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Title

Concentrated Greywater Treatment by Vermifiltration for Sub-Saharan Urban Poor

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JURY

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Laboratory for Water, Decontamination, Ecosystem and Health (LEDES)

Dedication

To my beloved parents: My father Tiruneh Adugna and my mother Yanbel Teshome

To my sisters and brothers

To my dear friends

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Amare Tiruneh Adugna,
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Abstract

Concentrated greywater generated from sub-Saharan urban poor is a problem when disposed of the street or other open spaces without any treatment. It is the main cause of environmental pollution and a health risk for the community. To alleviate the problem, on-site (decentralized) treatment options which are economically, socially and environmentally accepted are needed. In this research, a laboratory scale vermifilter model is studied to treat concentrated greywater generated from urban poor. A batch supply system was used in the experimental design to investigate necessary conditions for proper functioning of the vermifiltration system for hot climate areas. The 200 mm diameter PVC pipe filters were filled with fine sawdust, sand, and gravel. The vermifilters were inoculated with the locally available earthworm, *Eudrilus eugeniae,* to make a comparison with the control unit. The aim of the study was to investigate the potential of the vermifiltration technology as a treatment method for concentrated greywater generated from the sub-Saharan urban poor specifically in hot climatic areas. The study was designed to provide answers to the research questions: Can vermifiltration be another sanitation option for the sub-Saharan urban poor? Are the locally available earthworms good enough for vermifiltration? Do the layer thickness (fine sawdust and sand) composition have an effect on? Which microorganisms are working together with the earthworms? Is the behavior of the filter materials changed during vermifiltration process? The important design criteria: hydraulic loading rate and the temperature effect were investigated. The performance of the system was assessed by the removal efficiencies of pollution measured with some physico-chemical parameters (tCOD, dCOD, BOD_5, TSS, DO, VS, pH and temperature), nutrients (NH_4^+, NO_3^-, NO_2^-, and PO_4^{3-}) and coliforms. Considering the various parameters evaluated, a hydraulic loading rate of 64 $L.m^{-2}.d^{-1}$ (16 $L.m^{-2}.d^{-1}$/batch*four batches per day) gave a better performance. In all experiments, average removal efficiencies were > 90% for BOD_5 and TSS, 80%-90% for COD, 60%-70% for NH_4^+, 40%-50% for NO_3^- , 50%-60% for NO_2^- and PO_4^{3-}, and 1-4 log units for coliforms. It can be concluded from the results that the model system on the laboratory scale can successfully be applied to a pilot-scale when the environmental conditions are similar to this study. For efficient vermifiltration, the hydraulic loading rate should be at least 64 $L.m^{-2}.d^{-1}$, but below 191 $L.m^{-2}.d^{-1}$. Overall, this thesis demonstrate that, vermifiltration can be another sanitation option to treat concentrated greywater for the sub-Saharan urban poor.

Keywords: Batch system; *Eudrilus eugeniae;* Greywater; Vermifiltration

Résumé

Les eaux grises concentrées, générées par les populations pauvres en milieu urbain en zone sub-saharienne constituent un problème de sante public lorsqu'elles sont déversée dans les rues ou autres espaces publics sans traitement. Les eaux grises concentré sont l'une des principales causes de la pollution environnementale et constituent un risque sanitaire pour la communauté. Des options locales de traitement, économiquement, socialement et environnementalement acceptées sont nécessaires pour réduire ce risque. Dans cette recherche, modèle de la vermifiltration qui est une technique utilise sur le site de 2iE pour traiter l'eau grise concentrée générée par les populations pauvres en milieu urbain à Ouagadougou. Les conditions de fonctionnement adéquat du système de vermifiltration dans les zones chaudes ont été déterminées par un système d'approvisionnement par batch expérimental sélectionné. Les filtres en PVC de diamètre 200 mm ont été remplis de sciure de bois, de sable et de gravier dans le cadre de cette étude. Les vers de terre localement disponibles tels qu'*Eudrilus eugeniae* sont inoculés dans les vermifiltres à des fins de comparaison avec l'unité de contrôle. L'objectif de cette étude est d'examiner la faisabilité de la technologie de vermifiltration en tant que méthode de traitement de l'eau grise concentrée générée par les populations pauvres en zone sub-saharienne spécifiquement en climat chaud. Cela a été fait à travers l'étude de la contribution des vers de terre localement disponibles par comparaison avec l'unité de contrôle (sans vers de terre). Différentes charges hydrauliques, ont été testées l'objectivé e'étude est de fournir des réponses aux questions suivant : La vermifiltration peut elle être une technologie d'assainissement pour les pauvres des villes sub-saharienne ? Les vers de terre disponibles localement peuvent aider à l'élimination des polluants ? L'épaisseur et la composition de couche de matériaux filtrant (sciure fine et sable) composant le substrat ont elles un effet sur le treatment ? Le comportement des matériaux filtrant va-t-il changer durant le processes de vermifiltration ? Quels micro-organismes travaillent de concert avec les vers de terre ? Les critères importantes de conception : charge hydraulique et l'effet de la température environnementale ont été évalues. La performance du système a été évaluée par l'efficacité de l'abattement de la pollution measurables à partir des paramètres physico-chimiques (DCOt, DCOd, DBO_5, MES, OD, VS, pH and température), de la teneur en nutriments (NH_4^+, NO_3^-, NO_2^-, and PO_4^{3-}), et de la population de coliformes. Les colonnes de PVC sont ravitailles en batch. Considérant les divers paramètres évalués, une charge hydraulique de 0.5L/batch (quatre par jour) donne une meilleure performance. Dans toutes les expériences, des rendements d'élimination moyenne était > 90% pour DBO_5 et les MES, 80%-90% pour DCO, 60%-70% pour NH_4^+, 40%-50% pour NO_3^-, 50%-60% pour NO_2^- et PO_4^{3-}, et 1-4 U log pour les coliformes.

Des résultats obtenus, on peut conclure que le système de experimental peut être appliqué avec succès à sur le terrain quand les conditions environnementales sont similaires à celles de l’étude. Une vermifiltration efficace exige une charge hydraulique d’au moins 64 L.m^{-2}.j^{-1} mais en dessous de 191 L.m^{-2}.j^{-1} et de l’ombre. Globalement, cette thèse montre que la vermifiltration peut être une alternative en matière d’assainissement pour traiter les eaux grises concentrée au profit des populations pauvres en zone sub-saharienne.

Mots-clés: Eau grise ; *Eudrilus eugeni*ae; Système d’approvisionnement par batch; Vermifiltration

List of Publications

I. Original Published Papers:

- Adugna, A. T., Andrianisa H. A., Konate Y., Ndiaye, A., Maiga, A. H. 2014. Greywater treatment by vermifiltration for sub-Saharan urban poor. *Journal of Water, Sanitation and Hygiene for Development*, 4(4), 625-632. DOI: 10.2166/washdev.021.
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- Adugna, A. T., Andrianisa H. A., Konate Y., Ndiaye, A., Maiga, A. H. 2015. "Performance comparison of sand and fine sawdust vermifilters in treating concentrated greywater for urban poor." *Environmental Technology,* 36(21), 2763-2769, DOI: 10. 1080 /09593330.2015. 1046951.
  Available at: http://dx.doi.org/10.1080/09593330.2015.1046951

II. Papers under preparation:

- Adugna A. T., Andrianisa, H. A., Konate Y., Ndiaye, A., Maiga, A. H. Pollutant removal mechanisms in the vermifiltration system: Filter medium layer contributions.
- Adugna A. T., Andrianisa, H. A., Konate Y., Ndiaye, A., Maiga, A. H. Fate of filter materials, identification of microbial communities, and the influent and effluent flow patterns in the vermifiltration process.

III. Conference Papers (Oral Presentations):

- Adugna A. T., Andrianisa, H. A., Konate Y., Ndiaye, A., Maiga, A. H.. Concentrated greywater treatment by vermifiltration for the sub-Saharan urban poor during the 2iE 7th Edition Scientific Days, an international conference held in Ouagadougou, Burkina Faso on April 1-5, 2013.
- Adugna A. T., Andrianisa, H. A., Konate Y., Ndiaye, A., Maiga, A. H. Greywater treatment by vermifiltration for sub Saharan urban poor 3rd IWA Development Congress & Exhibition from14-17 October 2013, Nairobi, Kenya.
- Adugna A. T., Andrianisa, H. A., Konate Y., Ndiaye, A., Maiga, A. H. Greywater treatment by vermifiltration for sub-Saharan. 17th African water association congress from17-20 February 2014, Abidjan, Côte d'Ivoire.
- Adugna A. T., Andrianisa, H. A., Konate Y., Ndiaye, A., Maiga, A. H. Effects of filter media layer composition and depth on greywater treatment by vermifiltration. 9th IWA International Symposium on Waste Management Problems in Agro Industries from 24-26 November 2014, Kochi, Japan.

Résumé Substantiel en Français

Traitement des Eaux Grises Concentrées par Vermifiltration pour les Pauvres Urbains Subsahariens

Introduction

L'assainissement est important dans la sauvegarde de la santé et le bien-être de l'espèce humaine (Cairncross, 2003; Moe et Rheingans, 2006). L’assainissement adéquat est l'accès à l'assainissement qui est commode pour tous les membres du ménage, abordables, et qui élimine le contact avec les excréments humains et d'autres eaux usées (ONU-Habitat, 2003).

Il y’a eu des acquis considérable sur l'approvisionnement en eau potable, mais les problèmes des excréments et évacuation des eaux usées ont reçu moins d'attention. Le monde a rencontré les OMD pour l'eau potable en fin d’année 2011 (OMS, 2012), mais la cible pour l'assainissement n'a pas été atteinte. Actuellement, plus de 90 pour cent de la population mondiale ont accès à des sources améliorées d'eau potable, et 2,4 milliards sont sans accès à des installations sanitaires améliorées (OMS/UNICEF, 2015). La majorité des gens, qui manquent les installations d'assainissement améliorées sont des pays en développement, en particulier l'Afrique sub-saharienne et en Asie du Sud-Est.

En 2030, la population mondiale devrait atteindre 8,5 milliards (ONU, 2015) et la population de l’africaine subsaharienne à croître à 1,3 milliard (Velkoff et Kowal, 2007). Outre la croissance de la population, le taux annuel de l'urbanisation et de la formation de bidonvilles en Afrique est de 4,6 et 4% (Otiso, 2003). Dans les pays d'Afrique sub-saharienne, de la population urbaine totale, 62% vit dans les bidonvilles (ONU-Habitat 2008, 2009). La croissance démographique élevée dans les bidonvilles des zones urbaines est, non seulement en raison de la natalité, mais aussi la migration des zones rurales pour la recherche d'une vie meilleure.

Les eaux usées municipales générées par une communauté sont estimées à environ 80% de l'eau totale fournie pour la consommation (Metcalf et Eddy, 2003). L’eaux grise, composante majeure des eaux usées domestiques, est habituellement générée à partir de la vaisselle, des douches, des lavabos, et une buanderie. On estime que 50-80% des eaux usées des ménages sont des eaux grises (Al-Jayyous *et al.*, 2003; Christova-Boal *et al.*, 1996). Le déversement incontrôlé des eaux grises dans les rues et les espaces ouverts conduit à une détérioration de la rue, les flambées de maladies et les problèmes d'odeurs (Morel et Diener, 2006). En outre, les sources d'eau et les sols sont contaminés par des agents pathogènes, des nutriments et micro-polluants (Katukiza *et al.*, 2013; Nyenje *et al.*, 2013) et les maladies dues au rejet des eaux usées sont causées par des virus entériques, les bactéries et les protozoaires (Carr, 2001; Jaykus, 1997; Ashbolt, 2004; Montgomery et Elimelech, 2007).

Les options existantes d'assainissement à faible coût ne peuvent pas résoudre les problèmes de des eaux usées dans les pays triés pauvres. Par exemple, les filtres à sable intermittents ont été une option rentable pour traiter les eaux usées domestiques et industrielles mais le colmatage est le problème le plus fréquent (Netter, 1992; Healy *et al*., 2004). Les lagunes nécessitent aussi de grandes superficies de terres et un système d'égout (Pattarkine *et al*., 2006). La fosse septique a une faible efficacité de traitement et émet des mauvaises odeurs (Imhof *et al*., 2005). Par conséquent, il est nécessaire de développer des technologies à coût relativement faible avec une faible consommation d'énergie qui nécessitent peu d'entretien et respectueux de l'environnement. La vermifiltration est une alternative, notamment dans les pays en développement, car il nécessite moins d'espace par rapport à d'autres technologies décentralisées de traitement écologique des eaux usées (Xing *et al*., 2010). Beaucoup de recherches ont été menées en Chine, en Inde, en Australie, en France et dans d'autres pays sur la vermifiltration pour traiter les eaux usées domestiques. Cependant, peu d'efforts ont été faits pour l'utiliser à des petites et moyennes échelles (Kharwade et Khedikar, 2011; Li *et al*., 2009; Taylor *et al*., 2003).

Dans le processus de la vermifiltration, les polluants ont été éliminés grâce à la contribution des matériaux de litière, les médias filtrants, les lombrics et les communautés microbiennes (Li *et al.,* 2009; Zhao *et al*., 2010; Taylor *et al*. 2003; Wang *et al*., 2014). La performance dépend de la charge hydraulique (CH), du pH des eaux usées brutes, et de la température de l'environnement. La croissance des vers de terre est meilleure dans la gamme de température de 25-30°C mais au-dessus de 35°C ils meurent (Dominguez *et al*., 2011). Dans une étude de Pour l'expérience VF menée à Shanghai, le TCH a été augmentée pour maintenir la température en dessous de 35°C à l'intérieur du filtre pour éviter la mort des vers de terre (Li *et al*., 2009).

Il a été rapporté que est plus influente dans la production de la biomasse et le taux de croissance on poids des vers tandis que de la sciure de bois est meilleure pour la formation les cocons et la croissance ou nombre de la production de vers de terre (Manaf *et al*., 2009). En ce qui concerne les raté iut filtrants, l'argile, le sable, la sciure de bois grossier et le gravier ont été largement testés avec des profondeurs et compositions différentes (Kharwade et Khedikar, 2011; Li *et al*., 2009; Taylor *et al*., 2003). Les espèces majeures de lombric recommandées pour cette technologie sont les vers du fumier. *Eisenia andrei, Lumbricus rubellus, Perionyx excavatus* et *Eudrilus eugeniae* (Graff, 1998).

Des filtres avec différentes compositions ont également été testés. Par exemple, Li *et al*. (2009) ont utilisé un mélange de farine de bois précieux, de paillettes et de gazon en surface lit filtrant comme litière, farine de bois grossie et paille comme couche intermédiaire et du sable fin et grossier au pond. Kharwade et Khedikar (2011) ont testé un système avec le sol, sable et gravier de haut en bas. Un matériau de lit composé de sols et de sciure de bois dans la partie supérieure, et pavés en bas a été utilisé par Wang *et al.* (2014) pour étudier l'effet de la hauteur de vermifiltre. Wang et al. (2010) ont utilisé une pastille céramique comme support de filtre dans le vermifiltre. Taylor *et al.* (2003) ont étudié l'élimination de certains paramètres dans les filtres remplis de déchets organiques solides et d'autres médias.

Dans leur recherche, Kharwade et Khedikar (2011) ont constaté que l'utilisation d'*Eudrilus eugeniae* sur un système de filtration augmente l'efficacité globale de l'élimination de la DBO_5, DCO et MES en moyenne de 10% en 2-3h du temps de rétention. Le vermifiltre a été rempli avec 4 cm de gravier de 20 mm de taille, 3 cm de gravier moyen de taille 10 mm, 3 cm de sable et 12 cm de sol du bas vers le haut, respectivement.

Selon l'objectif expérimental, de nombreux matériaux ont été choisis en tant que matériau de filtration. Par exemple, Arora *et al*. (2014) ont constaté que le matériau de lit de la rivière et des boules de boue étaient mieux pour l'élimination des pathogènes. Wang *et al.* (2010) ont également signalé que le convertisseur scories-charbon du filtre à cendre a joué un rôle important dans l'élimination du phosphore. En outre, les déchets organiques domestiques (Taylor *et al*. 2003; Bajsa *et al*. 2003), le gravier, le sable, le sol et les copeaux de bois, l'écorce, la tourbe ainsi que la paille (Li *et al*., 2008 ; Sinha *et al*. 2008) ont été jugés performants pour l'élimination de la matière organique et des nutriments à différents niveaux.

Cependant, tous les matériaux filtrants ont une durée de vie limitée (Kropf *et al*., 1977). Par exemple, (Dalahmeh *et al*., 2011) ont découvert que les filtres avec de l'écorce et les copeaux de bois en paillis mixte ont montré une grande durabilité alors que le compost et la paille de blé étaient moins durables. Luth (2011) a également changé la sciure de bois tous les six mois dans le processus de traitement des eaux usées porcines. Dans notre recherche précédente (chapitre 5), il est rapporté qu'il y avait 40% de rétrécissement du lit filtrant dans le processus de vermifiltration menée pendant six mois. En règle générale, il y avait des modifications biologiques, chimiques et physiques sur le matériau de filtre pendant le processus de vermifiltration. La sciure et les déchets solides organiques ont été dégradés et réduits en volume et en teneur en éléments nutritifs avec le temps (Taylor *et al.*, 2003; Adugna *et al.*, 2015). Comme résultat, il a été nécessaire d'ajouter de nouveaux matériaux pour permettre le fonctionnement du système durant la période supplémentaire.

Cependant, autant que la vermifiltration pour traiter les eaux usées domestiques sont concernée, aucune recherche spécifique n'a été faite dans les pays subsahariens, en particulier dans la zone sahélienne.

Objectifs et portée de la recherche:

L'objectif général de cette recherche est de développer un modèle de technologie de vermifiltration à l'échelle de laboratoire et d'étudier son potentiel dans le traitement des eaux grises concentrées, générées par des familles modestes en milieu urbain, en particulier dans la région du Sahel.

Les objectifs spécifiques de la recherche de doctorat étaient de:

- Étudier la faisabilité de la technologie de vermifiltration comme une méthode de traitement des eaux grises concentrées produites par des familles pauvres modestes en milieu urbain dans les pays d'Afrique sub-saharienne, en particulier dans la zone sahélienne en développant un modèle à échelle du laboratoire.
- Étudier les performances des vermifiltres à sable et sciure, a différentes profondeurs selon les compositions, dans le traitement des eaux grises concentrées en milieu urbain pauvres.
- Étudier le rôle les couches du milieu vermifiltrant sur l'élimination des pollutants, i.e MES, tCOD, DO, pH, dCOD, NH_4^+, NO_3^-, NO_2^-, et PO_4^{3-} d'eaux grises.
- Etudier matériaux filtrants, communautés microbiennes, et le schéma d'écoulement de l'influent et de l'effluent dans le processus de vermifiltration.

Matériels et méthodes:

Dans nos tests nous avons utilité, des matériaux disponibles localement et à moindre coût ont été comme matériaux de litière (sciure de bois et la bouse de vache), les médias de filtre (sciure de bois, sable et gravier), des jerrycans et des tuyaux en PVC 200 mm de diamètre. Les vers de terre sont ceux qui sont trouvés localement. Les vers de terre ont été identifiés comme *Eudrilus eugeniae* aussi connu comme les lombrics africains. L'eau grise quotidienne recueillie dans un récipient en plastique de 60 L à partir d'un ménage pauvre urbaine à proximité du site de recherche.

Analyse des différents paramètres:

Méthodes d'analyse physico-chimique

DBO_5, DCOt, DCOd, MES, VS et FS ont été analysés selon la méthode standard (APHA, 1998). Les échantillons ont été filtrés à l'aide du filtre Whiteman GF/C de 0.45µm de porosité pour l'analyse de la DCO et de MES. Le pH a été mesuré avec un pH-mètre portable (WTW 3310) et la température avec un thermomètre digital (HI 93522 HANNA).

Méthodes d'analyse microbiologiques pour le composant liquide

Escherichia coli et coliformes thermotolérants ont été utilisés comme des bactéries indicatrices pour l'évaluation de la pollution microbiologique. La méthode de la plaque de propagation a été utilisée après une dilution appropriée des échantillons conformément à la procédure décrite dans la méthode standard pour l'examen des eaux et eaux usées. Chromocult Agar (Merck KGaA 64271 Darmstadt, Allemagne) a été utilisé comme milieu de culture.

Méthodes d'analyse des éléments nutritifs

L' analyse des éléments nutritifs a été faite pour l'ammonium, les nitrates, les nitrites et les phosphates utilisant le spectrophotomètre HACH DR/2000 à lecture directe dont les longueurs d'onde d'absorption sont respectivement 425 nm, 500 nm, 585 nm et 880 nm après ajout des réactifs correspondant aux échantillons pour chacun des paramètres: NH_4^+ a été analysé avec (réactif Nessler), NO_3^- (réactif Nitra Ver), NO_2^- (réactif Niter Ver) et PO_4^{3-} (réactif Phos Ver).

Méthodes d'analyse chimique des biosolides

Les boues accumulées au fond du vermifiltre a été analysé pour les paramètres de qualité chimiques par dilution des échantillons avec de l'eau distillée à 1:20 poids à rapport volumétrique et en agitant au moyen d'un Edmund Bühler GmbH SM-30 agitateur à 200 tpm (tours par minute) pendant 1 h. Ensuite, les échantillons ont été filtrés à l'aide du filtre Whiteman GF/C de 0,45 µm de porosité et analysés pour les concentrations de carbonate, de bicarbonate de calcium et de magnésium et après la détermination de l'alcalinité totale de la phénolphtaléine en titrant avec de l'acide sulfurique utilisant de la phénolphtaléine et l'orange de méthyle comme indicateurs respectivement. Enfin, les échantillons ont été analysés pour le silicate (silice, RH, silico molybdate méthode), les phosphates (Phos Ver 3 méthode), les sulfates (sulfamides Ver méthode), et les concentrations de tensioactifs utilisant l'extraction comme première étape et suivies par la caractérisation en utilisant des méthodes colorimétriques (HACH Procédure, 1998). L’azote Kjeldahl a été déterminé par la méthode de Kjeldahl. Les échantillons ont été filtrés à travers un GF/C 0.45 µm, filtre et dilués sur la base de l'exigence et mélangés respectivement avec le bon réactif.

