REVIEW ARTICLE

Sustainable Technology for Wastewater Treatment and Climatic Change Mitigation using an Innovative Vermifiltration Approach

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ABSTRACT: Environmental sustainability can be achieved through advanced natural, clean, and green technologies. Efficient and affordable strategies are required for water management, which is vital for environmental development. Vermifiltration, a natural bio-filtration technology, utilizes the enzyme activity of earthworms to digest organic waste materials present in the wastewater. This innovative approach creates a clean and green environment thereby supporting global food security. It plays a key role in climate-smart agriculture, addressing the complex challenges faced in modern farming practices. Earthworms decompose organic waste into valuable natural manure, enhancing soil fertility and improving soil physicochemical characteristics. Sustainable agriculture reduces the use of growth hormones and chemical fertilizers. This technology bridges sustainability to wastewater management through trickling filters that optimize the conversion of organic materials. Trickling filter-enabled vermifiltration extends the aerobic environment within the wastewater treatment system, promoting the effective decomposition of organic wastes. This novel treatment method improves hydraulic loading rate (HLR), hydraulic retention time (HRT), and other physicochemical parameters, maximizing the conversion of organic substances through the earthworms' eco-friendly engineering activity.

KEYWORDS: Vermifiltration; waste water treatment; climate smart; organic agriculture; sustainable development

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INTRODUCTION

The increase in water utilization over the previous century is about six-fold, compared to the rise of one percent per year reported by the UN World Water Development Report 2020 [1]. Climatic change and its consequences like storms, droughts, and floods lead to water stress and generate many unexpected problems in developing countries. Water quality is affected by the change in physiochemical conditions observed in water bodies and the decrease in dissolved oxygen (DO). Eutrophication creates a loss of habitat for the organisms that dwell in the aquatic environment. It is claimed that a rise in water temperature and a fall in DO have an impact on water quality. Through processes like eutrophication, the decline in DO will, in turn, cause a decline in the marine population and lead to the loss of their habitat. The treatment of wastewater is one potential solution to the current problem of water scarcity. Wastewater can be a potential resource if it is properly treated because it is a source of many important

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nutrients, including nitrogen and phosphorus.

One of a farmer's best friends is an earthworm that paves the way for the thoughts of Odum [2]. Role of nematode worms explained by Darwin [3] and breaking up of aggregates and interaction between soil and earthworm's gut microorganisms with the participation of nematode worms and microarthropod insects [4]. *Out of the 4400 earthworm species that have been reported worldwide, of which 509 species have been reported in India, Eisenia fetida, Perionyx excavatus, and Eudrillus eugeniae have the highest bio-accumulating potential. These species are among the most readily available for use in waste management* [5]. Earthworms are long, brown in colour, have symmetrical, segmented bodies without bones, and carry out typical physiological functions in environments with moisture levels between 60 - 75 percent and temperatures between 5 and 29 °C. According to the species and surrounding conditions, the average earthworm lives between 3 - 7 years. They are bisexual creatures that can produce up to three cocoons per worm each week, and 10 to 12 baby earthworms emerge from each cocoon [6]. Earthworms are extremely sensitive to dryness and light. While their activity was greatly reduced in the winter, heat can rapidly kill them. Due to the heat, they do not have a significant issue with the low temperature. Worms appear not to be particularly sensitive to obnoxious smells, as they like living and feeding on cow dung and even sewage sludge. They reduce all odour problems by killing anaerobes and pathogens that produce foul odours [7]. The earthworm's body was a bioreactor, and its coelomic fluid includes a huge number of microorganisms that actively contribute to the decomposition and neutralization of waste products in an environmentally beneficial manner. An innovative technique for wastewater treatment that is just as efficient as traditional filtration methods is called vermifiltration. The biofiltering ability of earthworms dynamically lowers the Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Dissolved Solids (TDS) [8]. A greater amount of reduction in BOD of nearly 90 %, COD of 80 to 90%, and TSS of 92% was recorded in the vermifilter based waste water treatment [7]. Enormous quantity of humus rich organic materials formed by the action of earthworms on the complex biochemical groups containing carbon, hydrogen, and nitrogen [9]. Being detritivorous and ecological engineers, earthworms support biomonitoring of soil health, which was utilized to conclude occurrence of heavy metals, contaminants, and pesticides levels. Earthworms are capable of converting insoluble material into soluble and bioavailable material and maximize the rate of decomposition through the presence of aerobic microorganisms in the earthworm and their enzymatic action. Potential disintegration of various organic molecules is mediated by the optimum population of microorganisms present in the mucus substance and intestine of earthworms. The nutrient cycling in the soil ecosystem, influenced by the soil microbes, happened through the action of earthworms [10].

This review's primary goal is to clarify 1) The important earthworm species that are suitable for vermifiltration technology based on their ecological types 2) The role of enzymes involved in the waste water treatment process and the importance of earthworm gut microbial enzymes for the waste water treatment strategies 3) To setup a novel model blended with a trickling filter with the vermifiltration unit 4) To ensure the sixth goal of sustainable development for the assurance of quality water to all; 5) Finally, climatic change mitigation by providing sustainable technology. The above objectives play a significant role in sustainable development. This study also integrates the possible ways for sustainability through vermitechnology in terms of linking the gap between various scientific findings, which helps the researchers find sustainable solutions for the current problems faced by the earth and humans.

Waste water treatment

The wastewater has been successfully treated for a long time using biological systems. There has been a significant amount of recent research in the field of enzymes used for wastewater treatment. Enzymes can also combine with specific bacteria that lack the capability of removing uncooperative and inert substances from wastewater. Advanced treatment methods, such as wastewater treatment based on enzymes, are more effective than traditional methods. The efficacy of many different enzyme types has been studied for the treatment of pollutants in wastewater. Enzyme types and sources have an impact on how effective they are at treating wastewater [11]. Due to specificity enzymes can only catalyze a single kind of reaction. Lipases, for instance, can catalyze the oxidation of fats, grease, and oils, while proteases can breakdown proteins. For organophosphates, carbamates, and other chlorinated organic compounds, carboxyl esterases speed up the hydrolysis of ester linkages. [12].

