except the vermicastings. Hence, the VF technology can also be termed as the zero-waste technology or green technology [32,89]. The produced vermicasting is highly nutritive in nature, containing 1.16 % N, 1.22 % P, and 1.34 % potassium (K) [69]. The microbes and enzymes present in the mucus enhance the bioavailability of the nutrients present in the vermicasting, thereby making them liable for the plant uptake [31].

On the other hand, the production of sewage sludge was found to be proportional to the volume of wastewater treated by ASP. Generally, 70–100 g sewage sludge is generated while treating 1 m^3 domestic sewage using ASP [95]. The conventional STPs are reported to produce the excess sludge up to (0.32 ± 0.08) kg TSS/kg COD removed [96]. In other way, it was (0.25 ± 0.06) kg VSS/kg COD removed. Even though, the sewage sludge produced from the WWTPs is rich in nutrients (45–49 g N/kg municipal sewage sludge, 22–30 g P/kg municipal sewage sludge, and 1.2–1.6 g K/kg municipal sewage sludge), the presence of pathogens and heavy metals prohibits its land application as fertilizer [32,97,98]. A prior treatment to the raw sewage sludge should be given before applying it as fertilizer or for the safe disposal of the sewage sludge in the midst of the environment.

Landfilling of sewage sludge is reported to liberate the highest quantity of GHGs (296.9 kg CO_2 eq./t sludge), followed by mono-incineration (232 kg CO_2 eq./t sludge) and carbonization (141 kg CO_2 eq./t sludge). Even, the composting of sewage sludge obtained from the conventional WWTPs has been reported to make substantial release of the GHGs [99,100]. In contrary, Since, VF ensures high pathogen removal from the domestic sewage, once the VF process is over, the vermicasting layer can be scrapped from the top of the vermibed and directly applied to the agricultural field as fertilizer without any further treatment [52,53]. The nutrients present in the vermicasting are readily available to the crops and plants, triggering the nutrient recycling potential of the VF process from the domestic sewage. Hence, it can be concluded that unlike the conventional wastewater treatment methods, the VF technology helps to maintain the nutrient cycle in the environment without imposing any threat to the environment, especially while treating the domestic sewage.

5.1.2. Overview of the LCIA studies on VF technology

In order to gather more detailed knowledge regarding the environmental sustainability of a particular technology, the researchers have to rely on the LCIA of that technology rather than its LCA [29]. However, very few studies are available on the LCIA of the VF technology while treating the domestic wastewater [28,29]. In order to carry out the LCIA of VF technology, the following impact categories have been decided by Lourenco and Nunes [29] in accordance with Corominas et al. [101] and Jeppsson and Hellstrom [102]: abiotic depletion (AD) (kg Sb eq.), acidification (AC) (kg SO_2 eq.), eutrophication (EUT) (kg PO_4^{3-} eq.), global warming potential (GWP) (kg CO_2 eq.), freshwater ecotoxicity (FWT) (kg 1, 4-DB eq.), marine aquatic ecotoxicity (MAET) (kg 1, 4-DB eq.), human toxicity (HT) (g 1, 4-DB eq.), ozone layer depletion (OLD) (kg CFC-11 eq.), terrestrial ecotoxicity (TE) (kg 1, 4-DB eq.), and photochemical oxidation (PO) (kg C_2H_4 eq.). On the other hand, Abello-Passteni [28] has considered climate change (CC) or GWP (kg CO_2 eq./kg BOD_5 removed), EUT (kg P eq./kg BOD_5 removed), FWT (kg 1, 4-DB eq./kg BOD_5 removed), and HT (kg 1, 4-DB eq./kg BOD_5 removed) as the environmental impact categories for determining the ecoefficiency of VF, ALs, and ASP while treating domestic wastewater in Chile. Among all the impact categories, the ecoefficiency indicators have been evaluated for CC or GWP and EUT for being frequently used in ecoefficiency works [28]. Basically, the ecoefficiency indicators can be calculated using the following relationship (Eq. 1), given in ISO 14045 [103].

$$\textit{Ecoefficiency indicator} = \frac{\textit{Value function}}{\textit{Environmental impact}} \ldots \tag{1}$$

The higher the value of the ecoefficiency indicators, the better will be the sustainability of the corresponding technology. Abello-Passteni [28] has taken the treated volume of wastewater (m^3) by each technology as the value function. Even though, he has specified four different impact categories, the ecoefficiency of the aforementioned technologies has been evaluated with respect to CC and EUT. He reported that the VF technology was the most eco-efficient technology in terms of both CC and EUT, portraying the highest indicator values. The CC indicator value for the VF technology was found to be 6.7 m^3/(kg CO_2 eq./kg BOD_5 removed), whereas the same for ASP and ALs were 3.8 and 3.4 m^3/(kg CO_2 eq./kg BOD_5 removed), respectively, indicating the ALs to be the least eco-efficient technology. Similarly, the EUT indicator value for the VF technology was 10,984.1 m^3/(kg P eq./kg BOD_5 removed) followed by ASP (10,518.5 m^3/(kg P eq./kg BOD_5 removed)) and ALs (5876m^3/(kg P eq./kg BOD_5 removed)). Thus, it can be stated that the ALs and VF had the maximum and the minimum environmental impact, respectively. The order of FWT (kg 1, 4-DB eq./kg BOD_5 removed) and HT (kg 1, 4-DB eq./kg BOD_5 removed) caused by the aforementioned technologies were VF < ASP < ALs and VF < ASP < ALs, respectively, signifying the VF and ALs as the best and the worst technologies, respectively with respect to the environmental sustainability.