Méthodes d'analyse de vers de terre

À la fin de l'expérience, les vers de terre ont été comptés, pesés. Les cocons ont également été comptés pour comprendre la dynamique de vers de terre après le tri à la main. Les vers de terre ont été pesés après lavage à l'eau distillée et séchés avec du papier de serviette.

Méthodes d'analyse microbiologiques pour les composants biosolides

La quantification de la population bactérienne dans la matière support du lit (sciure de bois) a été déterminée après la collecte des échantillons de 10 cm d'épaisseur sur la couche supérieure (chapitre 5). En outre, des échantillons de biosolides ont été prélevés six points de prélèvement des trois vermifiltres et une unité de contrôle (chapitre 6). Un gramme d'échantillon a été prélevé à chaque point des filtres d'échantillonnage et dilué dans 9 ml d'eau stérile et mélangé au vortex. Les dilutions ont été faites jusqu'à 15 fois et l'échantillon de 1 ml a été étalé sur la boîte de Pétri et mise en autoclave. Il a été analysé en utilisant la méthode de la plaque de diffusion avec de l'agar nutritif, gélose au sang, la gélose MacConkey et VRBG gélose pour les bactéries, et le dextrose gélose de Sabouraud pour les actinomycètes et les champignons. L’incubation a lieu pendant 18-24h à 37°C pour les bactéries et les actinomycètes, et de 5 à 7 jours à 30°C pour les champignons.

Les différentes unités formant des colonies (UFC) de développement sur le support ont été estimées et exprimées en CFU x 10^4 g^{-1} (pour les champignons), CFU x 10^6 g^{-1} (pour les bactéries) et CFU x 10^5 g^{-1} (actinomycètes) respectivement selon le procédé de Baron *et al.* (1994).

Résultats et discussion

La faisabilité du traitement des eaux grises concentré par vermifiltration pour les populations urbaines à faible revenus en zone sub-sahariens

Comparaison des performances de la vermifiltration de à l'unité de contrôle

Les rendements d'élimination moyenne de DBO_5, DCO, MES, *E. coli* et TTC au TCH de 191 $L.m^{-2}.j^{-1}$ étaient de 71%, 62%, 91%, 0,95 U log et 0,98 U log pour le vermifiltre, respectivement, et 59%, 56%, 85%, 0,93 U log et 0,90 U log, respectivement, pour l'unité de contrôle. À un TCH de 64 $L.m^{-2}.j^{-1}$, les efficacités d'élimination des mêmes paramètres étaient de 96%, 74%, 97%, 1,77 U log et 1,54 U log, respectivement pour le vermifiltre, et 93%, 66%, 94%, à 1,47 U log et 1,22 U log, respectivement pour l'unité de contrôle. L'efficacité d'élimination de chaque paramètre est légèrement plus importante lorsque le système a été alimenté avec TCH plus faible.

Dans leur étude, Li *et al*. (2009) et Kharwade et Khedikar (2011) ont rapporté que les efficacités d'élimination de la DBO_5, DCO et MES étaient de 90,6%, 86,8%, 94,7% et 90%, 77%, 75%, respectivement, dans le vermifiltre pour les deux recherches. Les résultats étaient légèrement différents du nôtre, ce qui pourrait être due à la différence dans les matériaux de litière, les espèces de vers de terre, la charge hydraulique et le type, la température et les caractéristiques des eaux usées.

Il n'y avait pas de différences significatives entre la vermifiltre et l'unité contrôle à l'exception de la DBO_5 et les MES quand on les compare en termes de concentrations des effluents et de l'efficacité de la suppression de 191 $L.m^{-2}.j^{-1}$. Pour 64 $L.m^{-2}.j^{-1}$, les MES et *E. coli* ont des différences significatives pour les deux concentrations des effluents et des rendements d'élimination. En termes de différences statistiques entre les vermifiltres pour TCH de 191 $L.m^{-2}.j^{-1}$ et 64 $L.m^{-2}.j^{-1}$, tous les rendements d'élimination sont significativement différents et à l'exception de la DCO et TTC pour la concentration de l'effluent. Par conséquent, plus le TCH n'est faible, meilleurs étaient les rendements d'épuration. La charge TCH de 64 $L.m^{-2}.j^{-1}$ a été retenue pour l'expérience suivante.

Outre le fait que les rendements d'élimination de la pollution sont meilleurs, les conditions à l'intérieur du vermifiltre ont été significativement améliorées par rapport à l'unité de contrôle. Le vermifiltre infiltre les eaux grises fourni dans les 1-3 minutes, mais l'unité de contrôle prend plus de temps que le test en raison de l'apparition de colmatage à mi-parcours durant la période d'essai. En outre, le matériau de la literie a été enrichi en matière organique potentiellement réutilisables en agriculture.

Comparaison des performances de sable et de sciure de bois en vermifiltres bois fines, avec différentes profondeurs et de la composition, dans le traitement des eaux grises concentré pour populations urbaine a faible revenus

Comparaison de performance de trois vermifiltres et entre l'unité contrôle

Les concentrations résiduelles moyennes de DBO_5, DCOt, DCOd et MES en sotie de vermifilters F1, F2 et F3 étaient toujours nettement inférieures durant le test à celles de l'unité de contrôle. Cependant, il n'y avait pas de différence significative *d'E. coli* et des concentrations résiduelles TTC (P > 0,05) entre F1, F3 et le contrôle, qui étaient inférieures à celles de F2. Les rendements d'élimination de la DBO_5 étaient de 96%, 93%, 96% et 62%; ceux de l'DCOt étaient de 84%, 83%, 80% et 55%; ceux de DCOd étaient de 90%, 87%, 85% et 63%; et ceux de TSS sont 98%, 98%, 99% et 97% en F1, F2, F3 et F4, respectivement. Les rendements d'élimination DCOt et DCOd présentent la même tendance.

Statistiquement, il n'y avait pas de différence significative entre les vermifiltres (p > 0,05) pour les concentrations résiduelles et les rendements d'élimination de la pollution organique, sauf pour DCOd. Cependant, les efficacités d'élimination de la DBO_5 et DCOt dans les vermifiltres étaient en moyenne 30% plus élevés que ceux du contrôle, alors que l'efficacité d'élimination de DCOd est en moyenne de 25% plus élevée. Les résultats pour la DBO_5 et DCOt de vermifiltres sont comparables aux résultats rapportés par Sinha *et al.* (2008) qui a effectué des essais à court terme dans un vermifiltre à l'échelle du laboratoire. L'unité de contrôle s'est également bien comportée dans l'élimination de MES, *E. coli*, et TTC. Les mécanismes d'élimination pourraient être dus à des activités microbiennes, l'adsorption et l'accumulation par l'ensemble du milieu de filtration, tel que rapportée par Sinha *et al.* (2007), Kharwade et Khedikar (2011), et Li *et al*. (2009). En outre, les effluents de F2 et F3 ont pu contenir des produits de dégradation de la sciure de bois soluble, ce qui pourrait expliquer les concentrations plus élevées de DBO_5 et DCOt résiduel dans F2 et F3 par rapport à celle de F1.

Evaluation des vers de terre

Durant la première semaine de l'expérience, les vers de terre présentaient une perte de poids, bobinage, région clitellum gonfle et certains décès qui pourraient être dus à la phase d'acclimatation des vers de terre à leur nouvel environnement. Le nombre de décès en F1, F2 et F3 était de 7, 6 et 7 représentants des taux respectifs de 3.5%, 3% et 3.5%. Cependant, quelques semaines après, les vers de terre ont dégradé la sciure fine avec les solides adsorbés des eaux grises et réduisant relativement le matériau de litière en taille et en forme plus petites que celles de l'unité de contrôle. Un constat similaire a été rapporté par Kharwade et Khedikar (2009). Les vers de terre sont riches en différents types d'enzymes et les communautés microbiennes qui peuvent aider à la biodégradation de la sciure de bois (Wolter *et al.*, 1999). Il a été observé une diminution de litière en hauteur dans chacun des trois vermifiltres tandis qu'une petite augmentation a été observée dans l'unité de contrôle en raison de l'accumulation de matières solides inorganiques et organiques mal dégradées des eaux grises.

Il y avait plus de vers de terre matures dans F2 que dans F1 et F3. Le nombre de vers de terre matures a augmenté de 14%, 56% et 16% après 6 mois et de 14%, 34% et 24% après 8 mois pour F1, F2 et F3 respectivement. Le nombre de vers de terre immatures était de 785, 178 et 790 après 6 mois et 140, 424 et 1 022 après-huit mois pour les F1, F2 et F3 respectivement. La diminution du nombre de vers de terre immatures et cocons pour F1 pourrait être due à des conditions défavorables dans les vermifiltres à savoir la présence d'un fort taux d'humidité quand les eaux grises percolent plus lentement en raison de la réduction de la porosité. Les vers de terre et les cocons plus immatures ont été enregistrés en F3. Le taux de croissance des cocons dans la sciure (litière) correspond aux résultats rapportés par Manaf *et al*. (2009).

De même, le poids des vers adultes a augmenté de 28,8%, 52,6% et 44,3% après 6 mois et de 3,3%, 33,9% et 17% dans le temps des deux mois supplémentaires pour la F1, F2 et F3 respectivement. Le poids des vers de terre immatures a dimunié de 26,8% pour la F1 et a augmenté de 37,5% et de 26% pour F2 et F3 respectivement entre les 6 et 8 mois de l'expérience. La perte de poids des vers de terre de la F1 pourrait être due aux conditions défavorables développées à l'étape initiale de colmatage. D'après les résultats, il est supposé que la réduction des matières volatiles par la sciure dans les vermifiltres était bonne pour la croissance et la reproduction des vers de terre avant le colmatage des filtres.

L'effet sur le matériel de literie

La moyenne solide volatile (VS) était d'environ 90% la proportion de la sciure de bois brute. Après huit mois de fonctionnement, il était de 54% dans F1, 63% dans F2 et 61% dans F3 mais 77% dans F4. Ces données montrent une réduction de 30% dans le VS de la sciure de bois du vermifiltre. Ce qui est semblable à la réduction de 37% de VS lors du lombricompostage des déchets verts (Frederickson *et al.*, 1997). Un colmatage fréquent a été observé dans l'unité de contrôle qui a cessé de travailler après quatre mois de fonctionnel. Cependant, F1, F2 et F3 se sont colmatés après 8, 9 et 10 mois (fin de l'expérience), respectivement. En plus de soutenir l'élimination des polluants et d'agents pathogènes, les vers de terre ont ainsi contribué à prolonger la durée de vie des filtres en particulier dans les vermifiltres de sciure de bois.

On a constaté que le colmatage dans les sols est produit en raison de l'accumulation solide, la formation de matière biologique, et la précipitation chimique dans les pores (Platzer *et al.*, 1997). Dans cette recherche, les vermifiltres et l'unité de contrôle ont accumulé aussi bien des solides organiques su' inorganiques. La précipitation chimique et l'accumulation de la communauté microbienne ont également été observées. Ainsi l'analyse l'échantillon, nivèle pour les composants inorganiques (FS) représente 47% et que le rapport VS/MES est de 53%. Encre qui concerne les précipitations chimiques om a obéré pour les sulfates, les carbonates, les bicarbonates de magnésium et de calcium des concentrations moyennes de 143, 2.072, 2.754 et 2.482 mg/Kg respectivement. L'adsorption de silicates, de phosphates et des tensio-actifs ailés en moyenne de 400, 143 et 11 mg/Kg respectivement.

Le rôle les couches du milieu vermifiltrant sur l'élimination des pollutants d'eaux grises.

Caractéristiques physico-chimiques des nutriments des eaux grises

Les eaux grises concentrées ne sont pas seulement riches en polluants organiques et agents pathogènes, mais aussi en nutriments. L'eau grise de mos échantillons présentait les teneurs élevés en NH_4^+, NO_3^-, NO_2^- et PO_4^{3-}.

L'évaluation des performances du vermifiltre et de l'unité de contrôle

Le vermifiltre et l'unité de contrôle ont tous révélé un méreau élevé de élimination des polluants principalement à la couche supérieure (actif) où les communautés microbiennes et vers de terre dominent. Il y avait des différences significatives pour les paramètres de qualité entre les différentes couches du vermifiltre et le contrôle ($p < 0,05$). Toutefois, pour les concentrations entre les couches des filtres, les différences sont significatives seulement pour la DCO, les MES, PO_4^{3-} et la DO (oxygène dissous). Lorsque les performances des deux filtres sont comparées à chaque couche, il n'y avait pas de différences significatives ($p < 0,05$), sauf pour la DCO la OD. Cependant, on constate que concentration de l'effluent en nitrates et en orthophosphate est faible même dans l'unité de contrôle.

Physico-chimique

La couche supérieure a éliminé plus de 90% de MES et 75% de la DCO à la fois dans le vermifiltre et l'unité de contrôle. Cependant, le vermifiltre avait un rendement légèrement meilleur que le témoin. Le pH et la concentration en OD ont augmenté le long de la profondeur alors que la température a diminué pour les deux filtres. Dans le vermifiltre, le pH de la couche supérieure active était de 7,6 tandis qu'en bas (à la sortie), il était de 8,75. L'augmentation du pH observé pourrait être due à des accumulations précipitées des carbonates, des bicarbonates et des produits chimiques dans le matériau filtrant au fond qui ont facilité les activités des vers de terre. Dans l'unité de contrôle, la couche supérieure à un pH de 7.6 et la couche inférieure 7.89, une différence de valeurs qui n'est pas significative. Plus de DO tir observée à la couche supérieure et elle diminue tout le long de la profondeur. Le vermifiltre avait une forte teneur en DO par rapport à la contrôle alors que la condition aérobie a été créée par l'existence de vers de terre et de la période de repos en raison du système d'alimentation en batch. Généralement, les taux d'élimination le plus élevés sont ont été réalisés au-dessus de 30 cm pour la plupart des paramètres de pollution et cela est en lien avec la constatation de Zhao *et al*. (2009) qui ont trouvé que l'efficacité d'élimination des polluants est la plus élevée lorsque la hauteur du vermifiltre est comprise entre 30 et 70 cm.

L'élimination des nutriments

La couche supérieure a éliminé en moyenne 45% et 39% de la concentration d'ammonium par le vermifiltre et par le contrôle. La bonne élimination de l'ammonium peut être due à la condition aérobie créée par les vers de terre. Taylor *et al.* (2003) ont constaté que la production de déjection de ver terre a oxygéné l'influent et facilité la nitrification par les microbes. En raison de la nitrification, les nitrates supplémentaires ont été produits, ce qui pourrait limiter la performance finale en nitrates. En outre, le taux élevé élimination en surface pourrait être due à de phénomène d'adsorption par la sciure de bois. Les travaux une de Wang *et al.* (2013), Wang *et al.* (2011) et Dalahmeh *et al.* (2011) sur l'activité de nitrification, la diversité et la composition bactérienne profils ont tous conclu que la dégradation de la matière organique et la nitrification se sont produites principalement dans les premiers 20 cm du filtre d'écorce.

L'élimination totale des nitrites et des orthophosphates était plus élevé dans l'unité de contrôle que le vermifiltre. Cependant l'élimination des nitrites était meilleure sur la couche supérieure du vermifiltre, résultat qui pourrait être dû à la contribution de la communauté microbienne et les vers de terre, en plus de l'adsorption par la sciure de bois. Fang *et al.* (2010) ont constaté que la fixation, l'adsorption et la co-précipitation dans des lits d'emballage des vers de terre étaient le principal mécanisme de l'élimination du phosphore. Les activités de la communauté microbienne et les vers de terre peuvent avoir augmenté la conversion du phosphore particulaire en orthophosphates solubles. Par exemple, Parthasarathi *et al.* (2007) ont identifié de manière significative les bactéries de solubilisation et de nitrification du phosphate dans les tripes et déjection des vers de terre. L'élimination des nitrates et des nitrites dans le même filtre montre que les deux conditions aérobies et anaérobies ou anoxiques existent à l'intérieur des filtres.

L'analyse des vers de terre et de la communauté bactérienne

Eudrilus eugeniae a montré une croissance significative et une bonne performante olé reproduction après s'être acclimaté au nouvel environnement. La condition dans le vermifiltre favorise l'augmentation de la population de vers de terre qui est importante une bonne élimination des polluants. Bajsa *et al*. (2003) ont découvert que la population de vers de terre joue un rôle important dans la stabilisation et l'adsorption de la matière organique et les éléments nutritifs dissous et en suspension à travers des processus complexes de biodégradation. Plus de communautés bactériennes ont été observées dans le vermifiltre que l'unité de contrôle.

Effet sur les matériaux de litière et médias filtrants

Les matières volatiles sont indicatrices du carbone organique. Les matières volatiles sont passées de 92% à 73% d'el échantillon pour le vermifiltre et 84% pour le contrôle. L'apparait la présence de vers de terre a favorisé la dégradation des matières volatiles. De même, Xiaowei *et al*. (2013) ont trouvé que des vers de terre favorisent la dégradation de la matière organique dans les biofilms et suspendu bio-colmatage par les actions conjointes de vers de terre et les micro-organismes.

Il y a eu un rétrécissement des matériaux de litière dans le vermifiltre l'épaisseur diminué de 12 cm dans le vermifiltre alors qu'elle a augmenté de 1 cm. Il y a donc eu une réduction de 40% de l'épaisseur dans la vermifiltre et environ 1,5% d'augmentation dans l'unité de contrôle. L'augmentation dans le contrôle pourrait être de l'accumulation de matières solides inorganiques et organiques des eaux grises lentement dégradables. Il y avait aussi une réduction significative de la cellulose à partir de la litière dans le vermifiltre que le témoin. Au bout de sept mois, 57% de la helocellulose dans la sciure a été réduite à 31% dans le vermifiltre et à 47% dans le contrôle. Ceci est similaire à Morgan et Burrows (1982) constatant que les vers de terre et les microbes agissent en symbiose et synergie pour accélérer la décomposition de la matière organique et ce sont les micro-organismes qui décomposent la cellulose. En outre, la porosité diminue dans tous les filtres, mais à un rythme plus lent pour les vermifiltres que l'unité de contrôle. La porosité diminue en raison de la réduction de la taille de la sciure de bois, l'accumulation de solides organiques et inorganiques lentement dégradés des eaux grise et la de la formation du mat biologique.

Etudier matériaux filtrants, communautés microbiennes, et le schéma d'écoulement de l'influent et de l'effluent dans le processus de vermifiltration.

L'évaluation des performances de l'unité de contrôle et des vermifiltres

La performance du VF2 de sciure était meilleure pour les paramètres physico-chimiques par rapport à d'autres matériaux utilities en vermifiltration notamment pour la bouse de vache VF3. Par ailleurs, le pH de l'effluent VF1de sciure était toujours inférieurs aux autres ce qui pourrait être dû au fait qu'il a été alimenté en eau potable. Pour l'élimination des nutriments, l'unité de contrôle était plus performance que les sciures et la bouse de vache des vermifiltres sauf pour l'ammonium. L'adsorption de la sciure de bois pourrait contribuer à l'élimination des polluants. (Harmayani et Anwar, 2012) ont constaté que la sciure de bois est un très bon adsorbant pour éliminer NH_4^+, NO_3^- et NO_2^- en solution aqueuse, en particulier à de faibles concentration inférieure. Les moulages de ver sont également connus pour l'adsorption des différents polluants chimiques (Prasad Amit Kumar *et al.*, 2013). Une meilleure nitrification peut également être réalisée en raison des conditions aérobies dans les vermifiltres et l'alimentation des eaux grises par batch. De même, Pell et Nyberg (1989c) ont signalé que la nitrification complète à lieu dans le top 15 cm couche de colonnes de filtre à sable. Cependant, la faible performance de la bouse de vache pourrait être due à la faible porosité et les nutriments déjà disponibles dans les excréments. L'élimination des nitrates peut aussi être due à des bactéries dénitrifiantes dans l'intestin des vers de terre (Svensson *et al.*, 1986; Elliott *et al.*, 1991; Matthies *et al.*, 1999).

Il y avait une réduction plus significative de la cellulose à partir de la litière (sciure de bois fine) dans les vermifiltres que dans l'unité de contrôle (figure 6-8 et le tableau 6-8). La faible dégradation dans l'unité de contrôle a montré que les bactéries sont responsables de la dégradation de la cellulose. Un constat similaire a été rapporté par Morgan et Burrows (1982). Les vers de terre ont réduit la taille de la litière, en réduisant progressivement le rapport C/N et ont augmenté l'aire de surface exposée à des micro-organismes qui ont facilité la dégradation (Dominguez *et al.*, 2004). En outre, les extractibles consistent en des graisses, des cires, des tannins, des résines, etc (Acharya *et al.*, 2008) et les non-extractibles de composants parasites sont constitués principalement d'éléments inorganiques tels que la silice, des carbonates, des oxalates, etc (Kodali et Pogaku, 2006).