Table 1: Types of Enzymes, Sources, Specific pollutants and Types of Wastewater treatment

Enzyme types	Sources of Enzymes	Wastewater	Specific Pollutants	References
Peroxidase	Soybean	Synthetic Wastewater	Methyl orange dye	[13]
Peroxidase	Turnip	Coffee processing	Phenolic Compounds	[13]
Lipase	Pig pancreas	Swine slaughterhouse	Crude fat	[14]
Lipase	*Pseudomonas aeruginosa* UKHL1	Oily wastewater	Oil	[15]
PETase	*Ideonella sakaiensis*	-	PET	[16]
Lipase	*Thermomyces lanuginosus*	Synthetic Wastewater	Tributyrin	[17]
Chloroperoxidase	*Caldariomyces fumago*	Synthetic Wastewater	Lincomycin	[18]
Laccase	*Coriolopsis gallica* (BS54)	Synthetic Wastewater	DCF	[19]
Laccase	*Coriolopsis gallica*	Synthetic Wastewater	Synthetic dyes	[20]
Laccase	*Yarrowia lipolytica* rM-4A	Palm oil mill	Phenolic compounds	[21]

In wastewater treatment, enzymes are widely produced by using bacteria and fungi. Hydrolytic enzymes like protease, lipase, amylase, and cellulose generated by hydrolytic microbes can break down complex materials like carbohydrates, proteins, and lipids into simpler substances. Phosphotriesterases could hydrolyze a variety of organophosphates [22], and haloalkane dehalogenases have to be capable to dissociate bond of carbon-halogen in the molecules of halogenated aliphatic compound [23]. To remove floatable grease (FG) inhibition and to progress the performance of digestion in an anaerobic procedure, three lipases—Lipase-I, Lipase-II, and Lipase-III—were used to hydrolyze FG in the food waste [24]. Under hydrolysis settings of 24 hours, 40°C - 50°C, and 1000-1500 L lipase inoculum, Lipase-I and Lipase-II successfully liberated long-chain fatty acids in these contaminants. Because Lipase-III demonstrated a relatively low hydrolysis rate, types and enzyme sources are essential for treatment of wastewater. Chlorpyrifos was degraded using laccase made by *Trametes versicolor* [25]. In 120 hours, two co-cultured yeasts, *Yarrowia lipolytica* rM-4A and *Candida rugosa*, were employed to extract ~98.5% of the triglycerides from effluent of undiluted palm oil mill. Horseradish peroxidase was used by Stadlmair et al. (2017), Bilal et al. (2018), and Garg et al. (2020), to degrade TrOCs, phenol, and methyl orange, produced by synthetic wastewater, textile, and leather [26–28]. The removal of pesticides and antibiotics from synthetic wastewater using Caldariomyces fumago's chloroperoxidase was studied by researchers in the year 2018 and 2019 [29–30]. Bacteria, fungi, and plants are significant sources for enzyme production, which helps remove pollutants from wastewater, but still, deep research is essential to ascertain suitable enzymes to proceed with assured wastewater treatment. The types of enzymes, sources, specific pollutants, and types of wastewater treatment reported by different authors are shown in Table 1.

Ecological Classification of Earthworms

Earthworms are grouped under the phylum Annelida, class Oligochaeta, family Lumbricidae, which comprises terrestrial organisms. There are many earthworms available with different sizes, feed habitats, and cocoon production rates based on the environmental conditions in which they prefer to proliferate. Ecologically, the earthworms are classified into three groups given by Bouché [35]. (i) "anecic earthworms", deep burrowing species that form cavities upright and feed on detritus (ii) "epigeic": small earthworms feed on litter and do not tunnel deeply in to the earth. Epigeic earthworms consume the organic matter that has decomposed on the soil's surface. And ingestion of soil by the earthworms was found to be limited. The earthworms appeared in dark colours and were small to medium in size. They can move rapidly, and they have relatively short lifespans. Burrowing of the earthworms was noted on the surface of the soil. (iii) "endogeic earthworms" ingesting soil and organic substance observed in soil. Endogeic earthworms' lives with the organic stuff occur in soil, and the size of the earthworms is medium and shows pigmentation. The earthworms move slowly, and they have an intermediate life span. They form subhorizontal burrows in an extensive and continuous manner. The earthworms ameliorate the soil structure by madding burrows, feeding on detritus, transforming organic matter and minerals to produce nutrient rich manure, and influencing the soil's quality and fertility.

Epigeic and anecic varieties of earthworms prefer to consume leaf litter and form many burrows in their habitat. The mixing of the leaf litter with the soil in the burrows by the earthworms was considered an external rumen that sustains favourable microorganisms. This kind of earthworm activity improves the degradation rate of litter blended with organic matter and increases the ingestion of soil organic matter by the worms [31]. The burrowing and casting activity performed by earthworms, act as an ecosystem engineer to decide the soil structure of the residing environment. Earthworms are phenotypic engineers responsible for soil structure through their biogenic behaviour [32]. The geophagous variety of earthworms also influences the environment through moisture, thermal, and feeding phenomena. They have a higher mobility rate and biomass conversion capacity. Globular and granular forms of earthworms are denoted by Blanchart et al., [36], and the worms create soil macroporosity [37]. They form compact castings on the surface in a continuous layer where the worms are not taking their feed [38].

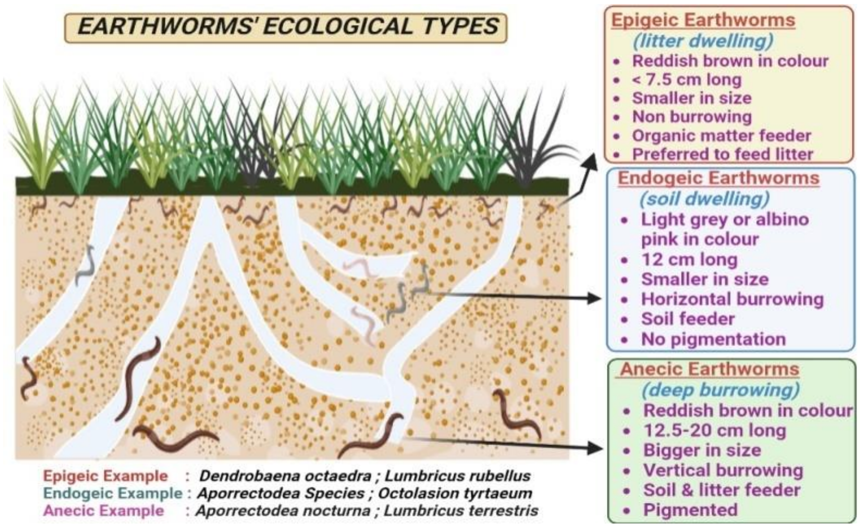

Figure 1: Schematic diagram representing the ecological types of earthworms

Mohan et al.,

Short-term processes

Digestion extends from hours to a few days through the generation of microsites in the rhizosphere-bearing soil present in the root tips. This activity is mediated by microorganisms and enzymes. Intermediate structures: This activity happened from a few days to a few weeks after the deposition of organic materials mixed with microbial activity [37]. Longer term stability of biogenic structures: The activity extended from months to years [39] based on the decomposition and soil dynamic properties, which form macro-aggregates to determine the hydraulic property of the soil [36, 38].