Another group of researchers, Lourenco and Nunes [29], have tried to determine the environmental sustainability of VF, small rate infiltration (SRI), CWs, and ASP by exploring their LCIA throughout the construction, operation, and dismantling phase while treating the domestic sewage coming from the small communities in Southern Europe. They found that the GWPs of CWs and ASP were 1930 and 264 kg CO_2 eq., respectively, whereas the GWPs were reduced to 135 and 183 kg CO_2 eq. when the above technologies were replaced with VF technology, respectively. The implementation of VF technology also lessened the AC and EUT impacts as compared to SRI, CWs, and ASP. The application of ASP has shown the AC impact value up to 6.36 kg SO_2 eq., whereas it was substantially reduced to 1.07 kg SO_2 eq. when ASP was replaced with the VF technology. Similarly, the implication of SRI, CWs, and ASP has yielded the EUT impact values up to 13.1, 26.1, and 20.7 kg PO_4^{3-} eq., respectively. These values were significantly reduced to 8.96, 8.97, and 7.51 when all the above-mentioned technologies were substituted by VF technology, respectively. This could be due to the lower emission of the nutrients due to the implementation of the VF technology. In addition, the vermifilters were also observed to significantly negotiate the FWT, HT, OLD, and PO as compared to the CWs, SRI, and ASP [29].

In light of the above discussion, it can be justified that the VF technology is the most environmentally benevolent alternative for treating the domestic sewage.

5.1.3. Preservation of water quality and aquatic ecosystem

As we already know, if the domestic sewage is directly discharged to the water bodies without any treatment, it will deteriorate the water quality. Apart from the conventional water quality parameters e.g., COD, BOD, NH_4^+-N, TN, etc., the domestic wastewater also embraces pathogens, heavy metals, and emerging contaminants (ECs) such as pharmaceuticals, personal care products, surfactants, etc. in significant concentration [4,5]. The presence of such pollutants in the water bodies will not only degrade the water quality, but also result in the outbreak of various water-borne diseases and destroy the aquatic ecosystem [2,3,31]. As already discussed, VF has the ability to remove pathogens from the domestic wastewater [42,52]. Not only this, the earthworms also have the ability to uptake the heavy metals [31] and ECs [4,104] from the wastewater. Being an aerobic process, the vermifiltered effluent contains significant DO [5]. Over the last few years, the VF technology has become a promising alternative for remediating the domestic sewage, especially with respect to organic and nutrient removal [1,4,5,11]. According to Arora et al. [53] and Singh et al. [2], the domestic wastewater, after being subjected to VF, meets the stringent discharge limits to the surface water. In addition, Arora et al. [53] and Kumar et al. [52] concluded that the effluent coming from the VF unit has met the WHO guidelines regarding the pathogen counts. As a consequence of the abovementioned reasons, the disposal of the treated effluent from the VF of domestic sewage does not captivate any difficulties in the survival of the aquatic lives. Hence, it can be concluded that the VF technology helps preserving the water quality and maintaining the balance of the aquatic ecosystem.

5.1.4. Preservation of soil quality and land-based ecosystem

Since the domestic wastewater contains heavy metals and ECs, the sewage sludge produced as a byproduct of treating the domestic sewage in the WWTPs also contains a fraction of the aforementioned pollutants [4]. Thus, even though, the sewage sludge produced from the ASP is enriched in nutrients, its direct application for the land improvement may result in the death of the soil-borne microbes, thereby hampering the land-based ecosystems [97,98]. Hence, the raw sewage sludge should be stabilized or treated before its application to the soil. However, the sludge treatment imposes negative impact to the environment due to the emission of the GHGs [99,100]. For instance, Daelman et al. [18] have found that up to 72 % of the total CH_4 production in the WWTPs came from the sludge treatment unit, whereas up to 10 % of the total N_2O production in the WWTPs has been contributed by the sludge treatment unit. In contrary, in VF, the earthworms act as the sludge digester by softening the ingested sludge using the grume excreted in the mouth of the earthworms. In addition, the sludge is further neutralized by the calcium (Ca) inside the esophagus. Then, in the earthworm's intestine, the neutralized sludge has been decomposed by the enzymes. Finally, this stabilized sludge is excreted at the top of the vermibed as vermicasting by the earthworms [105]. The vermicasting itself or after being converted to vermicompost acts as a nutritive plant food and improves the soil fertility on its land application [69]. The nutrients present in the vermicasting are readily available to the crops, strengthening its acceptability as bio-fertilizer. In addition, the microbes and enzymes released with the vermicasting are soil-friendly in nature, thereby helping in improving the soil quality. In fact, unlike the chemical fertilizers, the land application of the vermicasting or vermicompost does not impose any threats to the soil-borne organisms [5]. Being a chemical-free organic manure, vermicompost, on its land application, does not create any chemical toxicity on the soil-based organisms [89]. Hence, it can be concluded that the vermicasting as well as the vermicompost can be extensively employed as the organic manure in agriculture and horticulture for improving the soil fertility through the preservation of land-based ecosystem.

5.1.5. Preservation of air quality

From the LCA and LCIA of the VF technology, demonstrated earlier, it is clearly evident that the VF technology can potentially cut down the risk of GHG emissions and thereby minimizing the GWP to a great extent [28,29]. As a concluding remark, it can be stated that unlike the conventional (such as ASP) and other non-conventional wastewater treatment methods (such as CWs, ALs, and WSPs), the VF technology possesses zero to trivial deterioration of air quality during the course of remediating the domestic sewage, thereby promoting the preservation of air quality.

5.1.6. Reusability of treated effluent

The reusability of any treated effluent depends on its contamination level. The concentration levels of DO, organics (BOD and COD), pathogens, NH_4^+-N, and NO_3^--N in the effluent have been considered as the major indicators, governing the reusability potential of the treated effluent [2]. The effluent obtained from the VF of domestic sewage is almost crystal clear, odor-free, detoxified, rich in DO, and has neutral pH [5]. Thus, the effluent can be beneficially used for various non-potable purposes such as floor washing, toilet flushing, making cooling towers in the industries, etc. [31]. In addition, the effluent is also rich in nutrients, making it suitable to be used for the irrigation purposes [89,106]. Kumar et al. [60] have reported that the vermifiltered effluent can be potentially used for the irrigation and agricultural practices. Similar conclusion has also been made by Manyuchi et al. [74]. Table 2 represents the surface water discharge standards of various pollutants for the municipal WWTPs, the standards for the irrigation water quality, and the reusability potential of the vermifiltered effluent.