Évolution de vers de terre

Le développement de vers de terre dans les vermifiltres fournis avec les eaux grises, VF2-sciure et VF3-bouse de vache par rapport au vermifiltre fourni avec de l'eau potable a montré que les eaux grises sont source de nutriments. Des eaux grises fournies vermifiltres, il était possible d'obtenir des vers de terre et des cocons matures et immatures. Le VF2-sciure eu 202, 75 et 83 et de la bouse de vache avait VF3-148, 35 et 20 des vers adultes matures, immatures et les cocons respectivement. Le nombre de vers de terre et des cocons a diminué de manière significative en raison de la température élevée dans les mois de pointe de l'année pour le site.

Effet sur les matériaux filtrants:

Solides volatils et changement de la teneur en humidité

Les solides volatiles (VS) et la teneur en humidité (TH) dans les matériaux filtrants ont été analysés. La figure 6-6 petite le values pour VS et TH a 6 niveaux de prélèvement d les quatre filtres de. Le VF1-sciure vermifiltre fourni avec de l'eau potable a montré peu de diminution de la VS et une certaine augmentation de TH dans le temps le long de la profondeur du vermifiltre. Cependant, pour le reste des filtres, il y avait plus d’augmentation de VS le long de la profondeur dans le temps ce qui peut expliquer que davantage de VS (carbone) a été consommé là où les lombrics et les microbes dominent. D’une maniérée générale, le VS a diminué à travers le temps pour chacun des points d'échantillonnage.

Le pH change dans le temps en raison de l'eau grise outre les vers de terre et les activités microbiennes à l'intérieur des matériaux filtrants. Il y avait une accumulation de produits chimiques transformés ou précipités au-dessus de la couche de sable qui a augmenté le pH mais à une faible concentration pour VF1 puisqu'il a été alimenté en eau potable. Dans le chapitre quatre, les produits chimiques accumulés ont été analysés et om y contrôle pue la disponibilité de bicarbonate et de carbonate a augmenté le pH. L'accumulation de l'ammoniac peut également affecter le pH au bas des filtres.

Il y avait aussi une réduction beaucoup plus importante significative de la cellulose à partir de la litière (fin de la sciure de bois) dans les vermifiltres que dans l'unité de contrôle. Dans leur recherche, Morgan et Burrows (1982) ont conclu que les micro-organismes sont responsables de la décomposition de la cellulose dans la matière organique. Le niveau de dégradation ans l'unité de contrôle a montré que les bactéries sont responsables de la dégradation de la cellulose. Les vers de terre ont réduit la taille de la litière, en réduisant progressivement le rapport C/N et ont augmenté l'aire de surface exposée à des micro-organismes qui ont facilité là la dégradation (Dominguez *et al.*, 2004). Il en résulte que plus de cellulose a été dégradée dans le vermifiltre que l'unité de contrôle.

Des études sur le lombricompostage et vermifiltration conclu eut que le phylum dominante Proteobacteria est disponible (Danon *et al*., 2008; Fracchia *et al.,* 2006; Vivas *et al*., 2009; Limin Zhao *et al*., 2010). La répartition de la population microbienne varie avec la profondeur à la fois dans les vermifiltres et dans l'unité de contrôle à des taux différents. Les bactéries varient plus dans les vermifiltres que dans l'unité de contrôle. Arora *et al*. (2014) ont rapporté des résultats similaires pour le vermifiltres mais pas pour l'unité de contrôle. Le VF2-sciure avait plus de population de bactéries que le contrôle. Cela peut être dû à l'aération adéquate, la disponibilité de l'oxygène, en raison de l'activité des vers de terre. Les champignons étaient plus nombreux dans les vermifiltres car il y avait plus d'aération qui a renforcé leur développement. Parthasarathi *et al*. (2007) ont également analysé la diversité des champignons, des bactéries, des actinomycètes, des levures et des protozoaires dans l'intestin et des moulages *d'Eudrilus eugeniae*.

La porosité diminue dans tous les filtres, mais à un rythme plus lent pour le vermifiltres que l'unité de contrôle. Le ver de terre a digéré le solide avec l'amende de la sciure accumulée et le réduit en particules minuscules. Ce sure a augmenté la surface, et permis de rendre la matière facilement biodégradable par les bactéries. Au début de l'expérience, la filtration de surface et le taux d'infiltration était presque la même pour les trois vermifiltres et le contrôle. Cependant, au fil du temps il a changé à la fois de direction à vitesse différente, sauf pour le VF1-sciure alimenté avec de l'eau potable. Comme le montre la figure 36, le temps de filtration de surface varie de 10 secondes à 50 minutes pour le contrôle, 10 secondes à 845 secondes pour VF2-sciure, 48 secondes à 845 pour VF3-bouse de vache. Toutefois, pour VF1-sciure de bois, il est constant tout au long de l'expérience. L'échelle de temps de traitement des eaux usées dans le lit filtrant de lombricompostage est le temps de séjour hydraulique du lit. Ce temps est proportionnel à la profondeur du lit qui peut augmenter au fil du temps en raison de l'accumulation de moulages (Taylor *et al.*, 2003).

Conclusion

Il est suggéré que la vermifiltration pourrait être une option alternative pour l'assainissement des eaux grises en milieu urbain pauvre dans les pays au sud du Sahara. Le coût zéro pour la collecte et la capacité de traiter les polluants physiquement, chimiquement et biologiquement dans une seule installation rend la technologie moins coûteuse et sélective. Le dominant disponible au Burkina Faso lombric *Eudrilus eugeniae* a toléré les températures au-dessus de 40°C à l'intérieur du filtre et amélioré les conditions de vermifiltre. Les résultats ont montré que le filtre avec le ver de terre est légèrement plus efficace que le filtre sans les vers de terre dans l'élimination de DBO_5, DCO, TSS et Coliformes. Plus la CH est faible, meilleures étaient les efficacités d'élimination. Les vers de terre ont également été capables de survivre à des valeurs de pH plus bas que 4,37.

Cette étude a montré que la sciure fine peut être utilisée avec comme un support de filtre dans la vermifiltration et un substitut pour le sable. Cependant, l'ajout d'un peu de sable à la couche du fond est utile. De plus, la matière organique provenant des vermifiltres de sciure de bois peut être utilisée pour des activités agricoles. De vannière Schedule les, vermifiltres ont été plus performants et pour une période plus longue que l'unité de contrôle. Cependant, les vermifiltres ne peuvent plus soutenir la croissance des vers de terre après plusieurs mois de temps de fonctionnement due à la forte teneur en humidité causée par l'accumulation de matières solides inorganiques et organiques à dégradation lente qui kit réduit la porosité.

De notre étude, l'élimination majeure de polluants de l'eau grise concentrée a été réalisée au méreau de la couche supérieure (active) pour la plupart des paramètres. Ceci a été réalisé en raison de l'adsorption par la sciure de bois en plus des vers de terre et l'activité bactérienne. Le vermifiltre était plus performant mieux dans la plupart des aspects sauf avec les nitrites, orthophosphates et les MES. Cependant, il y avait des fluctuations de temps en temps pour les nitrates et orthophosphates et il y avait une incrémentation le long de la profondeur de la température moyenne et de l'oxygène dissous. Une augmente de el épaisseur peut augmenter de tout élimination des nitrates et la demande en oxygène restant. En outre, le plus grand nombre de la communauté microbienne disponible dans le vermifiltre peut être associé à l'incrémentation des vers de terre. Cela peut indiquer que les vers de terre ont favorisé un groupe de la communauté microbienne qui a contribué à accroître l'efficacité de l'élimination et de la dégradation de la sciure de bois. Le retrait de el épaisseur dans le vermifiltre a monté que la sciure de bois, principalement la source de carbone, a été dégrade par les vers de terre à la fois et la communauté microbienne comme source d'énergie. Généralement, le choix des matériaux de filtres appropriés permet aux vers de terre d'interagir avec les micro-organismes, en symbiose et synergie pour améliorer l'élimination des polluants.

La performance du vermifiltre VF3-bouse de vache inférieure à celle du vermifiltre VF2-sciure pourrait être due à la faible porosité de la bouse de vache qui peut être améliorée par mélange avec d'autres matériaux poreux appropriés pour le lit filtrant. L'autre raison est peut-être la provenance des polluants provenant de la bouse de vache qui pourraient se lessiver avec l'effluent. Le VF1-sciure alimenté en eau potable lessive aussi les polluants et a rendu la qualité de l'effluent faible par rapport à celui alimenté avec l'eau potable. Les bactéries, les actinomycètes et les champignons ont été identifiés et sont connus pour leur intégration avec les vers de terre.

Plus de bactéries ont été identifiées dans le VF2-sciure et VF3-bouse de vache par rapport aux autres. La distribution des bactéries dans les vermifiltres et l'unité de contrôle était supérieure en surface et diminue vers le bas. Relativement, le taux de diminution était plus faible pour l'unité de contrôle que peur les vermifiltres.

L'infiltration de surface et l'infiltration du fond ne varient pas de façon significative tout au long de l'expérience pour VF1-sciure de bois. Cependant, pour les autres vermifiltres, la filtration à la surface prend plus de temps à la fin de l'expérience. Surtout le contrôle prend plus de 1h à filtre. Enture le VF3-bouse de vache et VF2-sciure ont augmenté avec le temps à un taux moindre que l'unité de contrôle. Les eaux grises étaient source de nutriments à nourrir les vers de terre et les microbes en raison de la mort totale des vers de terre dans le VF1-sciure qui a été fourni avec de l'eau potable. Il y avait une différence de pH à travers le matériau filtrant suivant la profondeur qui pourrait par l'accumulation chimique être due aux vers de terre et l'activité microbienne ou de précipitation. Relativement, le pH est inférieur là où les vers de terre ont prévalu.

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List of Acronymes and Abbreviations

ANOVA	Analysis Of Variance
APHA	American Public Health Association
BOD_5	Biochemical Oxygen Demand
C	Concentration
CFU	Colony forming unit
COD	Chemical Oxygen Demand
Cm	Centimeter
Cr^{3+}	Chromium
CREPA	Centre Régional de l'Eau et l'Assainissement (Regional Center for Water and Sanitation)
d^{-1}	Per day
dCOD	Dissolved Chemical Oxygen Demand
D_{10}	Particle size at which 10% of the material is finer
D_{60}	Particle size at which 60% of the media is finer
DN	Diameter Nominal
DO	Dissolved Oxygen
EC	Electrical Conductivity
E. coli	*Escherichia coli*
et al.	and others
ETOH	Ethyl Alcohol
FS	Fixed Solids
G	Grams
GF/C	Glass Fibre Filters
h, hr	Hours
HRT	Hydraulic Retention Time
K	Log removal value
kg	Kilogram
Ln	Natural logarithm
Log	Logarithm
MDG	Millenium Development Goal
mm	Millimeter
MC	Moisture content

Mg/Kg	Milligram per Kilogram
Mg/L	Milligram per Liter
NH_4^+	Ammonium
NO_3^-	Nitrate
NO_2^-	Nitrite
OLR	Organic Loading Rate
°C	Degrees Celsius
pH	Potentiometric hydrogen ion concentration
PO_4^{3-}	Orthophosphate
PVC	Polyvinyl chloride
Q	Flow rate
s	Seconds
SD	Standard Deviation
T	Temperature
tCOD	Total Chemical Oxygen Demand
TSS	Total Suspended Solids
UNESCO-IHE	Institute for Water Education
VRBG	Violent Red Bile Glucose
V	Volume
VF	Vermifilter
VS	Volatile Solids
UFMG	Federal University of Minas Gerias
UN	United Nations
UN-HABITAT	United Nations Human Settlements Programm
TKN	Total Kjeldahl Nitrogen (mg/L)
±	Plus or minus
2iE	Institution for Water and Environmental Engineering
µm	Micrometer
µS	Microsiemens

Chapter 1

General Introduction

Chapter 1: General Introduction

1.1 Background

Sanitation is important for safe-guarding the health and wellbeing of human kind (Cairncross, 2003; Moe and Rheingans, 2006). Adequate sanitation is access to sanitation that is convenient for all household members, affordable, and one that eliminates contact with human excreta and other wastewater (UN-Habitat, 2003).

There has been considerable achievement on drinking water supply, but the problems of excreta and wastewater disposal have received less attention. The world met the MDG for drinking water by the end of 2011 (WHO, 2012) but the target for the sanitation has not been achieved. Currently, over 90 percent of the world's population have access to improved sources of drinking water, but 2.4 billion are without access to improved sanitation facilities (WHO/UNICEF, 2015). The majority of people, who lack the improved sanitation facilities are from the developing world, especially the sub-Saharan Africa and South-East Asia.

By 2030, the world population is projected to be 8.5 billion (UN, 2015) and sub-Saharan African population is expected to grow to 1.3 billion (Velkoff and Kowal, 2007). Besides the population growth, the annual rate of urbanization and slum formation in Africa is 4.6 and 4% respectively (Otiso, 2003). In sub-Saharan countries, 62% of the total urban population lives in slum areas (UN-HABITAT 2008, 2009). The higher population growth in urban slums areas is not only due to the birth rate but also the migration from rural areas of those seeking a better life.

This rapid population growth and decreasing availability of adequate collection and treatment facilities of the waste streams (excreta, greywater and solid waste) will result in a highly polluted environment and pose risks to public health. Wastewater collection and treatment is one of the main environmental concerns in areas that have large amounts of wastewater production (Suthar, 2009).

In most developing countries, cities are able to collect and treat less than 15% of wastewater before discharging into the final receiving systems (Mara, 2003). Especially in urban poor areas, there is no or little coverage for the collection and treatment of domestic wastewater, but it is worst in the sub-Saharan Africa. Pollution due to wastewater disposal is a common problem in the urban areas of the developing countries, particularly in lower-income urban areas (Mara, 1996).

Greywater, a major component of the domestic wastewater, is usually generated from dishes, showers, sinks, and laundry. The amount generated is estimated between 50-80% of household wastewater (Al-Jayyousi *et al*., 2003). In the slums of developing countries, the uncontrolled discharge of greywater on the streets and open spaces has led to a deterioration of street conditions, disease outbreaks and odor problems (Morel and Diener, 2006). Wastewater related diseases come from enteric viruses, bacteria and protozoa (Carr and Strauss, 2001; Jaykus, 1997; Ashbolt, 2004; Montgomery and Elimelech, 2007).

Yofe (2009) studied the greywater characteristics generated from the urban poor of the city of Ouagadougou, Burkina Faso and found it to be highly polluted with organic and inorganic pollutants, nutrients and pathogens (see Table 1-1).

Table 1-1. Mean values and standard deviation from the two sampling sessions describing shower, laundry and dish water (adapted from Yofe, 2009)

Parameters	**Shower**	**Laundry**	**Kitchen**
pH	**7.1** ± 0.9	**7.0** ± 0	**6.0** ± 0.2
Electrical conductivity (µS/cm)	**0.7** ± 0.21	**2397** ± 994	**1.0** ± 0.51
COD (mg/L)	**2513** ± 723	**7538** ± 2139	**2863** ± 1503
BOD_5 (mg/L)	**2050** ± 636	**6065** ± 1747	**2350** ± 1202
Total suspended solids (mg/L)	**1450** ± 71	**2700** ± 707	**1850** ± 1485
Ammonium (mg/L)	**13.6** ± 6.2	**44.6** ± 9.4	**5.9** ± 1.2
Total phosphorus (mg/L)	**24.3** ± 2.8	**24.6** ± 0.7	**18.1** ± 9.3
Potassium (mg/L)	**33.2** ± 7.1	**54.9** ± 11.2	**30.0** ± 4.2
Sodium (mg/L)	**73** ± 15	**144** ± 45	**88** ± 20.1
Fecal coliforms (CFU/100 mL)	**52500** ± 10607	**530000** ± 339411	**202500** ± 286378
E. coli (CFU/100 mL)	**375000** ± 530330	**117500** ± 166170	0

The following pictures show the open disposal of the greywater on the streets of the slum areas of the city of Ouagadougou (Figure 1-1).

Figure 1-1. Greywater on streets (Ouagadougou City)

The existing low-cost sanitation options are not solving the problems in urban poor areas of sub-Saharan countries due to many reasons. For instance, intermittent sand filters were proven to be a cost effective option to treat domestic and industrial wastewaters but clogging is common problem (Netter, 1992; Healy *et al.*, 2004). Lagoons require large areas of land and a sewer system (Pattarkine *et al.* 2006). Septic tanks have low treatment efficiency and emit foul odors (Imhof *et al.*, 2005). Therefore, it is necessary to develop technologies which are relatively low-cost, low-energy consumption, need little maintenance and are environmentally friendly.

There is tremendous need to develop reliable technologies for treating domestic wastewater which are simple in design, have good treatment efficiency, and low operating and capital cost (Wang *et al*., 2010). As a sustainable solution, individual households or a cluster of homes can treat their domestic wastewater in a decentralized manner at the source (Crites and Tchobanogous, 1998). Vermifiltration is desirable technology, especially for urban poor in the developing countries, because it requires less land area compared to other ecological and decentralized wastewater treatment technologies (Xing *et al.,* 2010). Furthermore, it can be used at the household level due to its simplicity of construction from locally available materials and earthworms which make the operation and maintenance simple with the ability to treat in single facility (Arora *et al*., 2014).

However, as far as vermifiltration for treating greywater is concerned, no specific research has been done in sub-Saharan countries, particularly in the Sahelian region. Therefore, the objective of this research was to develop a vermifiltration technology model at the laboratory scale and study its potential in treating concentrated greywater generated from the urban poor of the region.

Figure 1-2 presents the necessary steps followed in the greywater treatment by vermifiltration for this study.

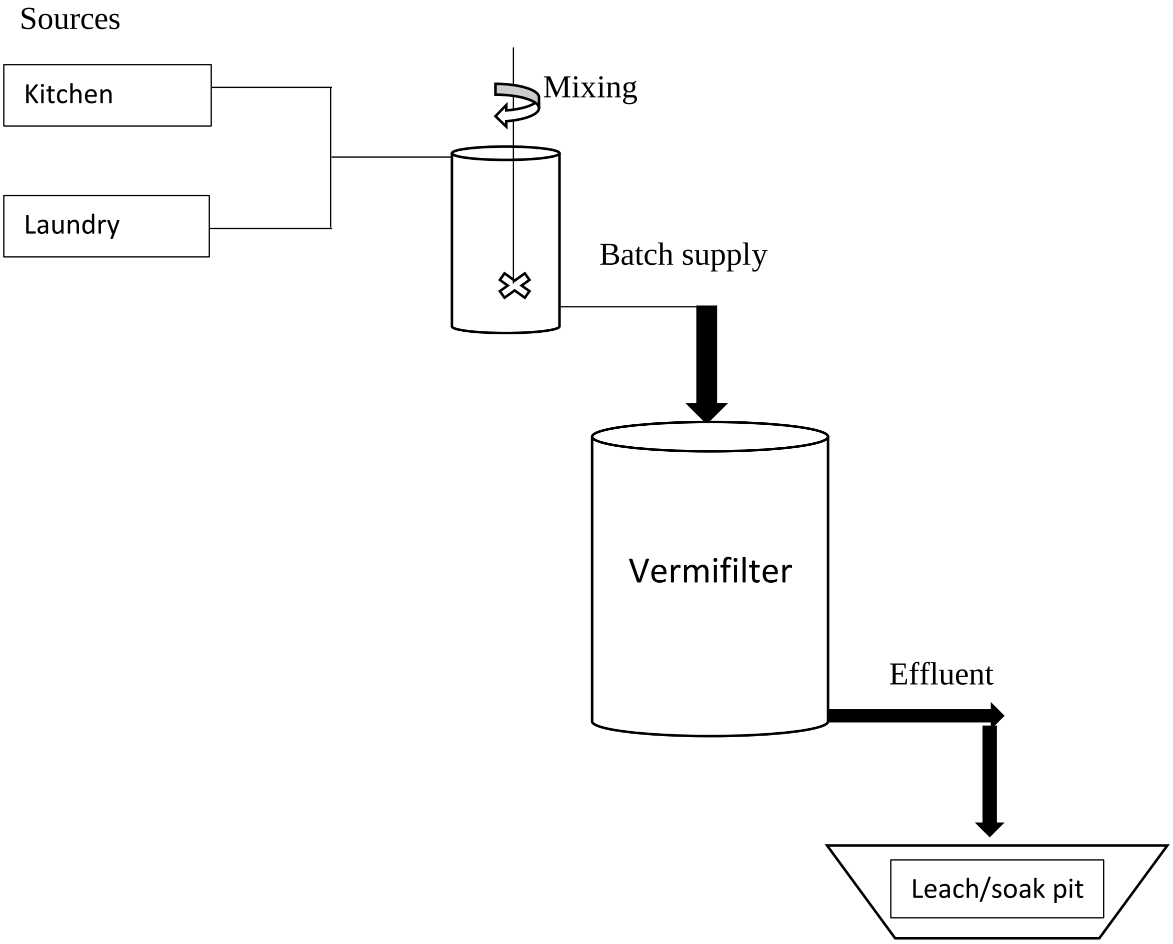

Figure 1-2. Greywater treatment steps by vermifiltration

1.2 Research Questions

The study was designed to provide answers to the following questions:

- Can vermifiltration be another sanitation option for the sub-Saharan urban poor?
- What are the critical factors that affect the vermifiltration process in the Sahel?
- Can the locally available earthworms help in the removal of pollutants from greywater?
- Which microorganisms are working together with the earthworms to treat greywater?