Pedogenesis

Soil structure was comprised of soil horizons generated with organic substance of soil. The physical characteristics of the soil are improved by earthworm creeping, which also accumulates soil surface deposits. Long-term pedogenesis formed the fertile topsoil. Earthworm activity is an essential factor in the conversion of organic matter and soil biodiversity. Five different roles played by earthworms include (i) the release of plant nutrients; (ii) the impact on the hydraulic properties of the soil; (iii) the control of pests, (iv) the improvement of the microbial load; and (v) the release of plant hormones [31]. Earthworms are capable of engineering, as evidenced by the effects they have on plants and soil-dwelling organisms [32]. To suit their preferred feeding habits, earthworms can dig either ephemeral orpermanent burrows [33]. There are three groups of earthworms classified based on their availability in ecological conditions: epigeics, anecics, and endogeics. Epigeic earthworms are found on the surface of soil containing a high amount of organic matter. Anecic worms are present in the top soil, which makes vertical furrows on the soil. They preferred to eat leaf litter mixed with soil. Horizontal furrows made by endogeic earthworms This kind of earthworm feeds more soil when compared with the other two types of earthworms, anecic and epigeic [34–35] (Figure 1).

Selection of potential Earthworms for Vermitechnology

Earthworms are employed to participate in the vermicomposting and vermifiltration processes by removing contaminants from waste water and restoring nutrients in the compost material. Treated and clean water obtained from the vermifiltration unit and worm cast can be utilised as natural manure. Both processes happened at normal room temperature, and they have not consumed any catalysts or chemicals for the treatment of waste materials present in the waste water. Earthworms are capable of removing nearly 98 percent of BOD, 90 percent of COD, 95 percent of Total suspended solids (TSS), most of the heavy metals, and reducing the concentration of nutrients [40–42]. Earthworms engulf all the contaminants, and the gut microorganisms are enzymatically useful for the treatment of organic wastes and finally excreted as worm castings, or natural manure. Bioremediation of heavy metals was also noted during the enzymatic changes that took place during Vermicomposting. Vermifiltration uses a relatively small amount of energy and gets rid of the majority of the contaminants present in waste water. The most common earthworms used for waste management include *Lambito mauritii, Lumbricus rubellus, Perionyx excavates, Eisenia and foetida, and Eudrilus euginiae*. These worms can tolerate toxic substances, have a high proliferation rate, and have potential decomposing abilities.

The vermibed consists of earthworms in the filter bed bearing soil, compost, and cowdung as inocula present in the earthworm active zone for the filtration of waste water [43]. The filter media have sand, gravel, and pebbles to make the filtration system aerobic with the involvement of earthworm activity. Based on the direction of flow, systems can be divided into the following types: horizontal flow systems, vertical flow systems, and hybrid and vertical systems that can be combined to form hybrid systems.

Recently, integrated filtration techniques with a combination of macrophytes and vermifiltration systems showed their effectiveness in waste water treatment. It improves the efficiency of the treatment strategy through vermifiltration by using many plants like *Phangmites australis*, *Saccharam spontaneins, and Canna indica* [44–45]. The macrophytes available in the system significantly removed the organic waste by taking it up as nutrients for their growth. In the macrophyte-vermifiltration system, the plants provide aerobic conditions through the rhozospere and make the environment helpful for the survival of microorganisms, which degrade the organic nutrients [46]. The aerobic nature noted in the filtration unit is retained by the supply of atmospheric oxygen to the unit through the rhizosphere. It makes the earthworms and microorganisms survive in the aerobic environment [46].

Epigeic earthworms are engaged in performing the vermi technological process. The following qualities were found to be involved in waste management strategies: (1) Colonization of the organic waste materials; (2) They consume, digest, and assimilate, in turn recycling the organic waste materials, with high tolerance for different kinds of environmental conditions (3) Minimum period of life cycle, higher reproduction capacity, and easy handling; (4) Constant vermicompost producers.

Mechanism of Vermifiltration Technology

Vermifiltration is an infiltration technique that is combined with biological means of wastewater treatment (Figure 2). Earthworms are adaptable decomposers and waste-eaters. An important component of the vermifiltration process is the earthworm. The earthworms can digest waste, decompose it, and stimulate biological activity in the waste water treatment process while also promoting the development of decomposer bacteria. Moreover, all these above processes can change the entire earthworm's body to act as a biofilter, which helps to absorb the contaminants present in the wastewater and significantly lowers the BOD, COD, TDS, TSS, and turbidity levels [47]. Vermifiltration involves the simultaneous operation of two processes: the microbial process and the vermiprocess. Earthworms promote and speed up microbial activity, which increases soil microorganism populations and improves soil aeration [48]. In the earthworm hosts, the millions of decomposer microbes present in the gut excrete these microbes in the soil, which also contains nutrients like nitrogen and phosphorous in their excreta called 'vermicast' [49]. The vermicast provides good "hydraulic conductivity" in vermifilter layers for sewage cleansing, due to its porous nature, which is similar to that of sand wastewater treatment[50] (Figure 2). Earthworms are adaptable decomposer and waste – eaters. In the vermifiltration process, the earthworm is crucial. The earthworms can digest waste that has undergone chemical degradation, digestion, decomposition, and biological stimulation. They also help decomposer bacteria grow during waste water treatment. Moreover, all these above process can change the entire earthworm's body to act as biofilter, it helps to adsorbing the contaminants present in the wastewater and significantly lowers the BOD, COD, TDS, TSS, and turbidity level [47]. Vermifiltration involves the simultaneous operation of two processes: the microbial process and the vermiprocess. Earth worm promotes and speed up the microbial activity which increases the soil microorganism populations and it improves soil aeration [48]. The millions of decomposing microbes that are found in the guts of earthworm hosts excrete these microbes into the soil, producing "vermicast," which is their excreta and includes nutrients involving nitrogen and phosphorous [49]. The vermicast provides good "hydraulic conductivity" in vermifilter layers for sewage cleansing, due to its porous nature which is similar to that of sand [50].