The data obtained from the various literature, compiled in Table 2, suggests that the domestic sewage, after being subjected to VF, satisfies the surface water discharge criteria and standards for its application as irrigation water. Liu et al. [63] have employed ceramsite-vermifilter for treating domestic wastewater. They found that the treated effluent portrayed the COD (51 mg/L), BOD (10.6 mg/L), and TSS (4.1 mg/L) concentration well below the permissible values, furnished in Table 2. The effluent had neutral pH and was devoid of pathogens, strengthening its acceptability as irrigation water. Similarly, Kumar et al. [60] also observed the effluent COD and NO_3^--N concentrations were 24–30 and <45 mg/L, respectively, favoring its agricultural application. Again, Kumar et al. [52] and Arora et al. [53] concluded that the pathogen concentration (480 and 457 MPN/100 mL, respectively) in the vermifiltered effluent was below the permissible range, mentioned by WHO (Table 2). From the above discussion, it can be concluded that the vermifiltered domestic sewage displays the potential to be reused in gardening, toilet flushing, floor washing, horticulture and agricultural practices, and fruits and vegetable farms.

5.2. Economic affordability

The global acceptability of any technology depends on its economic feasibility. In order to evaluate the sustainability of VF technology, its economic affordability has to be examined based upon the data available on capital cost, operation and maintenance cost, treatment efficiency, and residual management of the VF technology while treating the domestic sewage (Fig. 8). The concept of circular bioeconomy has also been explored to reinforce the economic viability of the VF technology.

5.2.1. Capital cost

Capital cost of a technology includes the costs of land acquisition, raw materials, energy consumed during its construction phase, transportation of raw materials to the treatment site, and installation of various equipment. From the life cycle inventory (LCI) proposed by Lourenco and Nunes [29], it has been observed that the land area required for SRI, CWs, and ASP were 2000, 594, and 95 m^2, respectively for treating the domestic sewage coming from the small communities with population 120, 120, and 500, respectively. When the aforementioned processes were replaced with VF technology, the land area requirements were astonishingly reduced to 12.5, 12.5, and 50 m^2,

Table 2
Discharge standards for municipal WWTPs and standards for irrigation water quality (specified by GB18918-2002 [107]) and reusability potential of vermifiltered effluent.

Pollutants	Surface water discharge standards for municipal WWTPs (Secondary standards) (mg/L)	Irrigation water quality standards (mg/L)			[c]Pollutant concentrations in the vermifiltered effluent (mg/L)
		Shucking vegetable	Dessert vegetable	Water cultivation	
COD	100	100	60	150	24–118
BOD_5	20	40	15	60	8–28
TSS	30	60	15	80	4.1–62
[a]pH	6-9	5.5-8.5	5.5–8.5	5.5–8.5	7.1–8.5
[b]FC	1000	2000	1000	4000	457–2624

[a] pH is unitless.
[b] FC is in cells/100 mL.
[c] The data has been collected from Adugna et al. [55], Arora et al. [53], Arora et al. [42,43], Kumar et al. [61], Kumar et al. [52], Kumar et al. [60], and Liu et al. [63].

respectively. Sinha et al. [31] inspected that the provision of 1–2 h HRT was sufficient to achieve substantial removal of organics and solids from the raw municipal sewage using the VF process (Table 1), cutting down the requirement of large footprint. On the other hand, the HRT to be maintained for WSPs, especially for facultative ponds, varies between 5 and 30 days, involving a larger footprint [7]. According to Taylor et al. [108], the construction costs of the vertical subsurface flow CWs (VSSF-CWs) and FWS-CWs were 0.20 €/user.m^2 (i.e., 16.80 rupees/user.m^2) and 0.29 €/user.m^2 (i.e., 24.40 rupees/user.m^2), respectively. The construction cost of the WSPs was very high as compared to the CWs and VF. The higher surface area requirement (2–7 m^2) triggers construction cost of the WSPs. Generally, up to 60 % of the total investment is accounted for the cost of land. Mara [109] reported that the construction cost of WSPs varied from 105 €/user (i.e., approximately 8826.30 rupees/user) in France to 343 €/user (approximately 28,832.60 rupees/user) in Germany. In contrary, the land area requirement for VF has been reported to be 0.25, 0.06–0.21, and 0.5–0.6 m^2/user in France [110], China [111], and India [112], respectively, which reduced the cost of land acquisition, leading to the reduction in the capital cost of the VF process.

Coming to the raw material requirement, the bed materials used in the VF process such as peat and wood flour [113], sawdust and vermicompost [62], woodchips, gravel, and quartz sand [55,77], riverbed materials, mud balls, and glass balls [60], sand and vermicompost [1], ceramsite and coal [114], etc. are locally available at very low cost and mostly obtained as the waste from the other activities. Since the packing materials are available in abundance, the acquisition of raw materials involves zero to minimal cost [29]. Apart from the bed materials, the vermifilters have to be incorporated with the earthworms (Fig. 9). Sinha et al. [31] reported that the cost of 500 earthworms was approximately 20 A$ (approximately 1126.40 rupees). The cost of earthworms is considered as the one-time investment because once the VF process is over, the earthworms can be taken out from the exhausted vermibed and employed in new vermifilters or sold to various farms as feedstock, thereby promoting the circular bioeconomy, which in turn cuts down the cost of the VF technology [89]. Unlike the conventional methods, owing to the decentralized treatment facilities and less area requirement, the VF technology can also be implemented in the vicinity of the domestic wastewater source. In fact, it can be applied for individual households as well as for the small communities, thereby reducing the cost of transportation of the wastewater from source to the treatment site [5]. Lourenco and Nunes [29] found that the raw materials to be used in ASP has been travelled for 26 km/PE, involving and additional cost of 104 €/PE (approximately 8742.24 rupees). Such expenses are not associated with the VF process. Apart from this, the VF technology does not necessitate the installation of the heavy-duty instruments, which makes the VF technology a cost-effective alternative (Singh et al., 2008). According to USEPA, the cost of construction of the centralized STPs in the rural area was up to 2,321,840–3,750,530 $ (approximately 176.76–285.56 million rupees).