1.3 Objectives and Research Scope

The general objective of this research was to develop and study a low-cost wastewater treatment technology which was proposed by the project ‘Stimulating local innovation on sanitation for the urban poor in sub-Saharan Africa and South-East Asia’ funded by the Bill & Melinda Gates Foundation in coordination with UNESCO-IHE, Institute for water education, Delft, the Netherlands. Hence, to develop a vermifiltration technology model at laboratory scale and to study its potential in treating concentrated greywater generated from the sub-Saharan urban poor, specifically in the Sahel was the aim of this research. The technology should be environmentally friendly, economically sustainable, socially acceptable, and require minimal space to be used by the impoverished communities at household level. The vermifilters and the control unit were made and composed of locally available low-cost materials and earthworms.

The specific objectives of the PhD research were:

- To study the feasibility of the vermifiltration technology for treating concentrated greywater generated from the sub-Saharan urban poor, specifically in the Sahel by developing a model at the laboratory scale.
- To study the effect of the composition of filter materials (sawdust and sand) on the vermifilters performance in treating concentrated greywater generated from the sub-Saharan urban poor.
- To study the role of vermifilter media layer in pollutant removal, i.e, TSS, tCOD, DO, pH, dCOD, NH_4^+, NO_3^-, NO_2^-, and PO_4^{3-} from greywater.
- To study filter materials, microbial communities, and influent and effluent flow pattern in the vermifiltration process.

The scope of this research was to construct a model for vermifiltration experiment at the campus of the International Institute for Water and Environmental Engineering, Ouagadougou, Burkina Faso and study the potential of the vermifiltration technology for treating the concentrated greywater generated from the sub-Saharan urban poor in hot climatic condition.

1.4 Description of the Project BMFG (SaniUP project)

The stimulating local innovation on sanitation for the urban poor in sub-Saharan Africa and South-East Asia project (SaniUP) was developed to address the needs of the 2.4 billion people worldwide who do not have access to improved sanitation. The project, started in 2012, is funded by the Bill and Melinda Gates Foundation. It has two principal objectives: (1) to stimulate local innovation on sanitation for the urban poor through research, and (2) to strengthen the sanitation sector in developing countries through education and training.

The project is co-ordinated by UNESCO-IHE and includes partners from Africa, Asia and Latin America. The partners are the Asian Institute of Technology (AIT) in Thailand, the Institute Technology Bandung (ITB) in Indonesia, the International Institute of Water and Environmental Engineering (2iE) in Burkina Faso, the Kwame Nkrumah University of Science and Technology (KNUST) in Ghana, Makerere University Institute of Environmental and Natural Resources (MUIENR) in Uganda, the University of Cape Town (UCT) in South Africa, the Federal University of Minas Gerais (UFMG) in Brazil and the Universidad del Valle in Colombia. Currently, 5 post-doctoral fellows and 20 PhD researchers are doing research in five research themes. The BMGF PhD research package themes are: (1) emergency sanitation (2) low-cost wastewater collection and treatment (3) smart sanitation provision (4) resource-oriented smart sanitation, and (5) faecal sludge management. This research work is within the theme of low-cost wastewater collection and treatment.

1.5 The Structure of the Thesis

This thesis comprises seven chapters. The first chapter, *Chapter 1*, gives a brief introduction about the back ground, the objectives and scope of the research, and the research questions. *Chapter 2* reviews different literature on vermifiltration. It explains the development of the vermifiltration technology and its components such as earthworms, bedding materials and filter media. Moreover, the chapter discusses the mechanisms of pollutant removal, the most important factors for the vermifiltration process, the greywater sources and characteristics, their effect on the environment and the treatment methods. Following the literature review, *Chapter 3* deals with the feasibility of concentrated greywater treatment by vermifiltration for sub-Saharan urban poor. It presents and discusses the earthworm identification, greywater characteristics, and the effect of temperature, hydraulic loading rate and pH on the vermifiltration process. Moreover, performance is compared for two different hydraulic loading rates. *Chapter 4* presents the effect of filter media composition on the performance of vermifilters. Different thicknesses of filter media, fine sawdust and sand, were compared in treating concentrated greywater by vermifiltration. *Chapter 5* presents the role of filter media layer in pollutant removal from greywater. The chapter explains the reasons for more removal achieved by the top layer and the importance of depth for better removal of some parameters. *Chapter 6* deals with filter materials, microbial communities, and influent and effluent flow in the vermifiltration process. As part of the vermifiltration system, the filter materials changed through time, and the changes are reported based on selected parameters. The microbial communities enumeration at various depths, and the influent and effluent flow pattern are reported. *Chapter 7* summarizes the conclusions and recommendations drawn from all experiments conducted. Finally, *Appendix 1* presents photos taken during the construction of the filters, earthworm counting and weighing, and a comparison of the degraded bed material with the raw sawdust, and *Appendix 2* presents the sieve analysis of sand.

Figure 1-3 summarizes the main steps that have been followed during the research period and the structure of the thesis report.

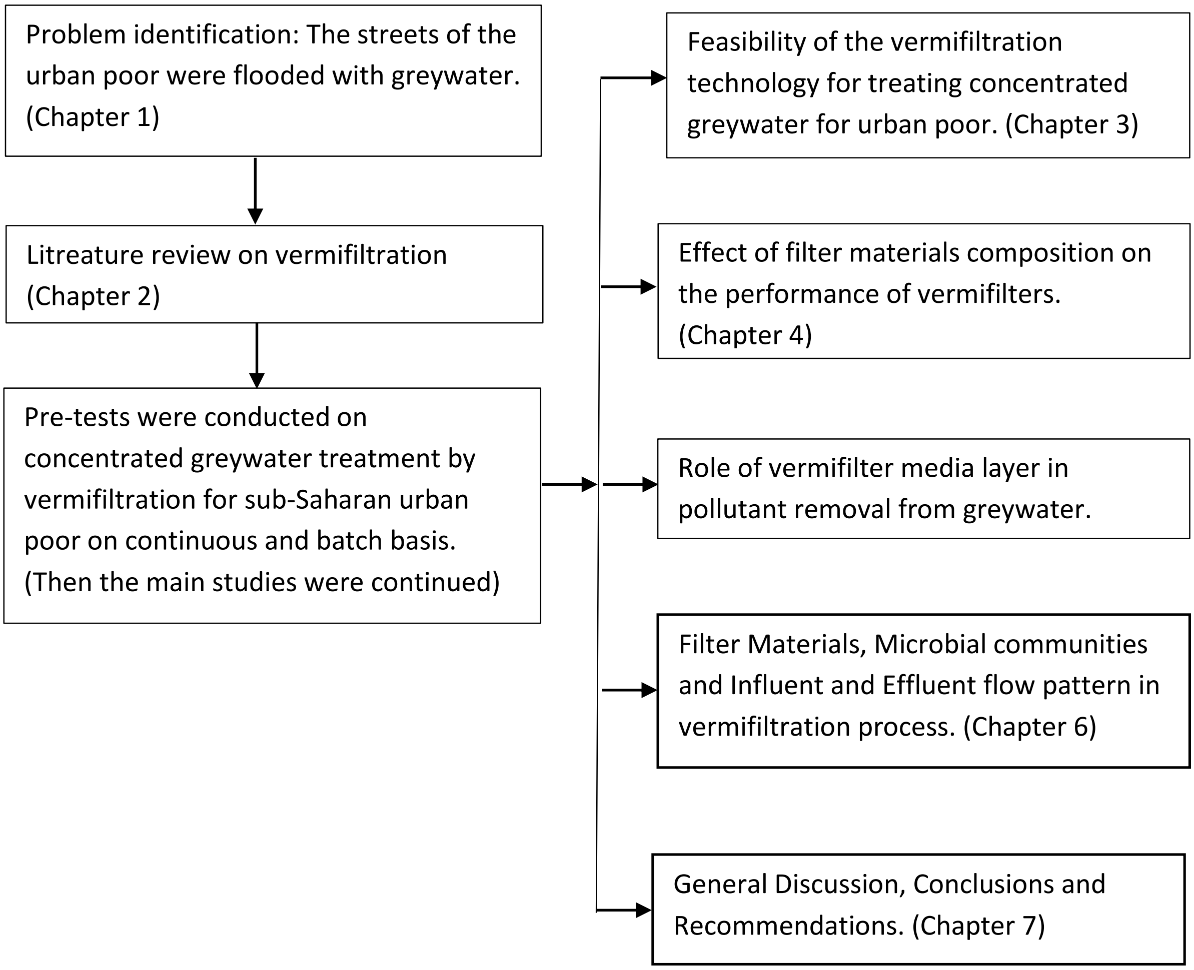

Figure 1-3. Thesis structure summary

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Chapter 2

Literature Review on Vermifiltration

Chapter 2: Literature Review on Vermifiltration

2.1 Greywater Treatment Methods

Greywater treatment methods range from simple treatment to more expensive that can treat the greywater to a high standard. The preliminary and primary treatment methods have been used to reduce oils, greases, fats, and solids. The secondary treatment methods, in addition to pathogens and nutrients reduction, have been used to remove most of the organic matter by biochemical reactions of microorganisms (von Sperling and Chernicharo, 2005). Tertiary or advanced treatment methods further improve the quality of greywater by removing nutrients and pathogens.

Some of greywater treatment technologies that have been tested and practiced are: flotation-grease trap (Sasse, 1998), septic/sedimentation tanks (Koottatep *et al*., 2006; Lound *et al*., 2005; Sasse, 1998), ponds (Mara and Pearson, 1998); filters like simple strainer and mesh filters (Christova-Boal *et al.*, 1996), nylon sock filters (March *et al.*, 2004), gravel filters (Al-Hamaiedeh and Bino, 2010), sand filters (Suleiman *et al.*, 2010), vertical flow filters (Ridderstolpe, 2004), horizontal-flow planted soil filter (Geller *et al.*, 1997), planted sub-surface filter and sub-surface flow filters (Dallas *et al.*, 2005), slanted soil system (Itayama *et al*., 2006); anaerobic systems like anaerobic baffled reactors (Koottatep *et al*., 2006) and upflow anaerobic sludge blanket (Ghunmi, 2009); Biological methods like fixed film biological rotating drums (Friedler *et al*., 2005 and 2006), biologically aerated filters (Bricks, 1998) and activated sludge (Hernandez *et al*., 2007); the chemical methods like photocatalysis (Parsons *et al*., 2000), electro coagulation (Lin *et al*., 2005) and conventional coagulation (Sostar-Turk *et al*., 2006); other advanced technologies like membrane treatment systems (Jefferson *et al*., 1999) and membrane bioreactors (Andersen *et al*., 2001). Furthermore, recycled vertical flow bioreactor, recycled vertical flow constructed wetlands (Gross *et al*., 2007a, b) and green roof water recycling system (Windward *et al*., 2008), have also been tested and practiced.

The small-scaled greywater treatment technologies that have been tested and practiced in the low income countries are: leach pit (Tilly *et al*., 2014; Parkinson *et al*., 2003), lava rock filters (Katukiza *et al*., 2013), sand filter (Rowe and Abdel-Magid, 1995), septic tanks (Koottatep *et al*., 2006), mulch bed (Morel and Diener, 2006), vertical (tower) garden (Morel and Diener, 2006; Adendorff and Stimie, 2005), constructed wetlands (Raude *et al*., 2009; Morel and Diener, 2006), slanted soil system (Maiga *et al*., 2014) and others.

However, the technologies have problems like clogging, odour and fouling, requiring frequent maintenance and regular cleaning, less or unstable removal efficiencies, demanding large area, expensive to implement and others.

2.2 The Vermifiltration

Vermifiltration is a decentralized wastewater treatment which is a simple, low-cost, reliable, energy-efficient technology. It was first advocated by the late Professor Jose Toha at the University of Chile in 1992 (Aguilera, 2003; Li *et al*., 2008; Nguyen, 2008; Xing *et al.*, 2010). Since then many vermifiltration experiments have been performed for treating municipal wastewater (Soto and Toha 1998; Bouché and Soto, 2004; Godefroid and Yang, 2005; Xing *et al*., 2005; Yang and Zhao, 2008; Yang *et al*., 2008), domestic wastewater (Taylor *et al*., 2003; Sinha *et al*., 2008, Xing *et al*., 2010), and organic wastewater generated from industries: gelatin, dairy, brewery and fruit juice industries (Sinha *et al*., 2013, Lim *et al*., 2014; Ghatnekar *et al.*, 2010; Sinha *et al.*, 2007), swine wastewater (Li *et al*., 2008), and sewage sludge reduction (Zhao *et al.*, 2010; Xing *et al*, 2012; Yang *et al*., 2013). Vermifiltration has also been integrated into constructed wetlands (Chiarawatchai, 2010; Tomar and Suthar, 2011; Xu *et al*., 2013a, b).

Most previous experiments were performed in the laboratory at a small scale level for a short period of time. Only few tests were done over longer periods and at larger scales, for instance, in the rural part of China (Li *et al*., 2008). The technology helped in the removal of suspended organic matter, pathogens, heavy metals and nutrients by biological, physical and chemical processes. The bedding material and the filter media remove pollutants physically by adsorption of molecules and ions, chemically by oxidation-reduction of organic matter and biologically by earthworms and their synergistic effects with microorganisms (Bouché and Soto, 2004).

The vermifiltration process removes different pollutants from the wastewater (greywater) using a vermifilter composed of filter media, bedding materials and inoculated with selected species of earthworms.

2.2.1 Earthworms and Microbial Communities

The earthworm gut is the ideal vicinity for bacteria, fungi, actinomycetes (Martin *et al.*, 1987; Govindarajan and Prabaharan, 2014) which are important in biodegradation. Earthworms promote the growth of microbial communities upto 1000 fold while passing through their gut (Edward and Fletcher, 1988). Moreover, the earthworm casts have been shown to exhibit more enzymatic and microbial activities (Loquet *et al.*, 1977; Tiwari *et al.*, 1989; Edwards and Bohlen, 1996; Elvira *et al.*, 1998; Parthasarathi and Ranganathan, 1999, 2000).

Earthworms belong to the order Oligochaeta, class chaetopodia, phylum Annelida and are categorized into: epigeic, anecic, and endogeic ecological groups based on their feeding and burrowing strategies (Brown, 1995; Bouché, 1977). Earthworms consume a wide range of organic materials including sewage sludge and microbes for their development and reproduction (Lavelle *et al*., 1997; Kwon *et al.*, 2009; Parthasarathi and Ranganathan, 2000) Table 2-1 presents the summary of the characteristics to classify the earthworms.

The most commonly utilized epigeic earthworm species are *Eisenia fetida*, *Eisenia andrei*, *Lumbricus rubellus*, *Perionyx excavatus* and *Eudrilus eugeniae* (Bajsa *et al*., 2003). Though they are found all over the world, *Eudrilus eugeniae* also called African night crawler, predominantly exists in West Africa.

Earthworms reproduce sexually through contact of their clitellum (Sinha *et al*., 2007) and start cocoon production at the age of 6 weeks to 6 months (Ismail, 1997). From each cocoon about 10-12 tiny worms emerge and under favorable conditions, an earthworm can multiply 28 times every 6 month (Hand, 1988). However, they can also lose their clitellum and become infertile if the environment is unfavorable (Edwards and Bolhan, 1996).

Table 2-1. Summary of characteristics to classify earthworms (Gajalakshim and Abbasi 2004)

Characteristics	**Epigeics**	**Endogeics**	**Anecics**
Body Size	Small	Large	Moderate
Burrowing habit	Reduced	Developed	Strongly developed
Longitudinal contraction	No	Little	Developed
Hooked chetae	Absent	Absent	Present
Sensitivity to light	Low	Strong	Moderate
Mobility	Rapid	Slow	Moderate
Skin moistening	Developed	Feeble	Developed
Pigmentation	Homochromic	Absent	Dorsal and anterior
Fecundity	High	Low	Moderate
Maturation	Rapid	Slow	Moderate
Respiration	High	Feeble	Moderate
Survival under adverse conditions	As cocoons	By quiescence	True diapause

2.2.2 Bedding Materials

For effective vermifiltration, earthworms need relatively stable habitat in the vermifilter that can be provided by bedding materials. The bedding materials should have the following characteristics: high absorbency, good bulking potential and low protein and/or nitrogen content (Mahmoud, 2011). Fine sawdust has been used as a bedding material in vermicomposting and vermifiltration in mixture with other materials (Manaf *et al.*, 2009, Li *et al.*, 2009). The bedding materials provide protection from extremes in temperature, the necessary levels and consistency of moisture, and an adequate supply of oxygen (Munroe, 2004).

2.2.3 Filter Media

The filter media can be any non-toxic material to the bacteria and earthworms that can help in the vermifiltration process. Sawdust, sand and gravel were chosen to be used as filter media in this research.

Sawdust, the primary filter material for this research, is composed of lignocelluloses and it is a main organic waste from sawmills. It can be used as a cooking fuel or a packing material and effective adsorbent for pollutants such as dyes, oil, salts, and heavy metals (Velizar *et al*., 2009; Baral *et al*., 2006). Its polysaccharide component is composed of 60-80% cellulose and hemicelluloses from the total (Acharya, 2008). Moreover, the sawdust is composed of extractives such as fats, waxes, tannins, resins, etc (Acharya *et al*., 2008) and the non-extractives such as silica, carbonates, oxalates, etc (Kodali and Pogaku, 2006). During decomposition, the water soluble components are metabolized first, followed by cellulose, hemicellulose and lignin, (Bagyaraj, 1988; Subha Rao, 2000) which changes the respective spectrum of micro flora decomposers.

Sand, the other primary filter material for this research, is the most common filter medium in any filtration for treating water and wastewater. Of the two types of sand filters, slow sand filters use a grain size of 0.15 to 0.35 mm and are used as a secondary treatment, while rapid sand filters usually use a grain size of 0.4 to 12.0 mm and are used as primary treatment (Rowe and Abdel-Magid, 1995). The other primary filter material, gravel, is usually used to hold the filter media from being drained out and develops biofilm to degrade some of the organic components from the partially treated greywater.

2.3 Mechanisms of Pollutant Removal

Pollutant removal by vermifiltration is achieved by the filter materials, earthworms and microbial communities. As shown in Figure 2-1, the filter materials remove bigger particles from wastewater by adsorption, sedimentation, and physical and mechanical straining (Jellison *et al*., 2000) while earthworms with the bio decomposer bacteria act as an aerator, grinder, crusher, chemical degrader and a biological stimulator (Dash, 1978; Sinha *et al*., 2002). Moreover, the grain size and specific surface area characteristics of the medium affect the adsorption and biofilm development (Stevik *et al*., 1999; Moore *et al*., 2001).

Biodegradation is the primary removal mechanism of organic matter in both the solid and liquid phase performed by the active biomass attached to solid surfaces (Campos *et al*., 2002; Rauch and Drewes, 2005). Microbial attachment is facilitated by adsorption (Trulear and Characklis, 1982; Li and DiGiano, 1983). High removal of pollutants would occur with smaller filter media particle sizes as it gives the optimum contact for biological activity (Huck, 1999) but the head loss increases (Goldgrabe *et al*., 1993).

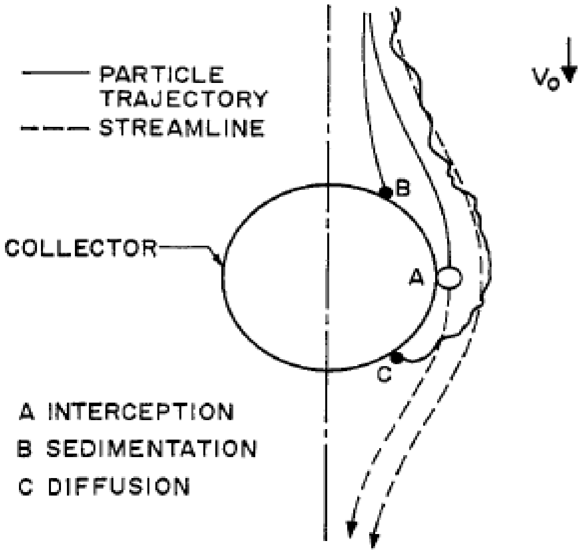

Figure 2-1. Particle separation mechanisms by filter materials during filtration process
(Source: Kuan-Mu Yao, l Mohammad T. Habibian, and Charles R. O'Melia.
Dept. of Environmental Sciences and Engineering, University of North Carolina, Chapel Hill, N. C. 27514, 1971)

2.4 Important Factors Influencing Vermifiltration

Though the important factors affecting the vermifiltration process vary from region to region, some of the most important factors are temperature, hydraulic loading rate, hydraulic retention time, pH (characteristics of the wastewater) and the density (number/mass per unit volume/unit area) of earthworms.

2.4.1 Temperature

Earthworms are sensitive to temperature change and require narrow temperature range to perform effectively (Neuhauser *et al.,* 1979, 1988; Graff 1982; Edwards, 1988; Edwards and Bater, 1992). Studies have shown that worms can survive temperatures ranging from 10°C to 30°C, but are most active between 15°C and 25°C (Neuhauser *et al*., 1988, Sinha *et al*., 2008). Figure 2-2 and Table 2-2 show the impact of temperature on earthworm biomass and their survival.