In order to process wastewater from small cities and residential colonies, vermifltration technology can be "decentralised," reducing the need for long-distance wastewater conveys and saving time and energy [51–52]. In this method, wastewater passes through the layer of activity, where earthworms convert organic matter into vermicompost, which is rich in humus. After that, the use of a filter medium begins the filtration process. The growth of microorganisms is supported by filter medium, which then results in subsequent secondary treatment. Because of the earthworms' grinding activity, the filter media has a greater total specific surface area, allowing for a greater uptake of inorganic and organic pollutants from wastewater. The filter media traps dissolved and suspended particles as they percolate, stabilizing them in the active layer through complicated bioprocessing. The dissolved components of the wastewater move down profiles, where they attract to the surface matrix of the substrate, and then undergo symbiotic microbial and enzyme breakdown by earthworms. Earthworms increase aeration through their burrowing activity and speed up microbial metabolism through raising the overall number of soil microbes, which increases the rapid use of absorbed organics, so clogging does not occur in vermifilters. The physicochemical characteristics of the wastewater are altered by the earthworms' and microorganisms' symbiotic and synergistic activity [53].

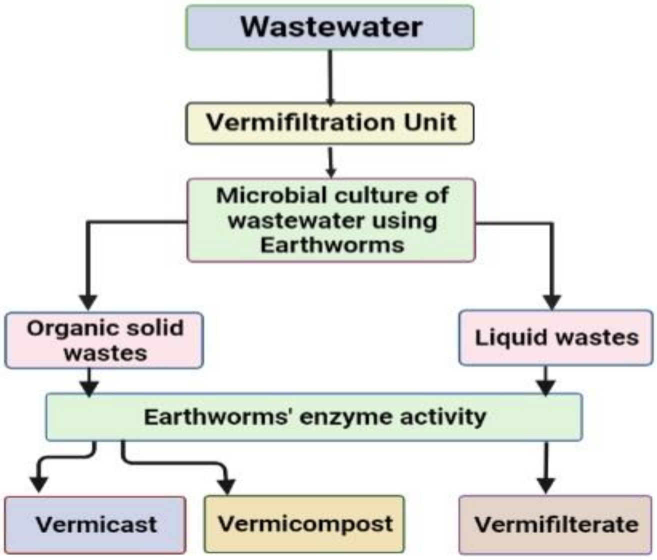

Figure 2: Flowchart representation of wastewater treatment by employing earthworms' enzyme activity

Vermifiltration Methods

Figure 3 represents the vermifiltration unit and vermifilter process utilized in wastewater treatment by trickling process. The design and implementation of the process in the vermifiltration unit are making it successful through their efficient performance. The biological activity provides an ambient environment for the gut microorganisms of earthworms. Optimization of flow rate is essential to increasing treatment efficiency.

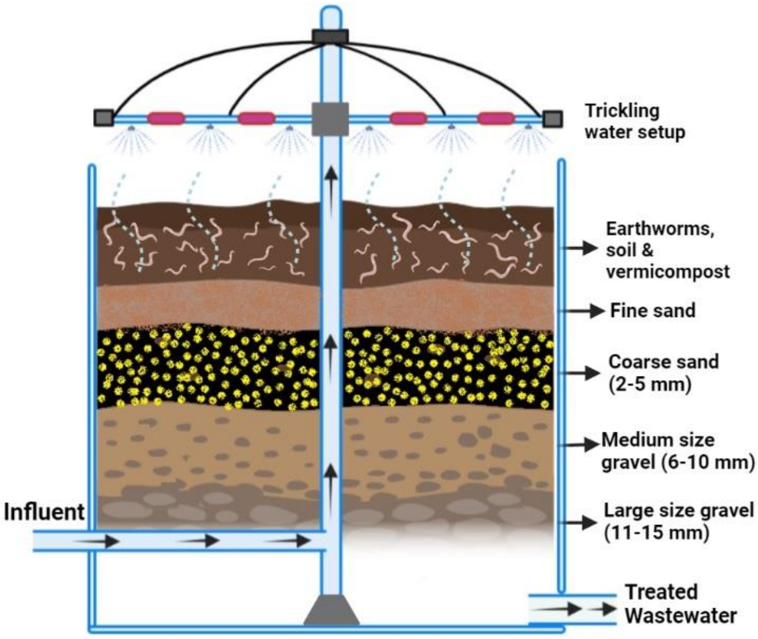

Figure 3: Vermifiltration setup utilized in the treatment of wastewater (influent from industrial/domestic wastes) by trickling filter technique

The hydraulic retention time (HRT), hydraulic loading rate (HLR), the density of the earthworm population, the C:N ratio, the temperature, the pH, the culture media, and the aeration are just a few of the variables that affect the speed and effectiveness of the vermifiltration process. To improve the efficiency of the Vermifiltration method, hydraulic retention time (HRT) and hydraulic loading rate (HLR) need to be examined and designed. HRT can be defined as the interaction time between waste water and earthworms in the filter media. The interaction time of waste water with the medium can be established by HLR. The volume and area of the media used for filtering relate HRT and HLR to one another. The contact time and HLR are inversely proportional, and the performance is directly related to the biochemical process of the Vermifiltration unit. The size and makeup of the treatment unit are taken into account when calculating HLR and HRT [8].

The amount of waste water used in the vermifiltration procedure unit can be used to calculate HLR using the formula provided below.

$$HLR = V/(AxT)$$

Where,

V - The volume of the unit's input sample water flow
A - Region of the processing unit for vermifiltration
T - The amount of time the unit's sample water spent flowing.

HLR is reliant on the quantity of active-feeding, reproductive earthworms per square inch of the vermi-filteration device. The worms' size, quantity, and viability are what determine the process. HLR considerably differs with the medium type, structure, porosity, and bulk density.

When treating waste water, hydraulic retention time (HRT) was determined using amount of time it takes for the waste water to flow through the vermifiltration unit. The retention time of the waste water used for the treatment in the vermifiltration unit is improving the earthworm's ability to absorb the medium (waste water). HRT is strongly related to the flow rate of waste water through the unit, the stocking material's volume, and the quality of the material. Earthworms execute treatment processes like physico-chemical, microbial, and enzymatic processes during their retention in the treatment medium. They can act on the available nutrients in the waste water, minimizing BOD, COD, and TDS. An important factor that influences the rate of waste water filtration in the treatment plant is the amount of time the earthworms that live in the filtering system take to complete their task. The formula can be used to calculate HRT.

$$HRT = (p \times Vs/Q)$$

Where,

Vs = Volume of the waste water flows in the filtration bed.
p = porosity of the earthworm's medium
Q = flow rate of the waste water in the filtration unit

With shorter HRT and longer HLR and reduces the amount of time that waste water, earthworms, and microbes come in contact with one another [54].