Unlike the conventional treatment methods, vermifilters are easy to construct and do not involve any external energy consumption, except during the earthwork (excavators may be used), throughout the construction phase [29]. Since they are easy to build, skilled manpower is not required to construct the vermifilters, cutting down the capital cost of the VF technology. Generally, in case of the conventional treatment plants, the installation of various heavy-duty equipment includes high energy consumption and to construct the WWTPs, skilled manpower is required, triggering the capital cost of the WWTPs [11].

Sharma et al. [84] have compared the capital costs of the various onsite domestic wastewater treatment systems. They have found that the capital costs of the septic tank with percolation area, membrane bioreactor (MBR), moving bed biofilm reactor (MBBR), sequential batch reactor (SBR), and CWs were 1132, 1800–2000, 1500, 620–900, and 1800 €/user, respectively (in Indian currency, the values are 95,156, 151,308–168,120, 126,090, 52,117.20–75,654, and 151,308 rupees/user, respectively), whereas Sinha et al. [112] have inspected that the capital cost of VF was only 100–150 €/user (i.e., 8406–12,609 rupees/user), indicating the cost effectiveness of the VF technology.

5.2.2. Operational and maintenance cost

The operational and maintenance cost of any technology involve the costs regarding the consumed energy during operational phase, bed material renewal (especially for VF), replacing or repairing the equipment or parts, engagement of the skilled manpower, sludge management, and chemical requirements. In addition, the longevity of the process also affects the cost of the process.

As previously mentioned, Lourenco and Nunes [29] have performed a LCA study on the VF technology and compared its sustainability with conventional ASP during the treatment of domestic sewage. They reported that during operational phase, including electricity consumption for lights, pumping the domestic sewage, recirculating the effluent, and mechanical aeration, the total energy consumed in ASP was 1.16×10^6 MJ/PE, whereas in case of VF, the consumption of energy was only during the pumping of wastewater in the operational phase. The natural aeration due to the earthworm's burrowing activity eliminated the requirement of external aerators, making the VF technology energy-efficient [1,11]. Thus, when ASP was replaced by the VF technology, the electricity consumption was drastically reduced to 4520 MJ/PE, lessening the operational cost of the VF process. Similarly, Abello-Passteni [28] also compared the sustainability of VF technology with that of the ALs and ASP. He has reported that the requisite electric powers for ALs and ASP were up to 5.5 and 3.0 kwh/kg BOD_5 removed, whereas for VF, it was only up to 1.7 kwh/kg BOD_5 removed.

Since the operation of VF is very simple and it does not require any heavy-duty instrument, it does not demand any skilled manpower. In contrary, the conventional WWTPs, employing ASP as the secondary treatment step, require skilled manpower, increasing the operational cost of the process. Thus, attributing to the same reason, the VF technology does not bear the expenses related to the repairing and replacement of any instrument or its parts, negotiating the maintenance cost of the VF process [5].

The production of sewage sludge is a compulsory consequence of treating the wastewater. The conventional WWTPs, especially employing ASP as the biological treatment facility, have been reported to produce humongous quantity of sludge which needs further treatment before its land application or disposal [5]. The provision of the sludge treatment facilities acquires a major portion of the total cost of treating the wastewater. For example, Wei et al. [115] have carried out a brief cost analysis of windrow composting of activated sludge obtained from the small- and mid-scale urban WWTPs in China. They observed that the total cost of windrow composting of the activated sludge was up to 349,000 $ (approximately 26.61 million rupees). Similarly, Ghazy et al. [116] have reported that the cost of the windrow composting facility in Egypt, handling 1–65 t sewage sludge/day, ranged between 74,000 $ (5.64 million rupees) and 79×10^4 (60.24 million rupees) per ton of the dry sewage sludge per day. On the other hand, the cost of construction of the engineered landfill was reported to be 65 $ (4956.25 rupees) per ton of sewage sludge in Australia. In contrary, the produced sludge, also known as vermicasting, has already been stabilized inside the earthworm's body and can be directly used as fertilizer without any further treatment [31]. The vermicasting can be easily scrapped from the top of the vermibed and can be replaced with the fresh bed materials [35]. Being a self-driven, self-improved, and self-powered zero-waste technology, the VF process possesses high longevity. The VF process has been reported to last up to 3–4 months or even 7–8 months without any difficulties, especially while treating the low-strength domestic sewage [5]. Owing to this everlasting nature, the cost of the VF technology gets reduced.

Apart from all the above-mentioned factors, the external chemical requirements also govern the operational cost of a technology. Abello-Passteni [28] investigated the external chemical requirements during the treatment of domestic wastewater in Chile using ALs, ASP, and VF. He observed that to remove 1 kg BOD_5, ALs necessitated 0.9 kg sodium hypochlorite, 0.1 kg chlorine, 1.1 kg ferric chloride, and 0.02 kg polymer, whereas the same for the ASP were 0.2, 0.04, 0.1, and 0.01 kg/kg BOD_5 removed, respectively. On the other hand, the VF necessitated only 0.1 kg sodium hypochlorite/kg BOD_5 removed for disinfecting the effluent, cutting down the cost of the process. On the other hand, in conventional nitrification and denitrification, just before the denitrification unit, the organic carbon sources such as methanol has been added externally to facilitate the growth of heterotrophs, enhancing the cost of the process [7]. In contrary, during VF, the nitrification and denitrification occur simultaneously inside the vermifilter without any external addition of the chemicals, making the VF technology economically affordable [5].

Machado et al. [117] have reported that the operational cost of the CWs varied between 0.17 and 0.28 €/m^2.year (14.4–23.7 rupees/m^2.year) (for FWS-CWs) to 0.21–0.34 €/m^2.year (17.8–28.8 rupees/m^2.year) (for VSSF-CWs). On the other hand, Mara [109] observed that the operational cost of WSPs was up to 4 €/user.year (338.40 rupees/user.year) in France. Again, Sharma et al. [84] have made an effort to compare the economic feasibility of various onsite domestic sewage treatment facilities. They reported that the operational costs of the septic tank with percolation area, MBR, MBBR, SBR, and CWs were 14, 50–70, 20–30, 4–7, and 175 €/user.year, respectively (in Indian currency, these values are 1184.40, 4230–5922, 1692–2538, 338.40–592.20, and 14,805 rupees/user.year, respectively. In contrary, the operational cost of the VF technology was reported to be only 0.05 €/m^3.year (i.e., 4.23 rupees/m^3.year), subjected to further decrease with the increase in the number of users [112,118].