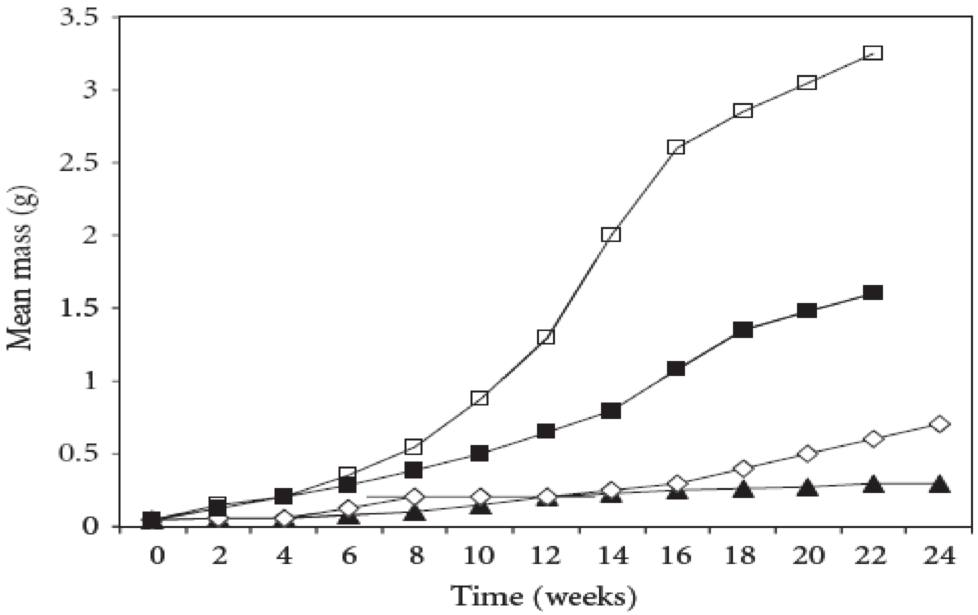

Figure 2-2. Typical earthworm growth curves obtained from periodic measurement of masses. Here *Lumbricus terrestris* was examined under constant temperature conditions
(□ 20; ■ 15; ◇10; ♦ 5◦C; adapted from (Butt, 1991).

Table 2-2. Comparison of some vermicomposting earthworm species in terms of the optimal and tolerable temperatures range (Edwards *et al.*, 2004; Edwards and I. Burrows, 1988; Blakemore, 2000)

Species	Temperatures ranges (°C)		Distribution
	Tolerated	Optimum	
Eisenia fetida	0-35	20-25	Temperate regions
Eudrilus eugeniae	9-30	20-28	Africa, India, North, and South America
Perionyx excavatus	9-30	15-30	Asia and Australia
Eisenia veneta	3-33	15-25	Europe

2.4.2 Hydraulic Loading Rate

The hydraulic loading rate affects the moisture content of the filter material which needs to maintain an optimum moisture content for earthworms' survival and reproduction as their skin needs to be moistened. An increase in hydraulic loading leads to a decrease in treatment

efficiency and adult earthworm abundance (Xing *et al.*, 2010). Moreover, increasing the hydraulic loadings leads to stronger scour for media surfaces, which is also responsible for a decrease in treatment efficiencies of vermifilter (Li *et al.*, 2008).
The hydraulic loading rate is calculated as follows:

$$HLR = Q/A \qquad (2.1)$$

Where HLR = Hydraulic Loading Rate ($L.m^{-2}.d^{-1}$)
Q = the flow ($L.d^{-1}$)
A = the surface area (m^{-2})

2.4.3 Hydraulic Retention Time

The hydraulic retention time is important parameter on determining the quality of the effluent. A reasonable HRT will allow the earthworms and bacteria to reduce BOD_5, COD and TSS, and other pollutants. For instance, Sinha *et al.* (2010) recommended a HRT of 30-40 minutes for significant reduction of BOD_5 loads between 200 and 400 mg/L of sewage supplied at continuous basis. However, for batch supply vermifiltration system, the time that various fractions of greywater spend in the vermifilter should be determined as the system is not closed from the bottom.

2.4.4 pH

pH is defined as the effective cologarithm concentration of hydrogen ions (H+) in moles per L. Earthworms can survive within a pH range of 5 and 9 (Edwards, 1988). However, earthworm reproduction is affected by pH at 6.5, 8.5 and 9.5 when compared to a control at pH 7.5 (Hughes *et al.*, 2007). The low number of juvenile earthworms at pH 6.5 and 8.5 may also imply that reproduction is inhibited at this point (Hughes *et al.*, 2007). Mathematically pH is expressed as:

$$pH = -\log 10\ [H^+] \qquad (2.2)$$

2.4.5 Porosity

Porosity is the amount of voids available in the filter materials. The porosity may decrease gradually due to the accumulation of solids, chemical precipitation and biomat formation. For instance, high concentration of organic matter and microorganisms enhance the growth of biofilms which may result in clogging (NSW HEALTH, 2000) and will affect the treatment efficiency and shorten system life span.

2.4.6 Moisture Content

Earthworms need moisture at optimum range of 60-75% (Sinha *et al*., 2010; Sinha and Valani 2011) for their reproduction and activities. However, Reinecke and Venter (1985) reported that a difference of 5% in the substrate has a significant influence.

The moisture content is determined by:

$$\mathrm{MC}\ (\%) = (\mathrm{Wet\ sample\ (g)} - \mathrm{Dry\ sample(g)}) \times 100 \div \mathrm{Wet\ sample\ (g)} \qquad (2.3)$$

2.5 Greywater

The quantity and characteristics of greywater depends on the existing water supply services and infrastructure, number of household members, age distribution, lifestyle characteristics etc (Morel and Diener, 2006). Since the drinking water consumption for the urban poor is 20-30 L/d/person (Ridderstolpe, 2004; Li *et al*., 2009), the greywater that can be generated is much less than the rich but highly polluted. Greywater comprises 50-80% of the household wastewater (Al-Jayyousi, 2003; Eriksson *et al*. 2003; Friedler and Hadari, 2006). On average, 10 $\mathrm{L.p^{-1}.d^{-1}}$ greywater is thrown out on the streets of Ouagadougou in slum areas (Orianna and Linda, 2010).

2.5.1 Sources and Characteristics

Greywater is non-toilet household wastewater produced by washing and cooking activities (Shafran *et al.*, 2005) which is generated from laundry, shower and kitchen. The characteristics of the greywater from developed and developing countries varies significantly. For instance, the greywater from a Danish household can have up to 900 different organic chemical substances and compound groups (Eriksson *et al.*, 2002). However, the greywater from the developing world, especially from the urban poor, contains mostly suspended solids, greases and fats, pathogens and chemicals derived from soaps and detergents. Table 2-3 presents the summary of untreated greywater characteristics from laundry, shower and kitchen sources.

Table 2-3. Summary of untreated greywater characteristics from each source (Queensland, 2002)

Wastewater sources	Characteristics
Laundry	Microbiological: variable thermotolerant coliform loads Chemical: sodium, phosphate, boron, surfactants, ammonia and nitrogen from soap powders and soiled clothes Physical: high in suspended solids, lint and turbidity Biological: high in biochemical oxygen demand (BOD_5)
Shower	Microbiological: lower levels of thermotolerant coliforms Chemical: soap, shampoo, hair dyes, toothpaste and cleaning chemicals Physical: high in suspended solids, hair, and turbidity Biological: lower levels of concentrations of biochemical oxygen demand
Kitchen	Microbiological: variable thermotolerant coliform loads Chemical: detergents, cleaning agents Physical: food particles, oils, fats, grease, turbidity Biological: high in biochemical oxygen demand

2.5.2 Effects of Greywater

Unless managed properly, greywater can affect public health and pollute the environment (land, water, air and bio system). Excessive watering with greywater on a small area will cause ponding that produces malodorous compounds by biological degradation. This creates aesthetic problem, pathogen growth and mosquito breeding which pose risks to public health (Christova-Boal *et al*., 1996; Dixon *et al*., 1999). The high number of pathogens, especially from the urban poor of the developing countries, may be introduced into greywater by hand-washing after using the toilet or changing infant diapers, baths, washing babies and small children, and from uncooked food products in the kitchen (Eriksson *et al*., 2002).

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Chapter 3

The Feasibility of Concentrated Greywater Treatment by Vermifiltration for Sub-Saharan Urban Poor

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Abstract

The treatment of greywater collected from an urban slum area of Ouagadougou, Burkina Faso, by vermifiltration was investigated using locally available sawdust as bedding material and *Eudrilus eugeniae* earthworm. The filtration system was made up of layers of sand, fine and coarse gravel from the top to the bottom which was spread inside a cylindrical DN200-PVC pipe. The fine sawdust and earthworms, density of 6370 worms/m^2, were added, while the same filtration system without earthworms was used as an experimental control. Batch experiments were conducted at ambient temperature, with hydraulic loading rate of 64 and 191 L.m^{-2}.d^{-1}. The raw greywater was highly concentrated with BOD$_5$ varying from 690 to 2200 mg/L and pH varying from 4.37 to 7.32. The results showed that *Eudrilus eugeniae* was able to tolerate temperatures above 40^{o}C and avoided odor and clogging problems inside the filter. The removal efficiencies of BOD$_5$, COD, TSS, *E. coli* and TTC were slightly significantly higher in the vermifilter than in the control system. Moreover, the pH at the exit of the system was close to neutral. Therefore, vermifiltration could be applied as an alternative low-cost technology to treat greywater for the urban poor in the hot climate areas.

Key words: *Eudrilus eugeniae*, Filter media, Greywater treatment, Vermifiltration

Résumé

Le traitement des eaux grises recueillies à partir d'un bidonville urbain de Ouagadougou, au Burkina Faso, par vermifiltration été étudiée en utilisant la sciure de bois disponible localement comme substrat et des vers de terre, *Eudrilus eugeniae*. Le système de filtration est composé de couches de sable, du gravier fin et grossier du haut vers le bas répandus dans un tube cylindrique DN200-PVC. La sciure de bois fine et les vers de terre, de densité de 6370 Les vers / m^2, ont été ajoutés, tandis que le même système de filtration sans les vers de terre a été utilisé comme un contrôle expérimental. Des expériences en batch ont été effectuées à la température ambiante, avec des charges hydrauliques de 64 et 191 L.m^{-2}.j^{-1}. Les eaux grises brutes étaient très concentrées avec DBO$_5$ variant de 690 à 2200 mg /L et le pH variant de 4,37 à 7,32. Les résultats ont montré qu'*Eudrilus eugeniae* peut tolérer des températures supérieures à 40 °C et éviter les problèmes d'odeurs et de colmatage à l'intérieur du filtre. Les rendements en l'abattement de la DBO$_5$, de la DCO, de MES, des *E. coli* et des CTT ont été légèrement plus important dans le vermifiltre que dans le système de contrôle. De plus, le pH à la sortie du système est proche de la neutralité. Par conséquent, la vermifiltration pourrait être appliquée comme une technologie alternative à faible coût pour traiter les eaux grises pour les populations pauvres en milieu urbain dans les zones à climat chaud.

Mots-clés: *Eudrilus eugeniae*, Les médias de filtrage, Le traitement des eaux grises, Vermifiltration

3.1 Introduction

The feasibility of the vermifiltration technology in treating concentrated greywater is studied based on the hypothesis that the hottest climate and the concentrated greywater, generated from kitchen and laundry, may affect the feasibility of the technology. Furthermore, knowing the performance of the locally available earthworms and identifying them were very important.

Many researches have been conducted in China, India, Australia, France and other countries on vermifiltration to treat domestic wastewater mostly at pilot and laboratory scale. It has been reported that vermifiltration has a great potential in decentralized treatment of domestic wastewater (Xing *et al.,* 2010) which may favor the urban poor for utilizing the technology. Kharwade and Khedikar (2011) also found the use of *Eudrilus eugeniae* on a filtration system increased the overall removal efficiencies of BOD_5, COD and TSS on an average of 10% for 2-3 h of the retention time. The vermifilter was filled with 4 cm of 20 mm size gravel, 3 cm of 10 mm size gravel, 3 cm of sand and 12 cm of soil from the bottom to top respectively.

The most widely tested filter materials, with various depths and compositions, have been organic solid waste, clay, sand, coarse sawdust and gravel (Taylor *et al.*, 2003; Li *et al.*, 2009; Kharwade and Khedikar, 2011). It has been also reported that newspaper bedding is more influential in worm biomass production and growth rate, while sawdust bedding is better for cocoons and the number of earthworms' production (Manaf *et al.*, 2009).

The vermifilter performance was also affected by the HLR, the pH of the raw wastewater, and environmental temperature. For instance, the growth of earthworms is best in the temperature range of 25-30^{o}C but above 35^{o}C they will die (Dominguez *et al.,* 2011). For vermifiltration experiment conducted in Shanghai, the HLR was increased to keep the temperature below 35^{o}C inside the filter to avoid the death of earthworms (Li *et al*., 2009).

However, as far as vermifiltration for treating greywater is concerned, no specific research has been done in sub-Saharan countries, particularly in the Sahelian area. The objective of this research was to study the potential of vermifiltration in removing organic pollutants and coliforms from concentrated greywater in a hot climate region, using locally available earthworm species, bedding materials and filter media. Attention was given on the effects of pH, temperature and HLR on removal efficiency.

3.2 Pre-tests

Pre-tests were conducted to identify the appropriate hydraulic loading rate range and to decide the mode of supply system, batch or continuous. Furthermore, the density of earthworms to be inoculated, the bedding material and the filter media type to be used were considered.

3.2.1 Hydraulic Loading Rate Determination for Batch Flow System

All experiments were preferred to be done on a batch basis after the continuous flow tests were unsuccessful due to the high concentration of the greywater. Considering 1000 $L.m^{-2}.d^{-1}$ (Li *et al.*, 2009) as optimum hydraulic loading rate, the flow rate per day was about 31 $L.d^{-1}$ for each filter and all the filters got clogged within one week after being supplied at continuous bases (Figure 3-1). Then a second trial was done by supplying 16 $L.d^{-1}$, half of the first assumption, at continuous basis but all the filters got also clogged within a week. Finally, 200 $L.m^{-2}.d^{-1}$ was tried at batch basis, four times per day, for each filter. Then the daily supply became about 6 $L.d^{-1}$ and for each batch 1.5 $L.d^{-1}$ was supplied at 8:00 am, 11:00 am, 2:00 pm and 5:00 pm and all the filters worked during the testing period.

Figure 3-1. Vermifiltration experiment at 1000 L.m^{-2}.d^{-1} at a continuous flow at 2iE campus in Ouagadougou, Burkina Faso

3.2.2 Bedding Materials, Filter Media and Earthworm Density Selection

The selection of filter materials was done based on the literature review and the availability of the materials in Ouagadougou and by the nearby. As filter materials, the fine and coarse sawdust, cow dung, sand and gravel were chosen.

For earthworms' density determination, there are different recommendations based on the number/mass of earthworms per surface area/cubic volume of the bedding material that can serve as the active layer. Soto and Toha (1998) recommended 5000-10000 worms per square meter to treat municipal wastewater. Based on the above recommendations, a trial was done for 400, 200 and 100 density of earthworms for one month. Taking into account the change in number and weight of earthworms in the vermifilters, the one inoculated with 200 earthworms was better (Table 3.1).

Table 3-1. The number and weight of earthworms at the initial and final stage

	Vermifilters		
	VF1	VF2	VF3
Initial number of earthworms	200	400	100
Final number of earthworms	174	226	80
Change in number (%)	-13	-44	-20
Initial wt of earthworms (g)	107	197	52
Final wt of earthworms (g)	109	118	38
Change in wt (%)	2	-40	-27

Therefore, the density of earthworms used during all experiments was 6370 worms/m^2 which is within the range recommended by Soto and Toha (1998).

3.3 Materials and Methods

3.3.1 Research Site

The experiment was conducted outdoor in the campus of the International Institute for Water and Environmental Engineering (2iE) in Ouagadougou, Burkina Faso. The city had average temperature of 24.8^{o}C in January, the coldest season, and 33.6^{o}C in April, the warmest one. The average daily minimum and maximum temperatures are 16^{o}C to 32^{o}C, and 26.5^{o}C to 42^{o}C, in January and April, respectively (Konate *et al.*, 2013). It is located between 12° 20' and 12°26' north latitude and 28° 1' and 1°36' west longitude. The vermifiltration system was provided with shade to protect from direct sunlight and rainfall as the earthworms are light and temperature sensitive. Figure 3-2 shows the location of the city and 2iE foundation.

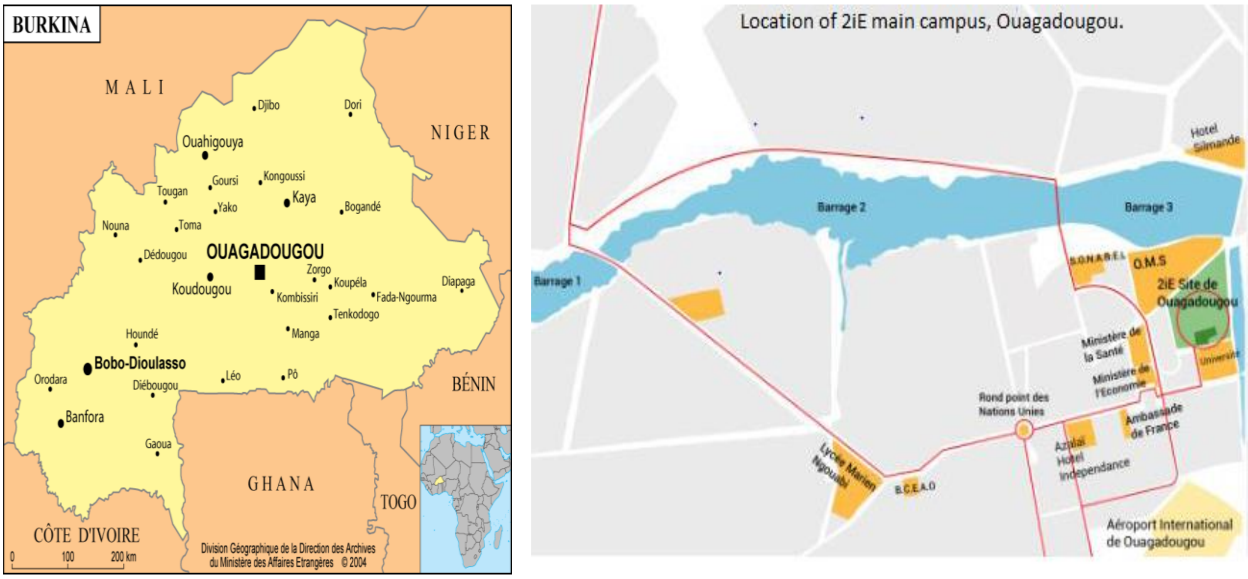


Figure 3-2. Location of the study site

3.3.2 Earthworms Collection, Culture and Identification

A stock of earthworms was collected from a moistened bank of a lake in Ouagadougou, Burkina Faso (Figure 3-3). The stock was brought to 2iE foundation research site and were cultured by feeding them with kitchen wastes, soil and cow dung, and by watering every day.

Figure 3-3. Earthworms and where they found and collected

These local available earthworms were identified scientifically: (1) by sending sample of earthworms to the known scientist Dr. Cs. Csuzdi from the Systematic Zoology Research Group of the Hungarian Academy of Sciences and Hungarian Natural History Museum, Hungary.

Samples of earthworms were killed in 75% ethanol and after 10 minutes, the 75% ethanol was replaced with pure ethanol (96%) and after one hour the preservation fluid (96% ETOH) was changed as described by Dr. Cs. Csuzdi. The 1:3 worm: ETOH ratio was used during preservation because the worms contain lots of water and can dilute the preservative which results in macerating the sample. And (2) by analysing using physical and macroscopic identification in our laboratory. The macroscopic identification of the earthworm species was done by a magnifying glass. The method allows in identifying the species based on counting the segments above the clitellum (Vijaya *et al.,* 2012) which is 14 for *Eudrilus eugeniae*.

3.3.3 Greywater Source and Collection

The greywater was daily collected in a 60 L plastic container from an urban poor household near the research site by manually driven cart (Figure 3-4). Upon arrival, it was thoroughly mixed and then supplied to the system in accordance with the selected HLR.

Figure 3-4. Greywater collection and supply to the vermifiltration system

3.3.4 Filtration System

The filtration system was made up of a cylindrical PVC pipe with a diameter of 200 mm and depth of 70 cm, in which the filter media, bedding material and earthworms were added. The same system without earthworm was used as a control unit. The filter media was made up of one layer of sand (40 cm thickness, particles size 0.08 to 16 mm), one layer of medium size gravel (5 cm thickness, grain size 20-40 mm) and one layer of coarse gravel (5 cm thickness, grain size 10-20 mm), from the top to the bottom. Then sawdust (10 cm thickness) was added to all filters. The sand has a uniformity coefficient of 1.36, effective size (d_{10}) of 0.118 mm and density of 1517.6 kg/m^3. The fine sawdust, composed of *Khaya Ivorensis, Mansonia altissima, Milicia excels* tree species, was collected from the nearby woodwork shop and had average pH of 6.47 with a density of 96 kg/m^3. The filter materials were washed with tap water pipe to remove the dust and other materials before introduced into the PVC. Figure 3-5 shows the filter materials used during the experiment.