Earthworm as an Agro-Engineer to Support Climate Smart Organic Agriculture

There is broad, though not unanimity, agreement that effect of change in climate are already felt and continue to be felt in environment around the world [55]. Organic agriculture has the potential to pave the way for decreased energy use and the mitigation of the harmful effects of energy emissions through the sequestration of carbon, the use of renewable natural resources, and the reduction or elimination of resources dependent on fossil fuels. Farmers can use organic farming as a low-cost management strategy to combat climate change by producing healthy agro-ecosystems and livestock. The effects of climate change on society are significant and diverse. Several reports have highlighted modifications to food supply and production as potential effects of climate change.

Organic farming is a ready-made strategy that maximizes the use of renewable resources and controls the flow of energy and nutrients in agro-ecosystems. In comparison to organic production systems, emissions from conventional production systems are always higher. Methane and nitrous oxide emissions from the soil are decreased by organic management techniques. According to the findings of numerous field tests, using organic manure, particularly vermicompost, increases soil organic carbon when associated to chemical fertilisation and increases sequestration of significant amounts of CO_2 from the atmosphere into the soil. Organic farming is a climate smart farming practice because of the reduced greenhouse gas emissions from crop production, improved carbon sequestration, and advantages of biodiversity.

Earthworm as an Ecosystem Engineer

Ecological engineers, also referred to as "ecosystem engineers," are organisms that create physical structures to alter the accessibility or availability of resources for other organisms. Their actions and the creation of biogenic structures can alter the community's structure [56]. Earthworms have the ability to alter the structural characteristics of soil, which has an impact on the microorganisms that live there. As a result, it is regarded as one of the soil engineers in temperate and tropical ecosystems. They control the organic content of the soil and affect plant growth [57-58].

They influence soil structures through (i) the formation of burrows that help with the movement of gas and water, (ii) the integration of litter into the soil, (iii) the blending of soil nutrients and organic material, (iv) decomposition of soil organic substance (SOM) & (v) the release of surface and/or subsurface casts [31].

Earthworms Vs Heavy Metals

Soil contamination by heavy metals needs to be addressed in order to ensure secure agricultural food products and water used for consumption [59]. As the soil was exposed to a wide range of metals expelled from industrial activities, municipal wastes, and urban traffic [60]. Mostly, the exposure of metals to soil might be in the dissolved ionic state. Recently, metal ions have been released into the environment due to the employment of metal and metal oxide nanoparticles through various nanotechnological applications [61]. The soil's fertility in turn depends upon the exposure to these metal nanoparticles' toxicity, which was uptaken by the soft bodied bio-organisms present in the soil. In 1992, Professor Jose Toha demonstrated the utilization of earthworms in a filtration technique now coined vermifiltration [62]. The vermifiltration technique was found to be a facile, energy-free, and sustainable technique that could be carried out with less investment. A plethora of studies were explored on the bioaccumulation of different heavy metals in the earthworm [63]. As per the Web of Science database, more than 1400 research articles were published in vermitechnology research, as reported by Xiao et al. [64]. Among the 1400 research articles, 140 represent the role of earthworms in absorbing different toxic elements (including heavy metals) that pollute the soil.

Earthworms are identified as excellent bio-organisms to perform waste management, wastewater treatment, water filtration, and so on [65–70]. In general, earthworms can tolerate a wide range of chemical pollutants, including organic and heavy metal pollutants that are existing in soil. Because these heavy metals can accumulate in an earthworm's tissue, earthworms can bioaccumulate heavy metals such as copper (Cu), zinc (Zn), cadmium (Cd), and lead (Pb), [71]. *Lumbricus rubellus, Eisenia foetida, Dendrobaena rubina,* and *Allophora chlorotica* have shown high potential to remove heavy metals [72]. Thus, earthworms help to maintain the nutrient cycle and biofertility of the soil. The heavy metals are entered into the earthworm body in two ways: adsorption on the surface wall of the body and absorption into the internal body through the intestinal digestion process [73-74]. The amount of heavy metals presents in the soil played a major role in determining how much of those metals the earthworm would bio-accumulate [75]. Tissue damage results from increased levels of heavy metal bioaccumulation, followed by notable morphological alterations, the secretion of an excess amount of mucus, and the bulging of clitellar segments [76].

A vermifiltration process was used to treat the textile dye effluent to produce significant results in controlling or removing the pollutant, including heavy metals [77]. The reduction of chemical oxygen demand (COD) levels is supported by the microflora that exists in the guts and by adequate enzyme release in earthworms [78]. Vermifiltration additionally lowers total dissolved solids (TDS), biological oxygen demand (BOD), and total suspended solids (TSS). The efficacy of vermifiltration technique depends on the bed material, operating conditions, and types of earthworms used in the bed layer [79]. Vermifiltration has a strong track record of successfully removing contaminants from domestic and commercial wastewater, according to recent research. The purified water obtained after the vermifiltration treatment was found to be suitable for reuse. However, the level of faecal coliform was found to be a hindrance to the reutilization of treated water. Heavy metals are removed at a rate of 51%–77% from industrial wastewater using vermifiltration, which lies within the approved limit [79].

Also, the municipal sewage sludge in the liquid phase was treated by vermifiltration. The heavy metals in their unstable form were stabilized by the earthworms in the filter bed. Mainly chemical speciation of heavy metals contributed to the high fraction of unstable heavy metals. These heavy metals were transformed into stable states due to the change in properties of sludge. These physicochemical properties of sludge include pH, phosphorous, chemical oxygen demand, etc., and played a key role in determining heavy metal stabilisation [80]. Further, the earthworms possess ingestion characteristics that allow them to bioaccumulate the heavy metals into their tissues. The statistical significance test has shown a value of $p<0.05$ for zinc metal and $p>0.05$ for lead and copper metal concentrations in the tissue of earthworms [80]. Earthworms *Allobophora chlorotica, Aprorrectodea tuberculata, Dendrobaena rubida, Dendrobaena veneta, Eisenia fetida, Eiseniella tetraedra, Lumbricus rubellus,* and *Lumbricus terrestris* were effectively engaged in the removal of heavy metals [15]. These earthworms great reduction of chromium from 194 mg/kg to 113 mg/kg was observed in the vermi remediation process [81]. The vermi accelerator had increased the activity of earthworms, which very well supported the microbial growth through aeration through tunnelling in the soil.