5.2.3. *Treatment efficiency*

The treatment efficacy of a particular wastewater treatment technology also determines its economic feasibility. In other words, it needs to be worthy investing on a particular technology in terms of its treatment efficiency i.e., the performance of a specific wastewater treatment technology needs to be considered before investing the money on it. The treatment efficiency of a wastewater treatment technology depends on the type of wastewater it is supposed to treat [7]. As already discussed, and portrayed in Table 1, it is clearly evident that the VF technology has the potential to substantially remove various pollutants, including organics, nutrients, and pathogens from the domestic wastewater. Arora et al. [53] and Kumar et al. [52] have concluded that the effluent coming out from the VF of domestic sewage satisfied the stringent surface water discharge standards in terms of pathogens and could be efficiently reutilized for various non-potable purposes. Hence, it can be rightly stated that the VF technology has shown enough promise to be potentially implemented for remediating the domestic sewage.

5.2.4. *Production of value-added byproducts and linkage to circular bioeconomy*

Apart from the trivial GHG emission, the following byproducts are obtained during the VF of domestic sewage: treated effluent as the liquid output and the vermicastings as the solid residue. In addition, once the VF process is over, the earthworms can also be taken out from the vermibed [3]. Chowdhury et al. [32] have mentioned that the doubling time of the earthworms is approximately two months. As a result, the number of earthworms obtained after the process is over will be more than the number of earthworms incorporated at the beginning of the VF process.

Owing to the nutritional value, the vermicasting itself or after being converted to the vermicompost can be potentially employed as the organic manure to improve the fertility of the soil [1,32]. The vermicompost is reported to have the ability to replace the conventional chemical fertilizers in the global market [89]. Moreover, a huge monetary investment is required to develop the infrastructure to produce the chemical fertilizers, which, in turn, increases the cost of the food production [32]. In addition, the crops produced by utilizing the chemical fertilizers also get contaminated by the toxic chemicals, which subsequently affects the human beings adversely after the consumption of the food. On the other hand, the cost of producing the vermicasting and vermicompost is trivial due to the abundant availability of the raw materials, including domestic wastewater. According to the report of the Status of Sewage Treatment Plants 2021, published by CPCB, the generation of domestic sewage from the Class I cities and Class II towns was approximately 29,129 MLD (as per 2001 census) [8]. Thus, the application of the vermicompost as organic manure helps in lessening the cost of food production. According to Sinha et al. [89], a significant drop in the cost of food production (up to 60–70 %) has been noticed by replacing the chemical fertilizers with the vermicompost. The produced food will be safe and chemical free. Sinha et al. [89] inspected that the risk of occurrence of any disease on consuming the foods has been reduced by 75 % due to the application of vermicompost as organic manure. Sinha et al. [119] have found that the application of vermicompost helps in reducing the harvesting time of the crops. This has helped the farmers to gain more profit by cultivating more crops in a single year using the same plot. In addition, the vermicompost is reported to have the capability to hold the soil moisture for longer duration, cutting down the water demand by 30–40 % [120]. In fact, vermicompost also helps in obtaining better growth and higher yield of the crops [106]. Webster [121] found that the application of vermicompost enhanced the grapes' production by 23 % than that using the chemical fertilizers. In light of the above discussion, it is clearly evident that the vermicastings and vermicompost can be a potential replacement of the chemical fertilizers across the globe. Devkota et al. [122] found that the production cost of vermicompost was 15.68 rupees /kg, whereas it has been sold to the market at 25 rupees/kg as the biofertilizer, obtaining a net profit of 9.32 rupees/kg of vermicompost, which, in turn, lessened the cost of VF process.

Similarly, the effluent obtained from the VF of domestic sewage embraces nutrients in high concentrations, thereby satisfying the criteria to be utilized in irrigation and agricultural practices [74]. Hence, it also adds positive economic value to the VF process.

The presence of earthworms adds 100–1000 times more value than the conventional processes [123]. The obtained earthworms can be again reutilized in other vermifilters. The earthworms can also be sold to the farmers or to the various farms such as poultry, dairy, and fishery farms as feedstocks since the earthworms are rich in protein content (65 % of the total wight of the earthworms) [89]. In Australia, the cost of 500 earthworms is approximately 20 A$ (1126.40 rupees) [31], whereas Devkota et al. [122] have found that the cost of production of one earthworm was only 0.40 rupees. In recent few years, vermiculture has become one of the fastest growing industries. Hati [124] found that the villagers in rural areas were gaining a yearly profit of 5–6 lakh rupees by selling the earthworms and vermicompost. Hence, the earthworms also indirectly help in reducing the cost of VF process. Few examples of the commercial business models, established/proposed worldwide, regarding the production and trading of the earthworms and vermicompost have been portrayed in Table 3.

In reference to the above discussion, it can be concluded that the VF technology helps in converting the wastewater coming from the households, communities, agricultural fields, and various farms into highly nutritive vermicastings. The vermicastings, after being converted to vermicompost, can be utilized in the agricultural fields and subsequently, the wastewater coming from the agricultural field through municipal sewer systems can be subjected to the VF process, thereby completing a cycle (Fig. 10). Moreover, the treated effluent can be employed for the agricultural and horticultural purposes, thereby imparting a positive economic value. The earthworms employed in the VF can also be taken out once the process is over and sold to various farms as feedstock. In fact, the same earthworms can also be incorporated into a new vermifilter, thereby completing a circle of economy. Hence, the VF technology converts the domestic wastewater with negative economic worth into highly nutritive effluent, vermicastings, and vermicompost having positive economic values using the earthworms (i.e., biological agent), thereby reinforcing the concept of circular bioeconomy (Fig. 10).