Sand

Earthworms

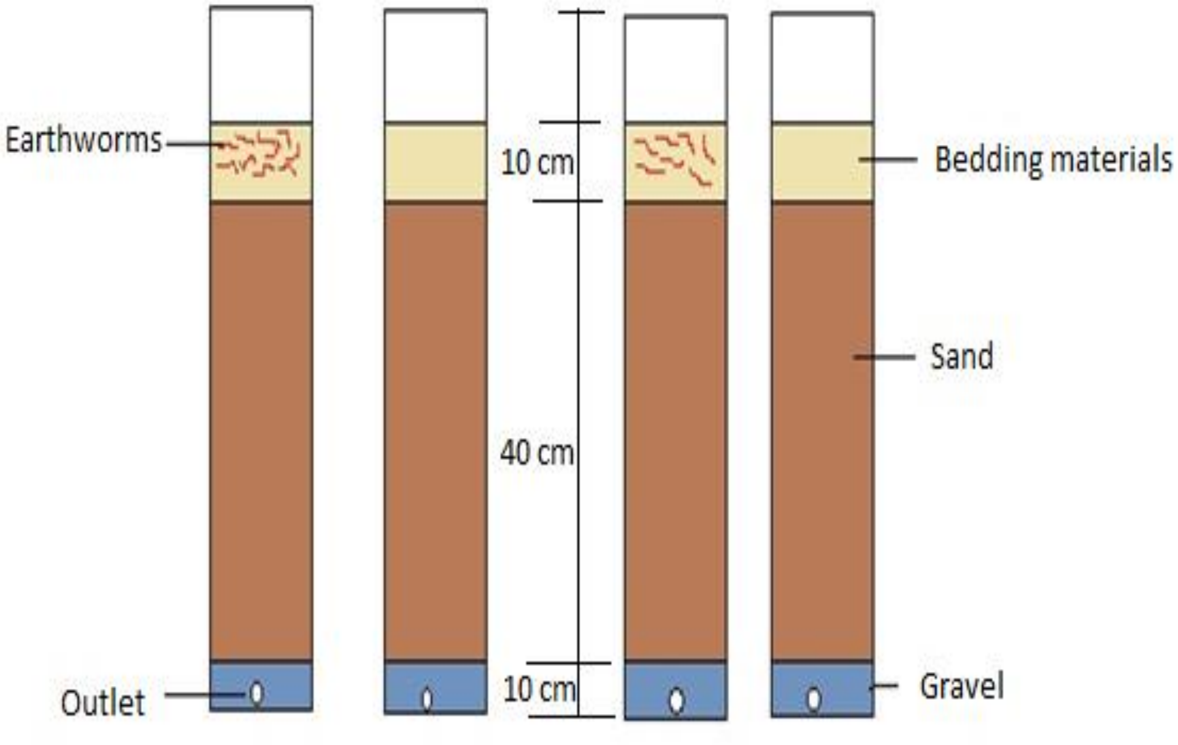
Gravel (20-40 mm aggregate)

Gravel (10-20 mm in aggregate)

Figure 3-5. The filter materials used in the experimentation

3.3.5 Experimental Set-up

As shown on Figure 3-6, a vermifilter and a control unit were constructed for each hydraulic loading rate. All the filters were filled with one layer of medium size gravel (5 cm thickness), one layer of bigger size gravel (5 cm thickness), one layer of sand (40 cm thickness) and one layer of fine sawdust (10 cm thickness) from bottom to top. The supply was done four times a day, at 8:00 am, 11:00 am, 2:00 pm and 5:00 pm after mixed thoroughly. Two feeding rates of 1.5 L and 0.5 L per batch were simultaneously tested for each condition (with and without earthworms) for a period of 13 weeks from February to May. Thus, these flow rates, 1.5 and 0.5 L per batch, gave approximately a daily HLR of 191 $L.m^{-2}.d^{-1}$ and 64 $L.m^{-2}.d^{-1}$ and a batch HLR of 43 $L.m^{-2}.d^{-1}$ and 16 $L.m^{-2}.d^{-1}$. Filter bed temperature, ambient temperature of the site and the water pH were checked and recorded four times a day, and analyses for BOD_5, COD, TSS and Coliforms were done once a week..



(a) at 191 $L.m^{-2}.d^{-1}$ (b) at 64 $L.m^{-2}.d^{-1}$

Figure 3-6. Filtration system for the two hydraulic loading rates

3.3.6 Analytical Procedures

3.3.6.1 Parameters measured on site

- **pH**

pH was measured using a portable pH meter (WTW 3310). The pH meter was calibrated using standard buffer solutions, having a pH of 4 and 7. The pH of the solution was temperature dependent, so it was very important to set temperature while calibrating and measuring pH of the sample. The pH meter measures the free [H^+] ion concentration in solution and measurements were done on site.

- **Temperature**

The temperature inside the filter materials and external environment was measured four times a day from Monday to Friday using digital thermometer (HI 93522 HANNA, Japan). The test was done before supplying the greywater to the filter at the site.

3.3.6.2 Physico- Chemical analyses

- *Total COD and dissolved COD analyses*

Both tCOD and dCOD were measured by using HACH DR/2000 direct reading spectrophotometer. The dCOD was analyzed after filtered by GF/C 0.45µm filter and vials with 0-1500 ppm were used. The sample heated with sulphuric acid and strong oxidising agent, potassium dichromate for 2h at 120°C in COD mineralizer (reactor WTW 24 tubes of 16 mm). Oxidisable organic compounds reacted with dichromate. These dichromate were reduced to green chromic ion (Cr^{3+}). When vials of 0-1500 ppm were used, the amount of Cr^{3+} produced was determined.

- *BOD_5 analysis*

BOD_5 was determined using BOD meter (WTW OxiTop). This method needed the appropriate size of sample and making it airtight and incubating in BOD incubator (B83650) at 20°C for 5 days. It was done by BOD self-checks with the respirometer and the reduction in oxygen causes a definite pressure difference which can be measured by a pressure sensor.

- *Total Suspended Solids*

TSS was determined by filtering the samples through pre-weighed GF/C 0.45µm filter as described in APHA, (1998) by gravimetric methods of analysis using an oven (Memmert 854. Schwabach, Germany). A specific volume of the sample was filtered through the filter paper. The filter paper with the solids retained was kept for drying at 100-103°C till constant weight achieved and will be weighed by precision balance with maximum load of 210 grams (B5381). Finally, the total suspended solid was determined as follows:

$$TSS = (WF, - WI) * 1000 / V_S \qquad (3.1)$$

Where: TSS = Total suspended solids in mg/L, WF, = Final weight of filter paper with the solids retained, WI, = Initial weight of filter paper, Vs = Volume of sample used.

3.3.6.3 Microbiology Analysis

Escherichia coli and thermotolerant coliforms were used as indicator bacteria for microbiological pollution assessment. The spread plate method was used after an appropriate dilution of the samples in accordance with the procedure in Standard Methods for the Examination of Water and Wastewater. Chromocult Agar (Merck KGaA 64271, Darmstadt, Germany) was used as culture medium. CFU of *E. coli* and TTC were calculated using the general formula :

$$\text{CFU of microbial communities g}^{-1}\text{ dry weight} = \frac{\text{Total number of colonies}}{\text{Dry weight of the soil (g)}} \qquad (3.2)$$

For liquid sample;

$$N = \frac{n}{V*d} \qquad (3.3)$$

Where N = concentration of bacteria (ufc/ml)

n = number of colonies

V = volume of sample (ml)

d = dilution

For solid samples;

The same formula was used as mentioned above for the liquid component and divided by 10 (the dilution factor) to find for the solid.

$$\text{Log removal value (k)} = \log_{10} \text{Cin/Cout} \qquad (3.4)$$

Where Cin = Concentration of the influent

Cout = Concentration of the outlet

K = Log removal value

3.3.7 Statistical Analyses

Microsoft Excel 2013 was used to carry out statistical analyses, develop the box and whisker plots, and figures. The results were expressed as mean ± standard deviation and the significant differences among samples were analyzed using the Mann-Whitney U-test at 5% significance level.

3.4 Results and Discussion

3.4.1 Greywater Characteristics

The characteristics of the raw greywater, showed a high concentration of organic matter, chemicals, solids and microbial indicators when compared to the wastewater tested for vermifiltration by other researchers (Table 3-2). The average concentration of $BOD_{5,}$ COD and TSS were 1598, 2049 and 1501 mg/L respectively for the greywater of this research. But the wastewater used by other researchers had average BOD_5 of 160, 297 and 23 mg/L, average COD of 324, 409 and 83 mg/L, and average TSS of 189 and 187 mg/L respectively. As a result, the BOD_5 was 10, 5 and 69 times, COD was 6, 5 and 25 times, and TSS was 8 times more concentrated compared to the wastewater used by other researchers respectively. Hence, the greywater from the sub-Saharan urban poor household was a high strength. It was collected from kitchen and laundary sources. The shower greywater was drained directly to the drainage system constructed by the household.

Generally, the greywater was highly concentrated, especially generated from the urban poor in the Sahelian region, where water shortage is an issue, because water was reused several times before final disposal. However, the greywater of this research had relatively similar physico-chemical characterstics compared to Maiga *et al*. (2014) (Table 3-3). But the average pH of the greywater from this research was slightly acidic which may be occurred due to putrescible wastes resulting in organic acids (Eriksson *et al*., 2002).

Table 3-2. Characteristics of the raw greywater

Parameters	**Present findings**		**Li *et al.* 2009**	**Xing *et al.* 2005**	**Taylor M. *et al.* 2003**
BOD_5 (mg/L)	Average	**1598**	**160**	**297**	**23**
	SD	429			9
	Maximum	2200			
	Minimum	690			
COD (mg/L)	Average	**2049**	**324**	**409**	**83**
	SD	430			23
	Maximum	2744			
	Minimum	1505			
TSS (mg/L)	Average	**1501**	**189**	**187**	-
	SD	630			
	Maximum	2340			
	Minimum	710			
pH	Average	**5.73**	-	-	-
	SD	0.79			
	Maximum	7.23			
	Minimum	4.37			
Conductivity (µS/cm)	Average	**1635**	-	-	-
	SD	681			
	Maximum	2520			
	Minimum	830			
E. coli (CFU/100mL)	Average	**$1.8*10^4$**	-	-	-
	SD	$1.2342*10^4$			
	Maximum	$3*10^4$			
	Minimum	$6*10^3$			
TTC (CFU/100mL)	Average	**$5.35*10^5$**	-	-	-
	SD	$3.322*10^3$			
	Maximum	$6.2*10^5$			
	Minimum	$2.1*10^3$			
Temperature (^oC)	Average	**26.1**	-	-	-
	SD	2.24			
	Maximum	20.9			
	Minimum	28.2			

Table 3-3. Average values of physico-chemical parameters of greywater (Maiga *et al.*, 2014)

Sources	EC (µs/cm)	T (°C)	DO (mg/L)	pH	TSS (mg/L)	COD (mg/L)	BOD_5 (mg/L)
Laundry	578.3	31.9	4.6	8.8	3060	6497.2	2743
Dishwashing	616.3	32.9	5.0	9.1	1533	3413	886
Shower	868.3	33	4.4	8.0	1093.5	1240.5	533

3.4.2 Earthworm Identification

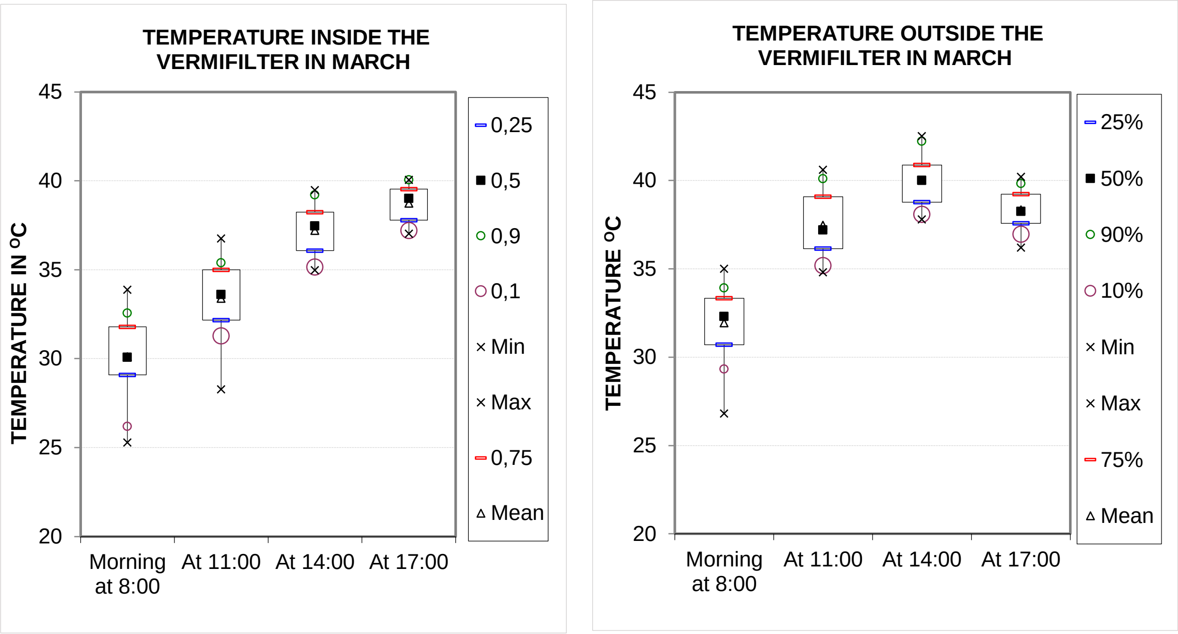
After sample of earthworms were sent to Dr. Cs. Csuzdi from the Systematic Zoology Research Group of the Hungarian Academy of Sciences and Hungarian Natural History Museum, Hungary, he confirmed that all specimens belong to the well-known African compost worm *Eudrilus eugeniae* (Kinberg, 1867) (Figure 3-7). Additionally, the earthworms were recognized by their two large combined female and spermathecal pores situated laterally on segment 14. This was done by counting the segments manually and using macroscopic magnification in the laboratory of our institution.

Figure 3-7. Female and spermathecal pores

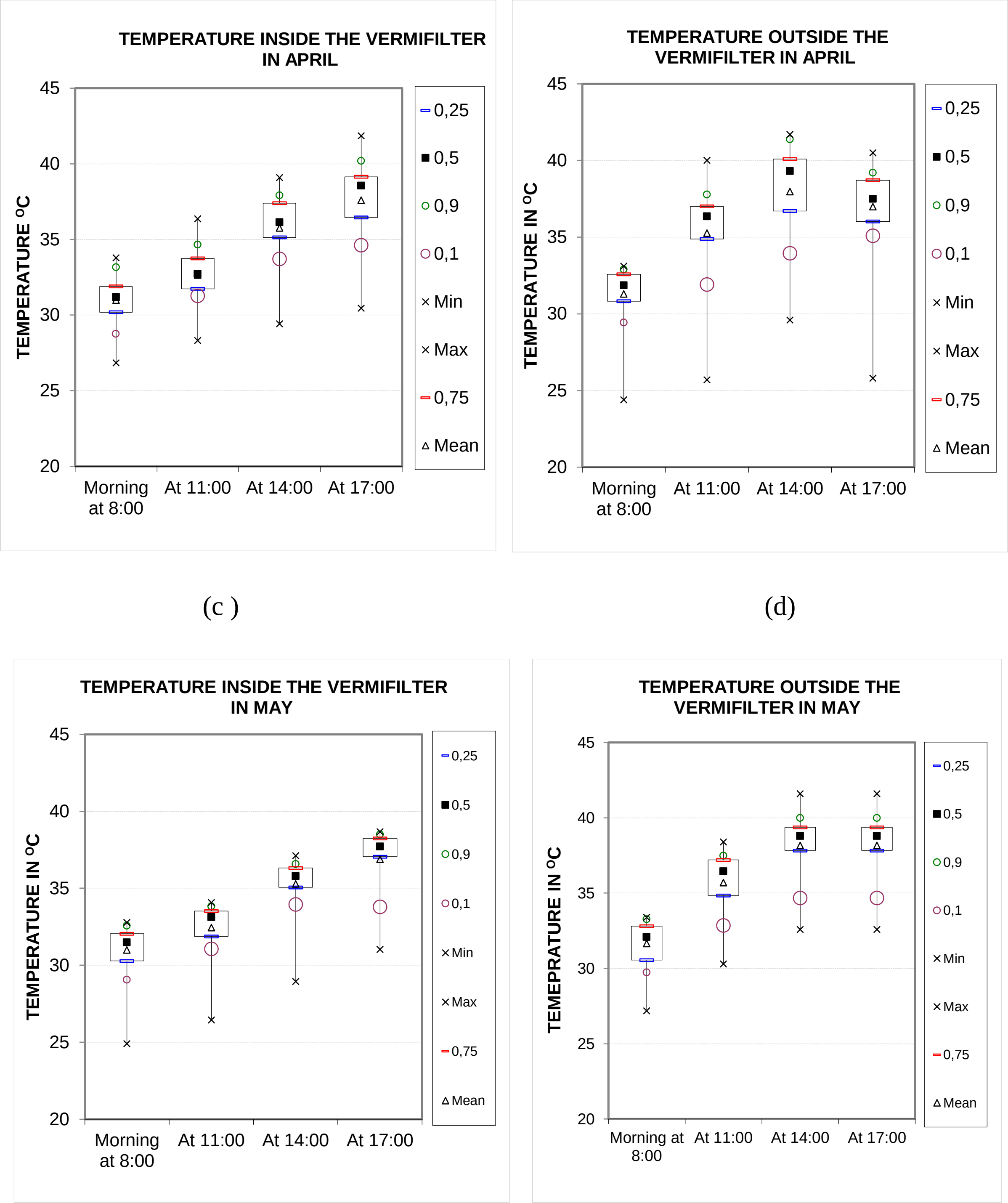
3.4.3 Effect of Temperature

Temperature was the most important factor to be verified because in most references and publications related to vermifiltration and vermicomposting, earthworms can't survive above 35°C. For instance, Li *et al*. (2009) used to cool the vermifiltration system to maintain the temperature below 35°C in order to avoid the death of earthworms. But this experiment showed that the *Eudrilus eugeniae* survived at 41.5°C. As our recording is only four times a day, there is probability that the temperature might have reached above 42°C. However, it was not yet clear for how many hours or days can they tolerate the highest temperature already recorded.

Figure 3-8 showed the average temperature inside the vermifilter (a,c,e) and the ambient temperature outside the vermifilter (b,d,f) at 8:00 am, 11:00 am, 2:00 pm and 5:00 pm for March, April and May. The temperature inside the system varied from 25°C to 41.5°C and the ambient temperature varied 24°C to 42.5°C. Inside the vermifilter, the highest temperature recorded was 41.5°C, at 17:00h in the middle of April. The dominantly available *Eudrilus eugeniae* tolerated this temperature well, which was different from the findings of (Dominguez, 2011), that *Eudrilus eugeniae* will die if the temperature is above 35°C. Usually when the temperature is above 35°C, the earthworms come to the top and interwoven each other, while remaining covered by a tiny layer of the bedding material to avoid dehydration.When it started raining, lots of cocoons were observed as the temperature decreased to 27°C which was within the optimum temperature range reported in the literature (Dominguez, 2011).



(a) (b)



(c) (d)

(e) **(f)**

Figure 3-8. Average temperature inside the vermifilter (a, c, e) and ambient air temperature outside the vermifilter (b, d, f) in March, April and May

3.4.4 Performance Comparison of the Vermifiter and the Control Unit

Table 3-4, Figure 3-9 and Table 3-5 presents the range, mean and standard deviation (SD) of effluent concentrations, the removal efficiencies, and p-values of the Mann-Whitney U-test, respectively, while comparing effluent concentrations and removal efficiencies of the VF and the control unit at a HLR of 191 $L.m^{-2}.d^{-1}$ and 64 $L.m^{-2}.d^{-1}$. As shown on Table 3-3, with a decrease of the HLR, the effluent concentrations reduced for both the vermifilter and control unit.

Table 3-4. Effluent concentrations of the vermifilter and the control unit at a hydraulic loading rate of 191 $L.m^{-2}.d^{-1}$ and 64 $L.m^{-2}.d^{-1}$

Parameter		**Effluent Concentrations**			
		Vermifilter	**Control**	**Vermifilter**	**Control**
HLR ($L.m^{-2}.d^{-1}$)		**191**		**64**	
BOD_5 (mg/L)	Average	**446**	**616**	**50**	**60**
	SD	159	166	22	54
	Minimum	130	300	20	40
	Maximum	780	960	100	180
	NS	13	13	13	13
COD (mg/L)	Average	**732**	**830**	**532**	**676**
	SD	180	187	330	327
	Minimum	435	592	435	592
	Maximum	1404	1463	1440	1463
	NS	13	13	13	13
TSS (mg/L)	Average	**73**	**116**	**25**	**59**
	SD	36	65	17	37
	Minimum	8	6	6	6
	Maximum	100	178	56	128
	NS	13	13	13	13
E. coli (CFU/100mL)	Average	**2070**	**2440**	**330**	**660**
	SD	775	1164	170	360
	Minimum	1000	1000	100	300
	Maximum	3000	3500	700	1500
	NS	10	10	10	10
TTC (CFU/100mL)	Average	**9025**	**9430**	**3000**	**5125**
	SD	10523	10541	4428	5618
	Minimum	1000	1000	500	850
	Maximum	10100	65000	11700	14000
	NS	10	10	10	10
pH	Average	**7.27**	**7.75**	**7.65**	**7.87**
	SD	0.1	0.2	0.3	0.3
	Minimum	6	6.1	7.2	7.21
	Maximum	8	8.1	8.1	8.3
	NS	13	13	13	13

NS, Number of samplings

From Figure 3-9 (box-and-whisker plots), the average removal efficiencies of BOD_5, COD, TSS, *E. coli* and TTC at HLR of 191 $L.m^{-2}.d^{-1}$ were 71%, 62%, 91%, 0.95 log units and 0.98 log units for the vermifilter, respectively, and 59%, 56%, 85%, 0.93 log units and 0.90 log units, respectively, for the control unit. At an HLR of 64 $L.m^{-2}.d^{-1}$, the removal efficiencies of the same parameters were 96%, 74%, 97%, 1.77 log units and 1.54 log units, respectively for the vermifilter, and 93%, 66%, 94%, 1.47 log units and 1.22 log units, respectively for the control unit. The removal efficiency of each parameter was slightly more significant when the system was fed with lower HLR.