Trichoderma brevicompactum (QYCD-6) is the intestinal fungus present in the guts of earthworm-*Pheretima tschiliensis.* This fungus was reported to exhibit multiple heavy metal tolerance [81]. Both active and passive taking of mixed heavy metals were analyzed to understand the removal mechanism. Heavy metals are removed either by biosorption or bioaccumulation process. Metals such as cadmium (II), chromium (II), copper (II) and zinc (II) are effectively removed biosorption process. Lead (II) was removed withhigher percentage (80%) by bio-accumulation process than the biosorption of around 20%. Minimum inhibitory concentration of 1600 mg/L was observed for lead (II) by the T. brevicopactum. The highest removal rate of 97.5% was recorded for the lead (II) while lowest removal rate for the other metal found to be 45.9%. Hence, it was clearly understood that the biosorption and bioaccumulation are the two major mechanisms involved in the vermi based filtration system [82].

Studies on vermifiltration using Lumbricus rubellus showed that heavy metals like chromium (Cr), copper (Cu), nickel (Ni), manganese (Mn), lead (Pb), and zinc (Zn) were reduced. The heavy metal removal studies were carried out with the three types of treatment. In the first treatment, spent mushroom bio-compost (SMC) along with organic soil were used for the testing in a ratio of 2:1. Cow dung and organic soil (2:1) were employed for the next treatment, and pure organic soil for the third testing. The heavy metal reduction rate was recorded to be 18% to 50% [83]. Especially treatment with mushroom compost along with the earthworms' bioaccumulation have shown higher order removal of chromium (35%), copper (19%), manganese (15%), lead (50%), nickel (18%), and zinc (19%). Iron and arsenic were greatly reduced by these treatments with spent mushroom bio-compost, cow dung, and organic soil. The reason for the better reduction of heavy metals by the mushroom bio-compost was due to the secretion of enzymes by the mycelium of the fungus. The chloragogen cells of the earthworm detoxify the absorbed heavy metal and neutralise it. On the other hand, lysosomes, a membrane of earthworms, help accumulate metals. These lysosomes released acid hydrolyses when the concentration of heavy metals rose. This breakdown explains the physicochemical alteration leading to death. After the uptake of heavy metals, earthworm life is retained due to the detoxification of metals through metallothionein (a metal-binding protein). A bioaccumulation analysis of heavy metals using *Eisenia foetida and Lampito mauritii* was reported. Lampito mauritii and Esenia foetida were found to have soil layer cadmium uptakes of 0.2571 mg/kg and 0.2610 mg/kg, respectively, in the match industry [84]. Similar to this, Hobbelen et al., [85] have discussed the bioaccumulation of heavy metals in Aporrectodea caliginosa and Lumbricus rubellus earthworms. The amount of the heavy metals, copper, cadmium, and zinc that were present in the soil determined how the study was conducted. The absorption amounts of these metals were analyzed with different sources like soil, pore water, and calcium chloride extracts of soils. The increased cadmium and copper levels and reduced pore water levels demonstrated that the amount of soluble metals impacts the absorption of metals into the earthworms' internal organs. But the heavy metals attached to organic matter and soil also contribute towards the absorption of heavy metals into the internal parts of earthworms [85]. Saxe et al., (2001) [86] had proposed the technique of utilizing body concentrations of *Eisenia Andrei* in the absorption of heavy metals. The parameters included are soluble organic carbon, metals, and pH. Heavy metals like cadmium, copper, and lead are absorbed (>96%) by the dermal exposure of earthworms. Whereas gut exposure was found to be the reason for a zinc earthworm body concentration of 18%. The behaviour of zinc was found to be more accurate when compared with that of other metals under investigation. According to its availability in the soil and the intestine, cadmium uptake by earthworms was experimentally studied by Oste et al., [75]. Metal absorption depends on pH dependent intestinal uptake. Further, the uptake of the contaminants by the earthworm was calculated with the equilibrium partitioning concept. A percentage of concentration of contamination was employed to determine the contaminant percentage in pore water and earthworms' body tissue. In this work, lime and manganese dioxide were used to detect the uptake of cadmium. Manganese dioxide was found to be helpful in removing heavy metals (here cadmium) from pore water without affecting the pH value. Triethanolamine (TEA) extraction was reported to be a useful tool in predicting the cadmium uptake by the tissue of earthworms [87]. Table 2 shows the different species of earthworms and their interactions with heavy metals through various processes.

Table 2: Role of earthworms in the removal of heavy metal

S.No.	Name of the Earthworms	Heavy metals	Name of the samples	Process	References
1	Eudrillus eugineae	Cu, Cd, Cr, Pb and Zn	municipal solid waste	Vermicomposting	[87]
2	Metaphire californica, Amynthas homochaetus, Amynthas pecteniferus, and Amynthas heterochaetus	Cd, Zn, Cu, and Pb	metal-polluted soils in a subtropical area	Bioaccumulation of heavy metals	[71]
3	Eisenia fetida	Arsenic	farm soils	Toxicity and bioaccumulation studies	[88]
4	Metaphire californica	Cd, Cu, Zn, and Pb	metals in earthworm at subcellular levels	subcellular fractions like cytosol, debris, and granules of earthworm studied	[89]
5	Aporrectodea caliginosa	Cd, Pb and Zn	partitioning tissue metal concentration	Toxicological effects of metals on organisms	[90]
6	Eisenia fetida	Cu	copper mine	Bioaccumulation and bioremediation studies	[91]
7	Eisenia fetida	Cd, Pb, Cu, Zn, Ni Cr	Compost samples	Bioaccumulation of heavy metals in the compost samples	[92]