5.3. Social acceptability

In addition to the environmental sustainability and economic affordability, the VF technology needs to be socially acceptable for its consideration as the sustainable wastewater remediation technology. The social acceptability of a particular wastewater treatment technology depends on the following factors: protection of public health, pubic involvement and community development i.e., the growth of local socio-economy, and aesthetics [15,84] (Fig. 8).

5.3.1. Protection of public health

Since the VF technology has the potential to substantially eradicate various pollutants including organics, nutrients, and pathogens from the domestic sewage, the outbreak of the water-borne diseases has been drastically reduced, reducing the risk of human toxicity [53,82]. In fact, Kumar et al. [52] and Arora et al. [53] have reported that the VF process can successfully eliminate the FCs from the domestic sewage and the treated effluent has satisfied the surface water discharge standards regarding the pathogen count. In addition, Kumar et al. [60] have postulated that the NO_3^--N concentration in the effluent obtained from the VF of domestic sewage was <45 mg/L. Thus, the discharge of the vermifiltered effluent to the surface water bodies would not cause the blue baby syndrome [2]. In addition, as already discussed, being an organic fertilizer, the application of vermicastings and vermicompost results in the production of safe and chemical free food, cutting down the risk of hazardous impact on the human beings due to the consumption of foods. Sinha et al. [89] have reported a drastic fall (up to 75 %) in the risk of occurrence of such diseases when the chemical fertilizers were replaced with the vermicompost. Generally, the effluent obtained from the domestic wastewater has been advised to utilize for non-potable purposes [31]. However, in rural areas, the people may use the surface water, which may accommodate the discharge from the vermifilter, for drinking purpose. Moreover, the human beings share the same food chain with the fishes [3]. Since the VF technology is capable of reducing the concentration levels of the contaminants below the permissible limits, it can be stated the implication of VF technology cuts down the risk of human toxicity to a great extent, thereby promoting the

Table 3
Business models for the production and trading of the earthworms and vermicompost.

Region/country	Enterprise/facility	Business model	Waste holding capacity	Current status	References
South Pacific Island countries (Samoa and Fiji)	–	Organic farming	–	Proposed	Pierre-Louis et al. [127]
Greece	Pylaia-Chortiatis municipality	Organic fertilizer production through food waste management	32.30 t/year		Conlen et al. [128]
Australia	–	Organic manure production	200 t/week	Existing	de la Vega [129]
Rochester, New York, US	Worm Power (World's largest VC facility)	Agri-business, organic farming, production of cattle feedstocks (corn grains)	16.33 t/week		
Portland, Oregon, US	Portland community college	Soil amending	6.176 t/year		
Monroe, Washington, US	Monroe correctional facility	Trading earthworms and vermicompost	10 t/month		
Seattle, Washington, US	Woodland Park zoo	Selling Zoo Doo through 'Endangered Feces' online lottery system	–		
Durham, California, US	The Worm Farm	Earthworm trading	204.12 kg/two weeks for each windrow facility		
Sancti Spiritus, Cuba	Finca de Casimiro	Selling organic fertilizer	54.43 kg/d		
Havana, Cuba	Vivero Alamar Organoponico	Selling fruits and vegetables produced by organic farming, Selling vermicompost	Manure from 7 horses and 13 bulls		
Guana-Coboa, Cuba	Granjita Feliz	Production and sale of food	Waste from 50 rabbits/d		
North-East India	–	Agri-business and organic fertilizer production	–	Proposed	Kadirvel et al. [130]
New Zealand	Maketu Hamilton Rotorua Te Puke	Production and sale of organic fertilizer	0.50 t/d 13,500 t/year 10,000 t/year 900 t/year	Existing	Quintern & Morley [131]
North Vancouver, Canada	Loutet Farm, Edible Garden project	Vermicompost trading (Mid-scale urban vermicomposting facility project plan)	Waste from 56 local businesses	Proposed	Hanam et al. [132]