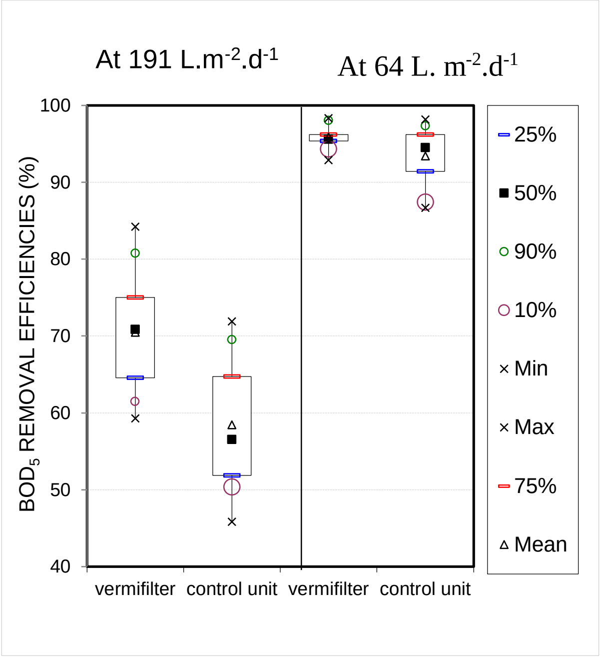
In their study, Li *et al.* (2009) and Kharwade and Khedikar (2011) have reported that the removal efficiencies of BOD_5, COD, and TSS were 90.6%, 86.8%, 94.7% and 90%, 77%, 75% respectively in the vermifilter for the two researches. The results were slightly different from ours which might be due to difference in the bedding materials, earthworm species, the flow rate and type, the temperature and the characteristics of the wastewater. Generally, the removal efficiencies were calculated as the percent removal for each parameter using the following equation:

$$R = (1 - Ce/Ci) \times 100 \tag{3.5}$$

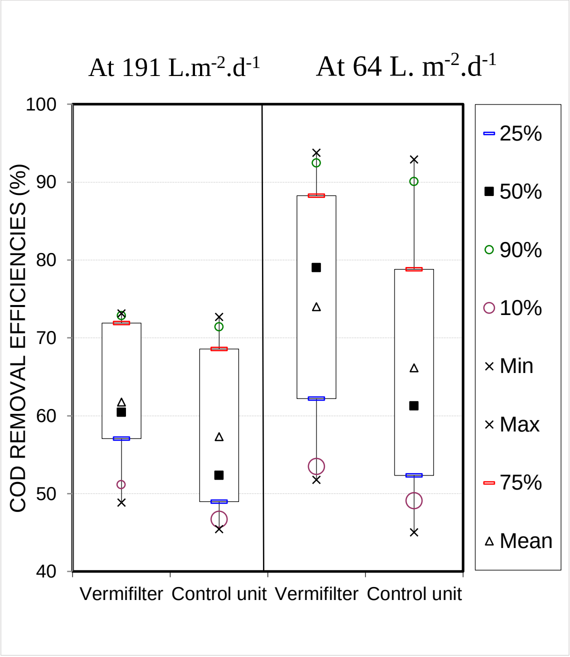
Where R = removal efficiency

Ci = the influent concentrations in mg/L

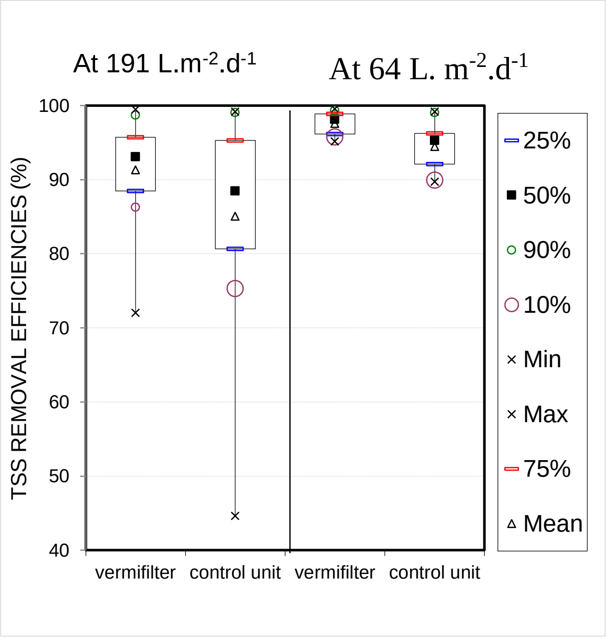
Ce = effluent concentrations in mg/L



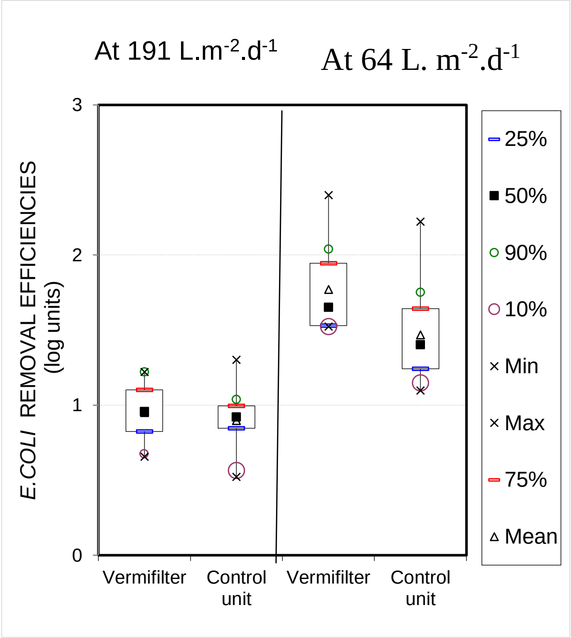
(a) BOD_5



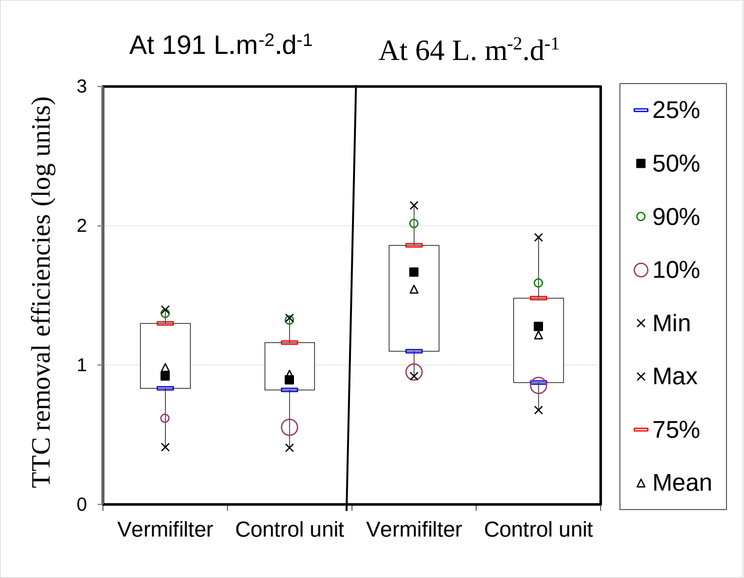
(b) COD



(c) TSS



(d) E. coli



(e) TTC

Figure 3-9. Box-and-whisker plots of BOD_5 (a), COD (b), TSS (c), *E. coli* (d), and TTC (e) removal efficiencies for the two hydraulic loading rates

As shown from Table 3-5, in general, there were no significant differences between the vermifilter and the control unit with exception of BOD_5 and TSS when comparing them in terms of effluent concentrations and removal efficiencies for 191 $L.m^{-2}.d^{-1}$. For 64 $L.m^{-2}.d^{-1}$, both TSS and *E. coli* have significant differences for both effluent concentrations and removal efficiencies. In terms of statistical differences among the vermifilters for HLR of 191 $L.m^{-2}.d^{-1}$ and 64 $L.m^{-2}.d^{-1}$, all removal efficiencies are significantly different and with the exception of COD and TTC removal for effluent concentration. Therefore, the lower the HRT the better were the removal efficiencies and in some of the coming experiments, the hydraulic loading rate of 64 $L.m^{-2}.d^{-1}$ or equivalently 16 $L.m^{-2}.d^{-1}$ per batch four times a day will be utilized.

Table 3-5. P-values of the Mann-Whitney U-test comparing effluent concentrations and removal efficiencies

Constituent	**At Loading rate 191 L.m^{-2}.d^{-1}**		**At Loading rate 64 L.m^{-2}.d^{-1}**		**The two vermifilters**	
	VF x Control (effluent concentrations)	**VF x control (removal efficiencies)**	**VF x Control (effluent concentrations)**	**VF x control (removal efficiencies)**	**VF at 191 L.m^2.d^{-1} x at 64 L.m^2.d^{-1} (effluent concentrations)**	**VF at 191 L.m^2.d^{-1} x at 64 L.m^2.d^{-1} (removal efficiencies)**
BOD_5	0.0133(*)	0.0009(*)	0.0511	0.0530	1,2E-06(*)	4,7E-08(*)
COD	0.3460	0.1120	0.3128	0.2278	0.05250	0.0237(*)
TSS	0.0372(*)	0.1917	0.0077(*)	0.0083(*)	0.0002(*)	0.0102(*)
E. coli	04151	0.5812	0.0213 (*)	0.0459(*)	4,2E-05(*)	1,8E-06(*)
TTC	0.9324	0.7432	0.3606	0.0996	0.1208	0.0057(*)

(*) p-values ≤ 0.05: sample medians are significantly different

As shown on Figure 3-10, besides the better removal efficiencies, the conditions inside the vermifilter were significantly improved compared to the control unit. The vermifilter infiltrates the supplied greywater within 1-3 minutes, but the control unit takes a longer time as the test continued due to the occurrence of clogging mid-way through the testing period. As far as odor is concerned, there was no odor problems in the vermifilter compared to the control unit. Moreover, the bedding material was changed into potentially reusable organic matter.

No clogging in the vermifilter

Clogging in the control

Potentially reusable organic matter

Figure 3-10. Conditions in the vermifilter and the control unit

3.4.5 Impact of pH

From Table 3-2 (above) the pH value of raw greywater varied from 4.37 to 7.23, probably due to the variation in concentrations of soap, detergents or type of food prepared in the house. In his study, Edwards (1988) concluded that the earthworms can survive within a pH range of 5 and 9. However, the earthworms survived at pH value of 4.37 for this research. However, when the greywater was highly concentrated, the earthworms tried to escape from the filter and returned back after few minutes. The difference in hydraulic loading rates affected the pH of the effluent. As shown in table 3-2, for the HLR of 191 $L.m^{-2}.d^{-1}$, the average pH of the effluent in the vermifilter was 7.27 and in the control unit was 7.52. This result shows that the earthworms helped the treated effluent to approach a neutral pH.

3.5 Conclusion

Finally, promising results were obtained during the test of the vermifiltration system in hot climate areas. It is suggested that this technology could be an alternative sanitation option for urban poor in these areas. The zero cost for collection and the ability to treat pollutants physically, chemically and biologically in a single facility at household level makes the technology cheaper and selective. The dominantly available *Eudrilus eugeniae* earthworm tolerated temperatures above 40^oC inside the filter and made the vermifilter odor free. Results showed that the filter with the earthworm is slightly more efficient than the filter without earthworms in removing BOD_5, COD, TSS and Coliforms. Moreover, the removal efficiencies of the vermifilter loaded with 64 $L.m^{-2}.d^{-1}$ was significantly higher compared to the one loaded with 191 $L.m^{-2}.d^{-1}$. Hence, the lower the HLR, the better were the removal efficiencies. The earthworms were also able to survive at low pH values of 4.37 which showed their tolerance to change in pH concentrations. It is recommended to conduct further test at longer intervals of time for a better understanding of the removal mechanism.

3.6 References

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Chapter 4

Effect of Filter Materials Composition on Vermifilters Performance

Chapter 4: Effect of Filter Materials Composition on Vermifilters Performance

Abstract

A comparative investigation was conducted for 10 months between sand and the fine sawdust vermifilters treating concentrated greywater generated from an urban poor household in Ouagadougou, Burkina Faso. Each of three vermifilters and one control unit were made up of cylindrical DN200-PVC pipes and filled with 10 cm of gravel at the bottom. On top of the gravel layer filter 1 (fully sand, F1) was filled with 40 cm of sand and 10 cm of fine sawdust, filter 2 (partially sand, F2) with 20 cm of sand and 30 cm of fine sawdust, respectively, and filter 3 (fully sawdust, F3) and 4 (control, F4) with 50 cm of fine sawdust only. Two hundred *Eudrilus eugeniae* earthworms were inoculated in each of the vermifilters. The vermifiltration system was supplied with greywater at a hydraulic loading rate of 64 $L.m^{-2}.d^{-1}$ on a batch basis. The removal efficiencies of BOD_5, tCOD and dCOD by vermifiltration were 25%-30% higher than the control, but little differences were observed in terms of total suspended solids and coliform removal efficiencies. Though there was no significant difference in the performance of the three vermifilters ($p > 0.05$), except for dCOD removal efficiency, the lifespan of F2 and F3 was longer than that of F1. Therefore, the fine sawdust can substitute sand as filter medium in the vermifilter.

Key words: *Eudrilus eugeniae*, Filter media, Greywater treatment, Vermifiltration

Résumé

Une étude comparative a été réalisée entre les vermifilters à sciure fine de bois et à sable pour traiter les eaux grises concentrées, générées à partir d'un ménage urbain pauvre à Ouagadougou, au Burkina Faso. Trois vermifilters et une unité de contrôle été constitués à partir de tuyaux cylindriques DN200-PVC. Deux des vermifilters étaient remplis de gravier, de sable de profondeurs variées et de sciure de bois fine du bas vers le haut. Le troisième vermifiltre et le contrôle étaient remplis de gravier et de sciure de bois fine de bas en haut. A chaque vermifiltre ont été ajoutés 200 lombrics, *Eudrilus eugeniae*, cultivés sur le site de recherche. Le système a été approvisionné de façon discontinue avec une charge hydraulique de 64 $L.m^{-2}.j^{-2}$. Les rendements d'abattement de vermifilters étaient d'environ 30% plus élevé pour la demande biologique en oxygène (DBO_5) et d'environ 25% plus élevés pour la demande d'oxygène chimique totale (DCOt) et la demande chimique en oxygène dissous (DCOd) par rapport à l'unité de contrôle. Cependant, il on more une petite différence mineure d'abattement pour les matières en suspension (MES) et les coliformes entre les vermifilters et le contrôle. Il n'y avait aucune différence significative entre les trois vermifilters pour toutes les concentrations et pour la plupart des efficacités d'abattement. En outre, la durée de vie des vermifilters était meilleure à celle de l'unité de contrôle. De cette étude, on peut donc considérer que la sciure de bois fine peut remplacer le sable comme milieu filtrant dans le vermifiltre.

Mots-clés: *Eudrilus eugeniae*; Substrat filtrant, Traitement des eaux grises, Vermifiltration

4.1 Introduction

After studying the feasibility of the vermifiltration technology to treat the concentrated greywater generated from the sub-Saharan urban poor, this chapter reports the effect of filter materials composition on the performance of the vermifilters. Do the change in the thickness of sawdust and sand layer in the vermifilters will affect their performance? To answer this equation, an experiment was conducted on effect of filter materials composition on vermifilter performance.

To improve the performance of the vermifilters, different filter media compositions have been tested. For instance, Li *et al*. (2009) have used a mixture of fine wood flour, chaff and turf at the top as bedding material, coarse wood flour and chaff as the middle layer, and fine and coarse sand at the bottom. Kharwade and Khedikar (2011) have used soil, sand and gravel from top to bottom. A bed material composed of soil and sawdust at the top, and cobble stones at the bottom were used by Wang *et al*. (2014) to study the effect of vermifiltration height. Wang *et al*. (2010) have studied a ceramic pellet as filter media in the vermifilter. Taylor *et al*. (2003) and Rajpal *et al*. (2014) have studied the removal of some parameters in filters filled with organic solid waste and other media. So far, no tests have been conducted to study the effect of different combinations of sand and sawdust layers on the efficiency of vermifilters. The aim of this study was to compare the performance of sand and fine sawdust vermifilters to the performance of a control unit for the treatment of concentrated greywater generated in homes of sub-Saharan urban poor, particularly in the Sahelian region.

4.2 Materials and Methods

4.2.1 Experimental Design

Three vermifilters and a control unit were constructed from DN200-PVC pipes with a total height of 70 cm. Figure 4-1 shows the longitudinal section of the four filters. Each of the four filters were filled at the bottom with a 5 cm layer of medium size of gravel (20-40 mm) over which a 5 cm layer of coarse gravel (10-20 mm) was layered. On top of the gravel layers, filter

1 (fully sand filter, F1) was filled with 40 cm sand and 10 cm of fine sawdust (0.05-5 mm), filter 2 (partially sand filter, F2) with 20 cm of sand and 30 cm of fine sawdust respectively, and filters 3 (F3) and 4 (F4) with 50 cm of fine sawdust only. A number of 200 *Eudrilus eugeniae* earthworms were initially added in F1, F2 and F3. F4 as a control, was not inoculated with earthworms. An outlet was added at the bottom of each filter to collect treated greywater. Moreover, each filter was supplied with uniformly mixed greywater at 16 L.m^{-2}.d^{-1} per batch four times a day at 8:00 am, 11:00 am, 2 pm and 5 pm.

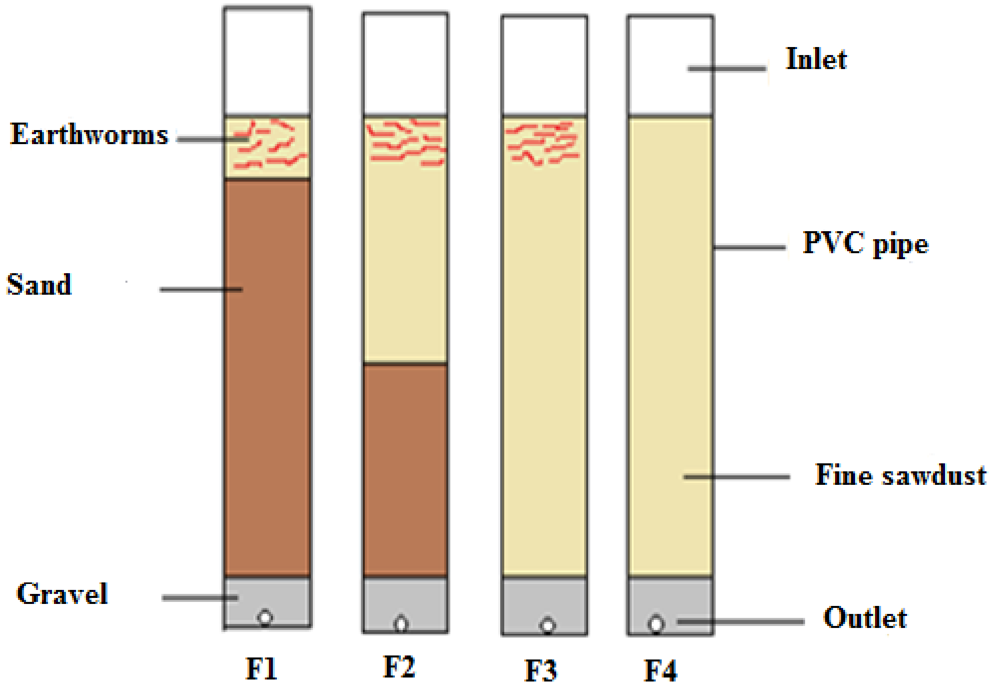


Figure 4-1. Longitudinal section of the filters: F1= Fully sand vermifilter, F2 = Partially sand vermifilter, F3 = Fully sawdust vermifilter, F4 = Control filter with sawdust

The filter media and bedding material were washed with tap water to remove dust and other impurities before the experiments were started. The sand had a uniformity coefficient of 1.36, an effective size of 0.118 mm and a density of 1517.6 kg/m^3. The fine sawdust, collected from a nearby wood workshop, was composed of *Khaya Ivorensis, Mansonia altissima and Milicia excelsa* tree species. It had an average pH of 6.47, a density of 96 kg/m^3 contained ligno-cellulosic material and rarely produced odor during its long-term biodegradation process (Terazawa *et al*., 1999).

The greywater used for the experiment was collected daily from a poor urban household. Sources of greywater were from dishes and laundry while the greywater from the shower drained directly to the drainage system constructed by the household. The four filters were fed four times a day on a batch basis with fresh greywater according to the procedure described by Adugna *et al*. (2014).

4.2.2 Water Sampling

The raw and treated greywater samples were analyzed once a week. Upon arrival at the research site, 0.8 L of thoroughly mixed greywater was collected in a plastic container that had been washed with detergent, rinsed with distilled water, and dried. The greywater was sent immediately to the laboratory to determine the initial concentrations BOD_5, tCOD, dCOD, and TSS. Following the same procedure, treated greywater was collected from the outlet of each filter and analyzed for the same parameters. Sterilized glass bottles were used to collect raw and treated greywater samples for immediate *E. coli* and thermotolerant coliforms (TTC) analyses.

4.2.3 Earthworm Monitoring

Physical observations were made to analyze the earthworms’ response to the variation in greywater concentration over the experiment. Earthworm analysis was done after 6 months, to understand the earthworm development in each vermifilter towards the end of the research, and after 8 months, to compare among the vermifilters before F1 stopped working. During the analysis, the whole filter columns were emptied by deposing the filter materials with the earthworms on flat plastic plates, taking care to maintain the layer distribution inside the filters. After separating and counting the earthworms, the filter materials were refilled to the respective filter immediately. Earthworms were analyzed as adult (mature), immature and cocoons (eggs). Mature earthworms have either a clitellum or sign of clitellum, while immature ones lack a clitellum (Stoscheck *et al*., 2012). Immature and mature earthworms were then counted and weighed on a wet basis after being washed with distilled water and dried with paper towel. The cocoons in each vermifilter were estimated after sampling 1/10th of the respective bedding material. All cocoons in the samples were counted and multiplied by 10 to determine the total number. The weight of earthworms was determined by a portable Scout TM pro balance. Then the earthworms were inoculated again to the respective vermifilters on the same day.