Mohan et al.,

8	Eisenia fetida	Cr, Cd and Pb	Compost samples	vermi-remediation	[93]
9	Eisenia fetida	Cd and Ni	Vermiculture	Metal induced DNA damage	[94]
10	Aporrectodea caliginosa and Lumbricus rubellus	Zn, Cd, Pb and Cu	Pasture polluted by waste from a metallurgic industry	bioaccumulation	[95]
11	Lumbricus rubellus and Aporrectodea caliginosa	Cd, Cu and Zn	field soils	Bioaccumulation of heavy metals	[85]
12	Eisenia fetida	Pb, Ni and Cd	Soil	Bioaugmentation - Metal induced DNA damage with increased enzymatic activities	[96]
13	Pheretima posthuma	Pb and Cd	Soil	Bio-assimilation	[97]
14	Eisenia fetida	Pb and Ni	Soil	Bioaugmentation – enzymatic activities	[98]
15	Eisenia fetida	Zn , Co, Cu, Ni, Mn a nd Cr	Sewage sludge amended soil	Bioaccumulation	[99]
16	Earthworm	Fe and Pb	Industrial Wastewater	Bioaccumulation	[100]
17	Eisenia fetida	Ar	Soil	Bioaccumulation - Oxidative stress	[101]
18	Eisenia andrei	CuO	Soil	Engulf of CuO nanoparticles by immune effector cells of Eisenia andrei	[102]
19	Earthworm	Ni	Soil	Biological refining, bioaccumulation of heavy metal in earthworm's tissue	[103]
20	Eisenia fetida	Ag	Soil	Bioaccumulation – preferably at chloragogen tissue, coelomocytes, and nephridial epithelium of earthworm.	[104]
21	Eisenia andrei	Metals – majorly Cd, Cu and Ni	Wastewater	Oxidative stress	[105]
22	Metaphire posthuma	Cu(II) and Zn(II)	Demonstrated for wastewater treatment (Aqueous Solutions)	Bioflocculation	[106]
23	Eisenia fetida and Eisenia andrei	Cd	For soil and wastewater treatment	Bioaccumulation and detoxification mechanisms	[107]
24	Eisenia andrei	TiO_2	For soil and wastewater treatment	Bioaccumulation	[108]

Mohan et al.,

25	Eisenia fetida	Cd^{2+}, Cr^{2+}, Pb^{2+} and Zn^{2+}	Sewage sludge amended soil	Bioaccumulation	[109]
26	Eisenia fetida	Zn, Pb, and Cd	Soil	Bioaccumulation	[110]
27	Eisenia andrei	Zn	Soil	Bioaccumulation	[111]
28	Eisenia feotida	Zn, Cu, Cd, Pb, Ni and Cr	Sewage sludge	Bioaccumulation	[112]
29	Lampito mauritii	Cd, Cu, Cr, Pb, and Zn	Soil	Bioaccumulation	[113]
30	Eudrilus euginea	Cd	Soil	Bioaccumulation	[114]
31	Alma nilotica	Co, Cd Ni, Pb, and Zn	Soil	Bioaccumulation	[115]
32	Eisenia feotida	Cd	Sewage sludge amended soil	Bioaccumulation	[116]
33	Lumbricus terrestris	Cu, Fe, Pb, Cd and Zn	Soil	Bioaccumulation	[117]

Earthworms and heavy metal metabolism

As we know, copper has been recognized as one of the essential minerals in animal metabolism, especially in haemoglobin and hemocyanin pigments, which activate enzymatic processes [118]. An excess amount of copper is toxic to animals [119], and the copper was noticed in the tissues and excreta of animals [120]. With various copper concentrations, Wenyu Yu [121] reported transcriptomics and metabolomics studies using the earthworm Eisenia fetida. The findings explained the ecological impact of copper on organisms that live in soil and demonstrated the molecular responses of earthworms to stress. Various enzyme activities of the earthworm (*Eisenia fetida),* including glutathione, catalase, and superoxide dismutase, were inhibited by the exposure to copper [122]. Toxicological studies of antioxidant enzyme activity and mRNA synthesis were carried out in the earthworms for histopathological responses [123]. Gene expression data obtained from the RNA-Seq method is considered a high throughput method [124], and this method can provide information related to transcription and gene expression data, which makes it possible to find novel biomarkers [125]. Histidine was increased in the tissues of earthworms with the contamination of soil by copper at a concentration of 160mg/kg of soil [126], and it was noted that the earthworm *Lumbricus rubellus was* found to be affected by the contamination of soil [127]. This approach, initiated by earthworm metabolomic studies, notes their significance as indicator organisms [128]. Disturbance of osmoregulation is studied by metabolomics and oxidative stress by proteomics. The metabolism of carbohydrates was studied for copper toxicity in the earthworm *Lumbricus rubellus* through transcriptomics studies [129]. Moreover, metabolomics profiling of *Eisenia* fetida coelomic fluid, coelomocytes, and tissues is helpful to study the systems toxicology based on NMR (Nuclear Magnetic Resonance), as reported by Griffith et al., [130]. The newly identified known and unknown metabolites were studied based on NMR and MS. This study clearly demonstrated the usefulness of high-field NMR in environmental research [130].

Metals pooled in the soil can be bioaccumulated in the tissues of earthworms, and the bioaccumulation of metal residues is part of an earthworm's life [131]. *Amynthas agrestis* and *Aporrectodea longa*, earthworms observed in the northern and eastern parts of the United States, showed a mortality rate of more than 90% after metal absorption [132–133]. Hodge et al., (2000) [132] found that the bioaccumulation of metals studied in the earthworm residual materials-related mechanism was not clearly understood.

The earthworm species Amynthas agrestis showed higher concentrations of calcium, magnesium, manganese, and copper in their tissues than Lumbricus rubellus. However, both species showed similar amounts of lead.

Amynthas agrestis was significantly releasing more concentrations of calcium, magnesium, manganese, copper, and lead to the soil where the earthworms were dwelling than the earthworm species *Lumbricus rubellus* [134]. The metal concentration of earthworm tissue is based on their preference to take soil and physiological features like the presence of calciferous glands in the earthworms belonging to the earthworm family *Lumbricidae* [135].

Emissions from Agricultural Production

Greenhouse gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are produced as a result of agricultural input. Like CO_2, methane and nitrous oxide both contribute to the rise in global temperatures. Eventually, CO_2 taken in from the atmosphere during photosynthesis will also be converted to sugar and released back into the atmosphere. Global warming may be significantly impacted by even minor changes in land use practices that affect the soil and methods of cultivation. Large amounts of CO_2 and N_2O can be released during the conversion of forest land to agricultural use and the cultivation of crops high in carbon. In addition to the production methods, agriculture uses more energy, primarily fossil fuels, and produces more CO_2 emissions. By producing energy from biomass, this can be avoided. Direct application of animal manure and crop residues to agricultural fields raises the carbon content of the soil. Methane is being released by the anaerobic decomposition of organic material. Animal digestive systems or ecosystems that have absorbed enough water may be to blame. Farm animals are the highest source of methane in agriculture during their digestion. Storage of manure in the agricultural field can form more methane. Manure storage can be minimized by the treatment of manure in biogas plants, which has reduced greenhouse gas emissions.