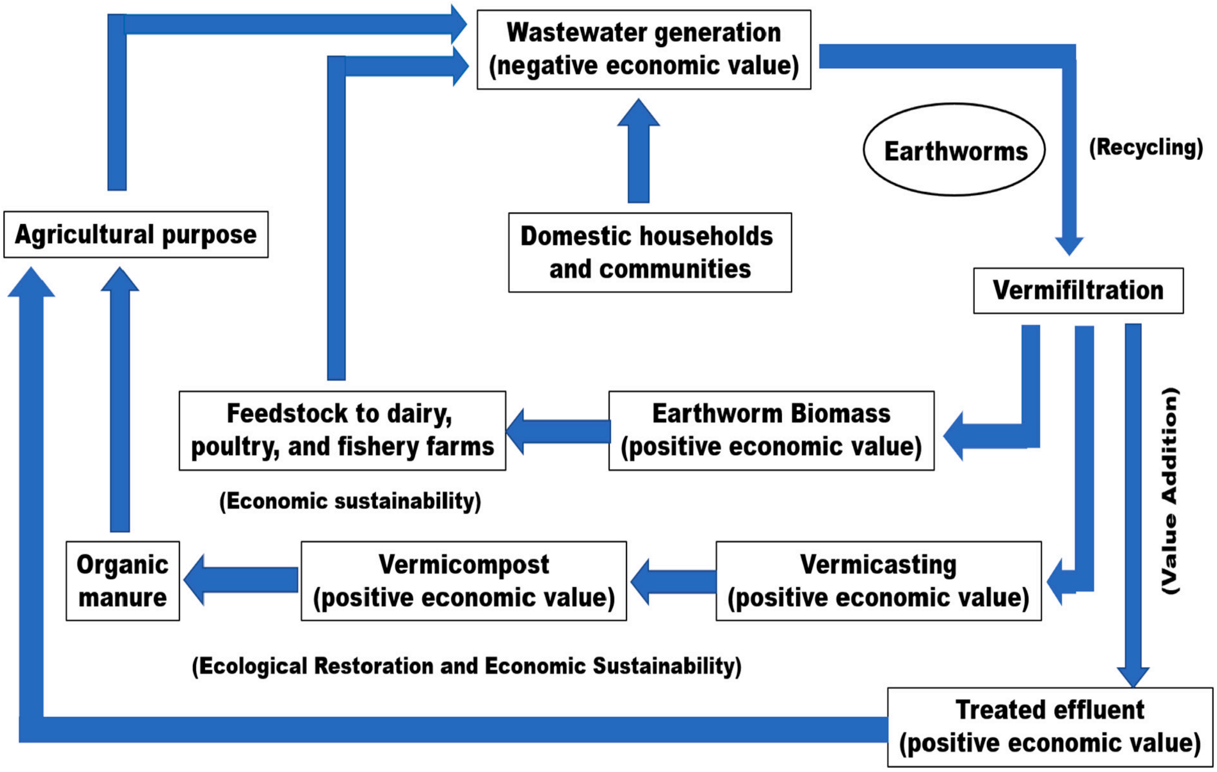

Fig. 10. Economic sustainability of VF technology from the perspective of circular bioeconomy.

protection of public health.

5.3.2. Growth of local socio-economy

Being an environmentally sound and decentralized wastewater remediation technology, VF can be effectively employed to remediate the domestic sewage generated from the individual households or small communities [5]. Owing to the ease of construction and operation of VF, the common people of the communities can take the decisions and actions by themselves, reflecting local values through a public process in which the common people have the sense of ownership over the decision making i.e., the common people can decide how to construct and use the system for their economic growth. In other words, VF ensures the public involvement which is not possible in case of the conventional wastewater treatment methods [15].

As already discussed, the VF of domestic sewage results in the production of various value-added byproducts such as vermicastings, vermicompost, treated effluent, and earthworms (Fig. 10). The vermicompost can be sold to the market as fertilizer. Devkota et al. [122] reported that the vermicompost has been sold to the market at a rate of 25 rupees/kg with a net profit of 9.32 rupees/kg. In addition, as already mentioned, the earthworms can also be sold to various farms as feedstock. Sinha et al. [31] observed that the price of 500 earthworms was approximately 20 A$ (approximately 1126.40 rupees). Hence, VF process also helps in boosting up the economy, which makes the local people in rural areas attracted towards the VF process. Since it is a decentralized method, all the members of the community can equally take the benefits of the VF facility. Moreover, the treated effluent can be used for various non-potable purposes by the beneficiaries. It also promotes social resiliency and stability through the wise use of the resources. Thus, due to the implementation of the VF technology for treating the domestic sewage, all the members of the community will be able to prosper to their highest potential through appropriate natural resource-based development. In other words, the VF technology, as a whole, helps in the community development [15].

Hence, through the public involvement and community development, the VF technology ensures the growth of local socio-economy.

5.3.3. Aesthetics

Another parameter that plays a pivotal role in determining the social acceptability of a wastewater treatment technology is the maintenance of the aesthetic assets [15,84]. As we already know, the burrowing activity of the earthworms makes the VF process naturally aerobic. Being an aerobic method, VF process does not produce any pungent smell. Basically, by tunneling action, the earthworms inhibit the action of the anaerobic microorganisms releasing mercaptans and hydrogen sulphide [31]. Hence, the VF technology does not cause any nuisance to the surrounding people, thereby maintaining the social aesthetics. Being a decentralized method, VF technology can also be employed in small-scale communities or individual households and it does not occupy large space. In addition, unlike the conventional aerobic wastewater treatment methods, VF process does not produce any sludge, promoting the conservation of social aesthetic values. The effluent coming out from the VF of domestic sewage is crystal clear and rich in DO [1,31]. Thus, its disposal to the surface water bodies does not cause any color change of the water. Apart from this, the disposal of the vermifiltered effluent does not result in the formation of algal bloom inside the surface water bodies [2,60]. Furthermore, as discussed earlier, VF helps in maintaining the balance of the aquatic as well as the soil-based ecosystems [2,53], thereby strengthening the concept of preserving the aesthetic assets.

In light of the above discussions, it can be concluded that the VF technology has satisfied almost all the criteria to be regarded as the sustainable treatment alternative for treating the domestic sewage. Especially, in rural and urban communities of both the developing and developed countries, the provision of the centralized WWTPs may not be fruitful in near future as the sustainable wastewater treatment facility owing to the accrescent need for the clean water. Hence, the need of this hour is to treat particularly the domestic sewage coming from the single households and small communities in decentralized manner employing the VF technology, thereby ensuring the reduction of the burden of the organic loads on the conventional WWTPs. In view of the analyses made throughout the review work, the advantages of implementing the VF technology over the conventional wastewater treatment methods, especially for treating the domestic sewage have been schematically portrayed in Fig. 11.

6. Future perspectives

Even though, the VF technology has been extensively employed in remediating the domestic sewage, the researchers have faced few challenges, especially during the field-scale implementation of the VF technology, which need further attention.

- ➢ The earthworms cannot sustain higher HLRs and are unable to survive in water-logged condition for longer duration, which restrict the scaling up of the VF technology. This issue needs special attention of the researchers.
- ➢ The earthworms are very sensitive to the seasonal variations. During summer, the earthworm's skin gets dried up, restricting the movement of the earthworms, which, in turn, ceases the activities of the earthworms. In monsoon, the earthworms may get injured by the direct impact of the rain drops, reducing the efficacy of the VF technology. Similarly, in winter, the activity of the earthworms gets drastically reduced. This is a serious issue and needs to be encountered for the successful implementation of the VF technology in field-scale applications.
- ➢ To ensure substantial removal of the nutrients from the wastewater, sufficient contact time has to be provided, which engages large footprint, negotiating the scaling-up of the VF technology, especially where the space is limited. This has to addressed to further reinforce the sustainability of the VF technology.
- ➢ Over the last few years, an awareness has been observed among the researchers to adopt various strategies and techniques to further improve the performance of the VF technology. Various researchers have provided a thermal insulation layer (elasticity plastic filler layer) at the vermibed surface to protect the earthworms from the external freezing [113,125]. Some researchers have incorporated the macrophytes to protect the earthworms from the direct impact of the rain and extreme heat of the sun [1,33]. In addition, the macrophytes impart some distinct advantages including rootzone aeration, accommodation of the microbes at the rhizosphere, enhancement of the porosity of the vermibed media, and nutrient uptake from the wastewater, further improving the treatment efficacy of the vermifilters [11]. The issue regarding the operation of the vermifilters at higher HLRs can be overcome to some extent by adopting the step feeding of the influent at multiple points [1,126]. In step feeding, the flowrate of the influent gets divided among different influent ports. Thus, the HLRs from each port becomes substantially less as compared to the single point wastewater feeding approach. In addition, in step feeding mode, the uniform distribution of the wastewater over the entire surface of the vermibed reduces the risk of ponding. Recently, to address the concern related to the area requirement of the VF process, the researchers have implemented baffled vermifilters [37,38] and hybrid vermifilters [1,33]. In baffled vermifilters, the provision of baffles increases the effective length of travel of wastewater inside the vermifilter by ensuring the curvilinear movement of the wastewater, thereby facilitating sufficient contact time for substantial nutrient removal from the wastewater by engaging smaller area. On the other hand, in hybrid vermifilters, the wastewater has to pass through a VSSF vermifilter followed by a HSSF vermifilter. In VSSF vermifilter, the aerobic condition prevails, whereas in HSSF vermifilter, anaerobic condition becomes predominant [30,48]. Thus, the provision of the hybrid vermifilter improves the redox condition of the system, triggering the organic and nutrient removal efficiency of the VF technology within a minimal footprint. However, the application of all the aforementioned modifications has been mostly limited to the lab-scale. Hence, further research is of utmost importance to examine the feasibility of the aforementioned advanced vermifilters in field-scale applications.

7. Conclusion

In the present review, the mechanisms taking place in VF and the contribution of the earthworms in remediating the domestic sewage are comprehensively elaborated. On analyzing the performance of the VF technology, based on the data compiled in this review work, it can be

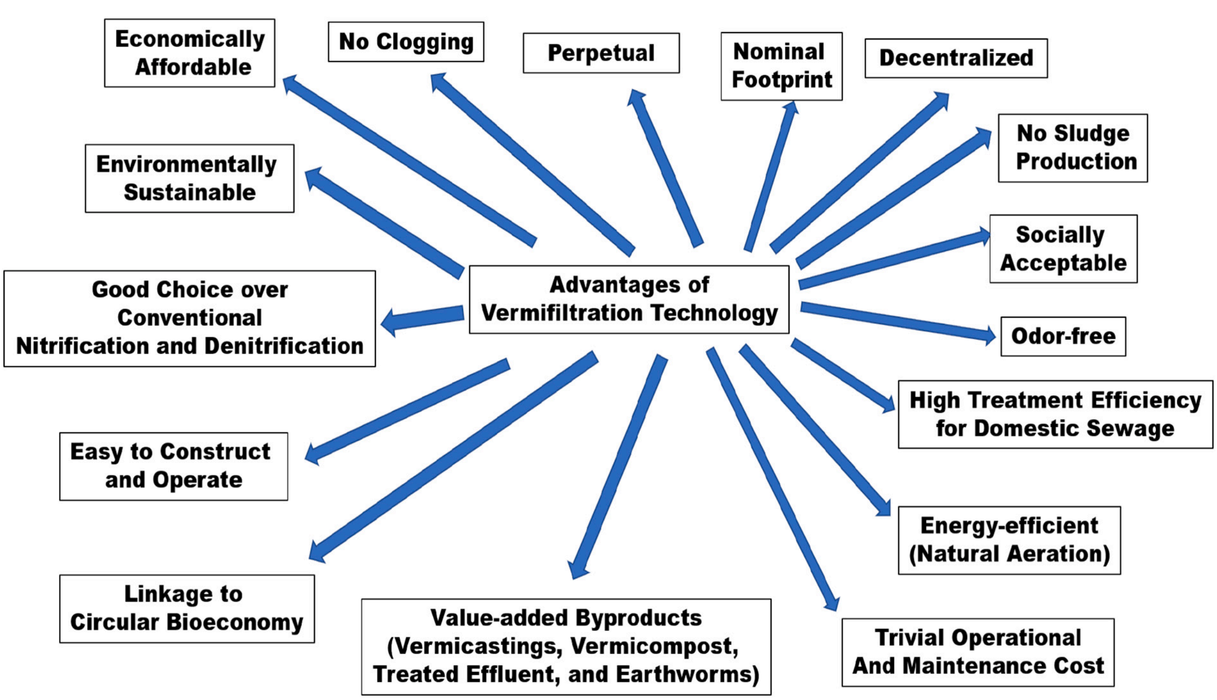

Fig. 11. Advantages of VF technology for treating the domestic sewage.

concluded that the VF technology has displayed its worth in countering the pollutants present in the domestic sewage. In fact, the disposal of the vermifiltered effluent to the surface water bodies is absolutely safe. The VF technology is found to be more advantageous than several pioneer wastewater treatment technologies such as ASP and other non-conventional wastewater treatment technologies such as CWs, ALs, and WSPs, especially regarding the treatment of domestic sewage. The detailed analyses on the LCA and LCIA of the VF technology portrays that the VF technology can potentially reduce the environmental nuisance by negotiating the GHG emissions and sludge production, justifying the VF technology as a zero-waste technology or green technology. Taking into consideration the strict environment protection policies worldwide, the VF technology can be regarded as an eco-innovation in the field of wastewater treatment. Furthermore, the energy efficiency and the production of the value-added byproducts improve the economy of VF process. In addition, its linkage to circular bioeconomy makes it an economically viable option. The VF technology also satisfies the social acceptability criteria by promoting public involvement, community development, and preserving the social aesthetic aspects. Hence, as a concluding remark, it can be stated that the full-scale implementation of the VF technology would help the society to achieve the three bottom-lines of sustainability: environmental sustainability, economic affordability, and social acceptability.

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.

Data availability

All data, models, and code generated or used during the study appear in the submitted article.

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