It has been discovered that nitrous oxide can be produced through the nitrification of ammonium to nitrate or the denitrification of nitrate to dinitrogen. The availability of mineral nitrogen in the soil affects the formation of nitrous oxide in both scenarios. Numerous soil factors, including a high soil water content, the presence of anaerobic conditions, a large amount of organic substance, and the soil's pH, have an impact on the bacterial nitrogen cycle. By avoiding excessive nitrogen fertilization and minimising ammonia and nitrate leaching and volatilization losses, nitrous oxide emissions can be decreased. Nitrous oxide emissions can be effectively decreased by increasing soil aeration. Globally, agricultural CH_4 and N_2O emissions rose by over 17% between 1990 and 2005, with average annual emission increases roughly 60 Mt CO_2-eq/yr [136]. A significant amount of greenhouse gases come from the production of livestock.

Food consumption and impacts on climate

The consumption of food, beverages, tobacco, and other stimulants accounts for 21-31% of all greenhouse gas emissions in Europe, according to Lake et al., [137] reports on food and climate change. Food products, including meat and dairy products have the biggest impact on the climate. According to Weber and Matthews [138], only 11% of greenhouse gas (GHG) emissions are related to transporting food, while 83% are related to the production phase. According to Stern [139], the production of fertilizer accounts for 38% of all agricultural greenhouse gas emissions worldwide. The next largest category, livestock, accounted for 31%, primarily as a result of enteric fermentation by ruminants. Rice farming in wetlands contributed 11% to emissions, which were then followed by manure management at 7%. According to the Food and Agricultural Organization (FAO), deforestation for grazing and the production of animal feed may account for up to 18% of all greenhouse gas emissions globally [140]. In order to address the severe lack of resources for people, sustainability is dependent on two key elements: water and energy [141].

Environmental Impact of Organic Farming

Both conventional farming and organic farming produce greenhouse gas emissions. This has an impact on both the carbon content of the soil and the methane and nitrous oxide emissions the soil produces. The greenhouse gas emissions from organic and conventional farming have been compared in a number of studies. While organic and conventional systems produced different amounts of emissions, the majority of studies showed that emissions from organic systems were lower. Nitrogen supply to crops and soil organic matter turnover are both enhanced by organic farming. Organic farming will have a largely favorable impact on greenhouse gas emissions. [142].

The benefits of organic farming over conventional systems include: a) Avoiding the usage of chemical fertilizers, growth hormones, and pesticides that result in minimum energy consumption; b) cultivating legume crops that increase biological nitrogen fixation that reduces nitrous oxide emissions c) More green manure crops can be cultivated; d) Soil structure can be improved during organic farming, which reduces nitrous oxide emissions. A review of the literature shows that research work has been conducted within organic farming and was recommended to decrease emissions of greenhouse gas. For this to happen it is necessary to feel the complete organic farming management. Growing perennial nitrogen-fixing plants for bioenergy and using anaerobic digestion to create biogas and improve the quality of manures are just two examples of the many ways organic farming systems can be made more climate-friendly. Mohan et al., [143] experimentally proved the potential of organic cultivation using *Rhizobium* and Farm Yard Manure as Soil Supplements improved the growth and yield of *Glycine max* during the field application studies.

Composting and Climatic change

Amlinger et al., [144] reported that many kinds of gases are being released into the atmosphere during composting, viz., CO_2, NH_3, CH_4, Volatile Organic Compounds (VOCs), and N_2O. Carbon dioxide was a significant gas that got released during aerobic composting. CO_2 have shown greater potential to cause global warming—34 times and 298 times more potent than emissions of methane and nitrous oxide, respectively [145].

Different kinds of organic molecules are observed in the waste mixtures utilized for composting. Microorganisms are employed in the degradation of these organic wastes. Compounds that degrade slowly include lignin, cellulose, and hemicellulose. Sequestered carbon might be viewed as an enduring carbon sink when the finished fertilizer is applied as manure or a soil conditioner. The amount of carbon from applied compost that is retained in soil over a 100-year period, ranging 2 % - 16% relying on volume of lignin found in the waste. In alkaline pH conditions, high temperatures facilitate the decomposition of lignin and cellulose during the composting process [146]. Long-term storage and composting further degrade lignin, lowering the amount of carbon that might otherwise be stored in the soil.

Direct emissions of N_2O from nitrification and denitrification processes may continue during the curing phase of composting and during the prolonged storage of the finished compost, and reduced airflow because of compaction brought on by the decomposition of structural amendments may increase CH4 emissions [147]. Even though these emissions have been said to be lower than those that occur during the active stage of composting [148], they could nevertheless increase noticeably if the mature compost includes a lot of nitrogen or enters anaerobic conditions. Additional CH_4 and N_2O emissions can be expected when the completed compost is held prior to use, per a number of studies [149]. Nevertheless, these emissions only account for a small percentage of the total greenhouse gas emissions from the full life cycle of waste in a treatment system, including composting, provided that the storage time is not excessively long. Therefore, the overall amount of direct greenhouse gas emissions from composting can be decreased by eliminating a drawn-out drying phase and long storage of finished compost.

CONCLUSION

The impact of earthworms on the organic market and soil fertility demonstrates the importance of improving soil fertility and the efficacy of agricultural practices for improving the long-term circumstances of small-scale producers and their terms of trade. Earthworm-based agro-ecosystems can enable the amelioration of soil to help farmers, thus reducing the need for expensive chemical fertilization and synthetic agricultural inputs. The formation of the organic network engineered by the worms can increase the yield of agro-products in a healthier way. Microbial enzymes play a vital role in nutrient cycling in the environment. Waste water can be treated efficiently by the enzymes; particularly, the earthworm's gut contains a variety of microorganisms that consistently release the enzymes. The microbial enzymes released from the gut of earthworms naturally disintegrate the complex waste molecules in the waste water. The aerobic environment created by the novel trickling filter method combined with the vermifiltration process. This envisages the important feature of providing a natural aerobic atmosphere around the waste water treatment area by providing optimum HLR and HRT for the survival of earthworms and the liberation of microbial enzymes in the area where the waste water treatment process occurred. Earthworms play an imperative engineering role in efficient waste water treatment, reduction of organic waste, and the enhancement of the filtrate quality that is depleted from the filtration unit. This creates a strong foundation to find solutions to ensure a sustainable goal and climatic change mitigation to limit the temperature to 1.5. The present effort strongly influences the scientific community to nurture the importance of sustainable development. The important ecological role played by the tiny organism earthworm and its humble service to the mother earth and ecological balance. A holistic approach is the need of the hour to manage the menace of waste water stagnation and to find novel methods like trickling filter based vermifiltration that create aerobic amelioration of waste water into biologically treated water for a sustainable future.

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