4.2.4 Biosolid Monitoring

VS analysis was used to determine the degradation of the fine sawdust with the adsorbed solids from the greywater. Representative samples were collected in the depth range of 10 cm from the top layer of each filter. The samples were first dried at 105°C in oven to totally avoid the moisture then the dried samples were burnt at 550°C in furnace for 3 - 4 hours to determine the volatile solids after calculating the mass reduction from the dried samples. All mass measurements were done after the samples were cooled in a desiccator.

4.2.5 Analytical Methods

Temperature, pH, BOD_5, tCOD, dCOD, TSS, *E. coli* and TTC concentrations TS was measured with the same methods and procedure mentioned in Chapter 3. Additionally, VS and FS were analyzed in accordance with Standard Methods (APHA, 1998). The samples were filtered using Whiteman GF/C 0.45µm filters for dCOD and TSS analyses.

The accumulated sludge at the bottom of the vermifilter was analyzed for chemicals by diluting the samples with distilled water at 1:20 weight to volume ratio and stirring using an Edmund Bühler GmbH SM-30 shaker at 200 rpm for 1h. Then, the samples were filtered using Whiteman GF/C 0.45µm filters and analyzed for carbonate, calcium and magnesium bicarbonate concentrations after determining phenolphthalein and total alkalinity by titrating with standard sulfuric acid using phenolphthalein and methyl orange as indicators respectively. Finally, the samples were analyzed for silicate (silica, HR, the silico molybdate method), phosphate (the phos Ver 3 method), sulfate (the sulfa Ver method), and surfactant concentrations using extraction as first step and followed by characterization using colorimetric methods (HACH Procedure, 1998).

4.2.6 Statistical Analyses

Microsoft Excel 2013 was used to carry out statistical analyses, develop the box and whisker plots, and figures. The results were expressed as mean ± standard deviation and the significant differences among samples were analyzed using Kruskal-Wallis ANOVA and Median tests at 5% significance level using MS Excel XLSTAT 2014 (version 16.4.07).

4.3 Results and Discussion

4.3.1 Performance of the Vermifilters and the Control Unit

Table 4-1 reports the range, mean and standard deviation (SD) of the concentrations of BOD_5, tCOD, dCOD, TSS, *E. coli* and TTC, and pH in the influent and the effluent of the four filters.

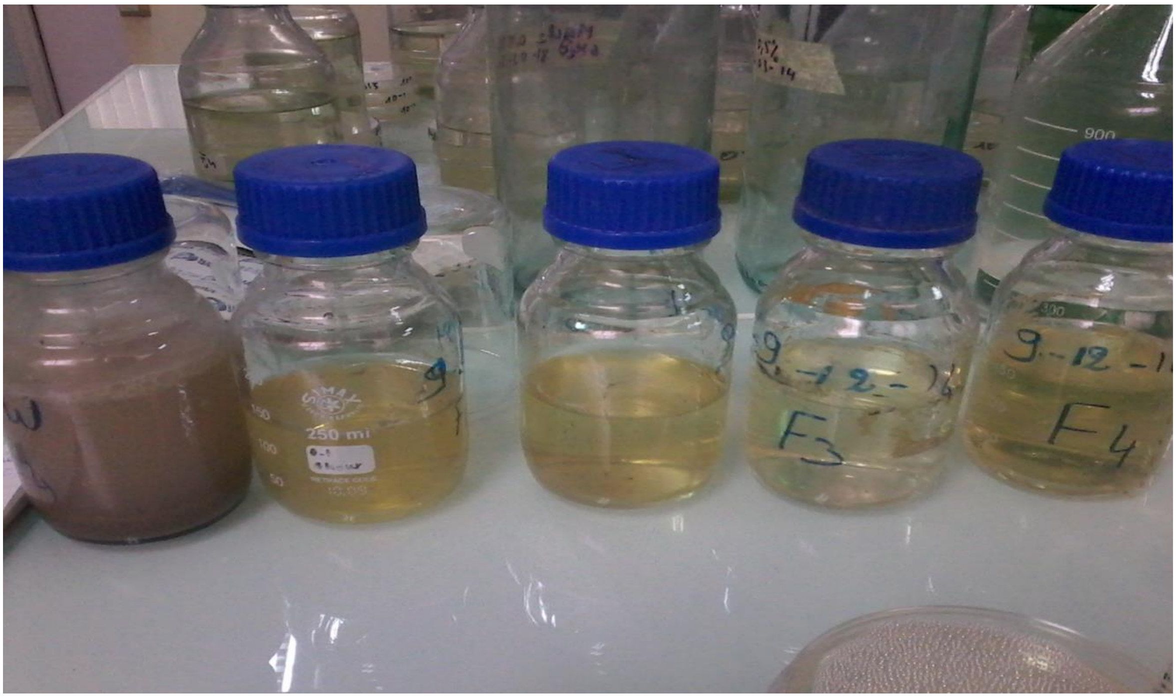
Figure 4-2 and 4-3 show the appearance of the raw greywater and effluents from the vermifilters and the control unit, and the box-plot removal efficiencies of BOD_5, tCOD, dCOD, TSS, *E. coli* and TTC.

As shown in Table 4-1, the mean residual concentrations of BOD_5, tCOD, dCOD and TSS in F1, F2 and F3 were always significantly lower than those of the control unit (Table 4-2). However, there was no significant difference of *E. coli* and TTC residual concentrations ($p > 0.05$) between F1, F3 and the control, which were lower than those of F2 (Figure 4-4).

Table 4-1. Concentrations of BOD_5, tCOD, dCOD, TSS, *E. coli*, TTC and pH in the influent and the effluent of the four filters

Parameters		Influent	Effluent			
			Vermifilters			Control
			F1	F2	F3	(F4)
BOD_5 (mg/L)	Average	**1039**	**38**	**65**	**41**	**468**
	SD	188	54	116	56	402
	Minimum	700	0	0	20	20
	Maximum	1350	420	600	460	1000
	NS	38	32	38	35	21
tCOD (mg/L)	Average	**2225**	**330**	**374**	**421**	**897**
	SD	1197	211	181	191	422
	Minimum	1255	95	59	95	237
	Maximum	6848	872	698	778	1775
	NS	45	38	45	41	28
dCOD (mg/L)	Average	**1555**	**212**	**284**	**306**	**724**
	SD	653	153	148	148	399
	Minimum	708	56	38	85	171
	Maximum	3284	764	644	1074	1766
	NS	43	36	43	39	26
TSS (mg/L)	Average	**2250**	**29**	**27**	**21**	**51**
	SD	1397	44	27	35	45
	Minimum	650	3.33	1.00	3.33	3.33
	Maximum	5340	210	93	180	177
	NS	44	37	44	44	29
E. coli (CFU /100mL)	Average	**$3.3*10^{5}$**	**176**	**416**	**314**	**270**
	SD	$4.5*10^{5}$	369	1128	531	398
	Minimum	$9*10^{3}$	0	0	0	0
	Maximum	$2.2*10^{6}$	1700	7500	2370	1600
	NS	47	41	47	44	32
TTC (CFU /100mL)	Average	**3.3**$*10^{6}$	**1686**	**2645**	**1074**	**1136**
	SD	$6.6*10^{6}$	6448	7353	1277	2362
	Minimum	$1.4*10^{4}$	0	0	0	0
	Maximum	$2.18*10^{7}$	$4.2*10^{4}$	$3.9*10^{4}$	$2.3*10^{4}$	$8.6*10^{3}$
	NS	47	41	47	44	32
pH	Average	**5.8**	**7.94**	**7.81**	**7.83**	**7.16**
	SD	0.82	0.29	0.37	0.29	0.79
	Minimum	4.26	7.1	7.11	7.00	5.26
	Maximum	7.80	8.6	8.48	8.4	8.38
	NS	51	44	51	47	34

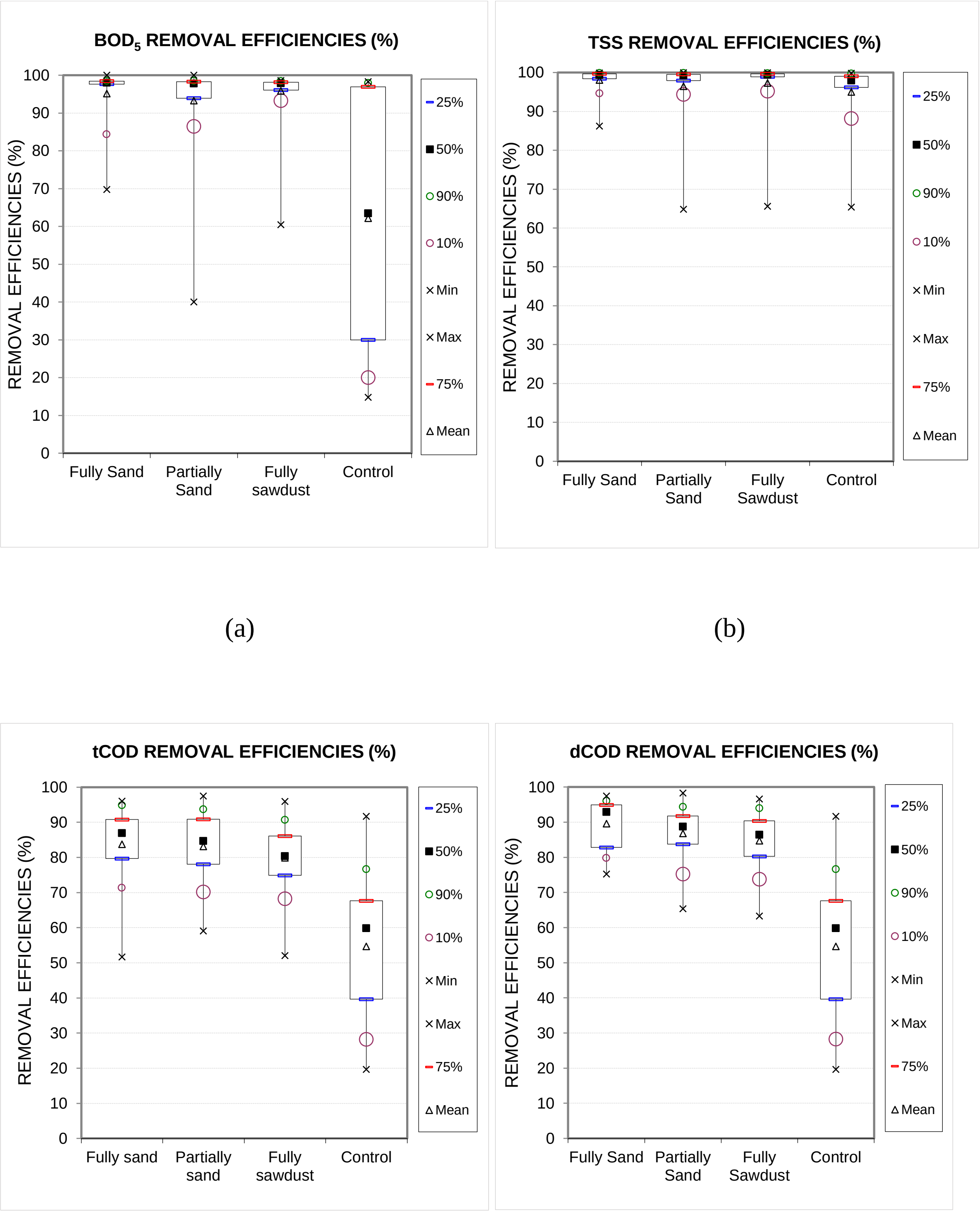
NS, Number of samples.



(a) **(b)** **(c)** **(d)** **(e)**

Figure 4-2. Appearance of the raw greywater (a) effluent from fully sand vermifilter (b) effluent from partially sand vermifilter (c) effluent from fully sawdust vermifilter (d) and effluent from the control unit (e)

As shown in Figure 4-3, the removal efficiencies of BOD_5 were 96%, 93%, 96% and 62%; that of tCOD were 84%, 83%, 80% and 55%; that of dCOD were 90%, 87%, 85% and 63%; and that of TSS were 98%, 98%, 99% and 97% in F1, F2, F3 and F4, respectively. The tCOD and dCOD removal efficiencies show the same trend (Figure 4-3(c, d)).



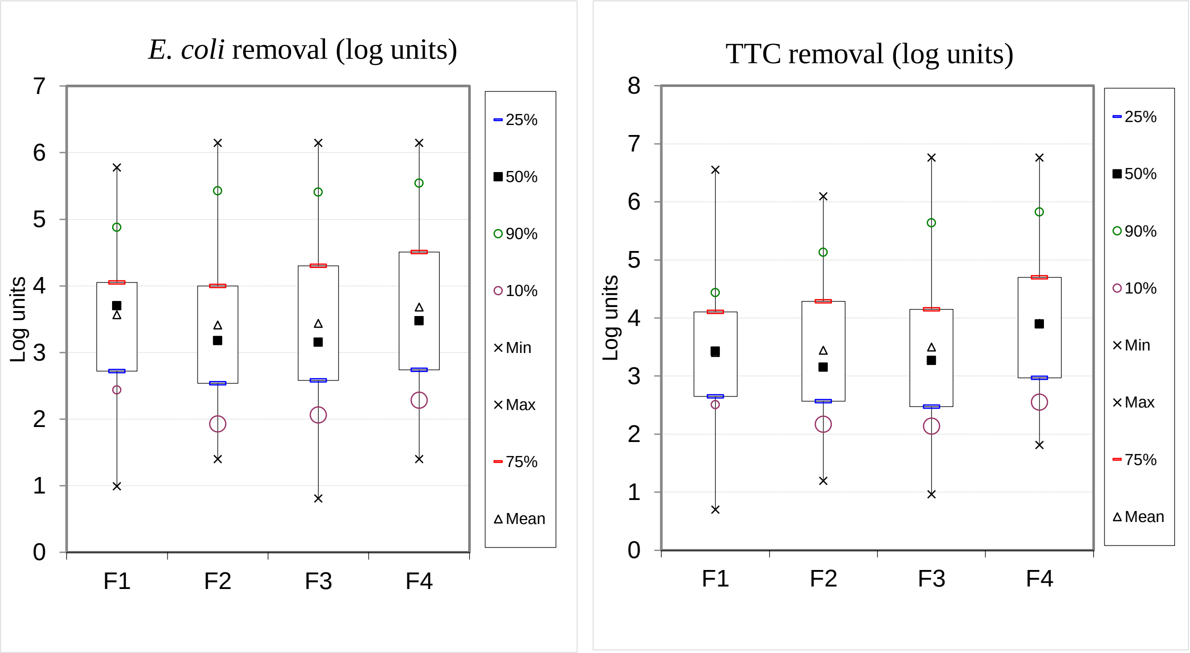
(a) (b)

(c) (d)

Figure 4-3. Box-plots of BOD$_5$ (a), TSS (b), tCOD (c), and dCOD (d) removal efficiencies

There was no significant difference among the vermifilters ($p > 0.05$) for the residual concentrations and removal efficiencies except for dCOD. However, the removal efficiencies of BOD$_5$ and tCOD in the vermifilters were on average 30% more than those of the control, whereas dCOD removal efficiency was on average 25% higher. The results for BOD_5 and tCOD of vermifilters are comparable to the results reported by Sinha *et al.* (2008) who conducted short-term tests in a lab-scale vermifilter.

The control unit also performed well in removing TSS, *E. coli*, and TTC. The removal mechanisms could be due to microbial activities, adsorption and accumulation by the whole filter media, as reported by Sinha *et al.* (2007) and Kharwade and Khedikar (2011). Furthermore, the effluents of F2 and F3 might have contained soluble sawdust degradation products, which could explain the higher concentrations of residual tCOD and BOD_5 in F2 and F3 when compared with that of F1.



(a) (b)

Figure 4-4. Box-plots of *E. coli* (a) and TTC (b) removal efficiencies

Table 4-2. P-values for concentrations and removal efficiencies between vermifilters and control unit, and among vermifilters using Kruskal-Wallis NOVA and Median tests at 5% significance level using MS Excel XLSTAT 2014 (version 16.4.07)

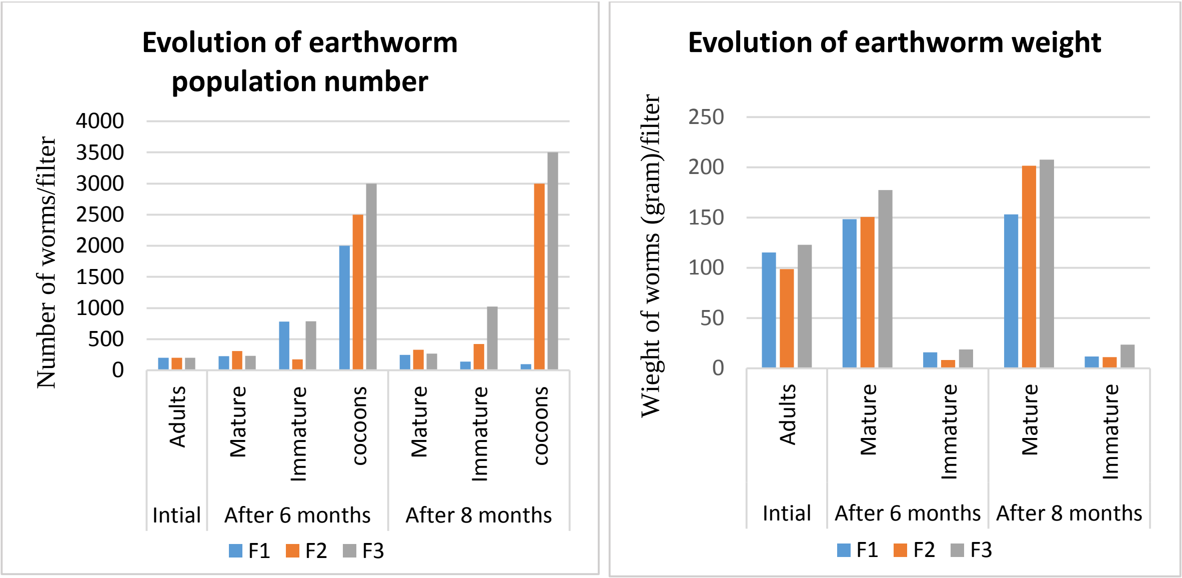
Constituent	**Vermifilters x Control (effluent concentrations)**	**vermifilters x control (removal efficiencies)**	**Among vermifilters (effluent concentrations)**	**Among vermifilters (removal efficiencies)**
BOD_5	0.0001(*)	0.0001(*)	0.732	0.533
t COD	0.0001(*)	0.0001(*)	0.115	0.063
d COD	0.0001(*)	0.0001(*)	0.055	0.033(*)
TSS	0.034(*)	0.027(*)	0.481	0.623
E. coli	0.474	0.616	0.705	0.519
TTC	0.427	0.331	0.867	0.963

(*) p-values ≤ 0.05: sample medians are significantly different

4.3.2 Earthworm Monitoring

In the first week of the experiment, the earthworms' exhibited weight loss, coiling, swollen clitellum region and some deaths which may be due to the acclimatization phase of the earthworms to their new environment. The number of deaths in F1, F2 and F3 were 7, 6 and 7 which is 3.5%, 3% and 3.5% respectively. However, after a few weeks, the earthworms have degraded the fine sawdust with the adsorbed solids from the greywater and made the bedding material relatively smaller and uniform in size compared to the control unit. A similar finding was reported by Kharwade and Khedikar (2009). Earthworms are rich in different types of microbial communities and enzymes that can help in biodegradation of the sawdust (Wolter *et al.,* 1999). There was a decrease in bedding material height in each of the three vermifilters while a small increase was observed in the control unit due to the accumulation of inorganic and poorly degraded organic solids from the greywater.

Figure 4-5 presents the evolution of earthworm population number (a) and weight (b) in each vermifilter. As shown in Figure 4-5(a), there were more mature earthworms in F2 than in F1 and F3. The number of mature earthworms increased by 14%, 56%, and 16% after six months and by 14%, 34% and 24% after eight months for F1, F2 and F3 respectively. The numbers of immature earthworms were 785, 178 and 790 after 6 months and 140, 424 and 1022 after eight months for F1, F2 and F3 respectively. The decrease in the number of immature earthworms and cocoons for F1 might be due to the unfavorable condition developed in the vermifilter, i.e., the presence of higher moisture content as greywater percolated more slowly due to the reduction in porosity. More immature earthworms and cocoons were recorded in F3. The cocoons increment in sawdust (bedding material) corresponds to the findings reported by Manaf *et al*. (2009).



(a) (b)

Figure 4-5. Evolution of earthworm population number (a) and weight (b) in each vermifilter

Similarly, as shown in Figure 4-5(b), the weight of the mature earthworms increased by 28.8%, 52.6% and 44.3% after six months and 3.3%, 33.9% and 17% increment in the additional two months' time for F1, F2 and F3 respectively. The weight of immature earthworms decreased by 26.8% for F1 and increased by 37.5% and 26% for F2 and F3 respectively between the sixth and eighth months of the experiment. The earthworms' weight loss in F1 might also be due to the unfavorable conditions which developed at the initial stage of clogging. From these results, it is assumed that the conditions in the vermifilters were good for earthworm growth and reproduction before the filters became clogged.

4.3.3 Effect on Bedding Material

Earthworms reduced the volatile solids (organic carbon) in the bedding material. The average VS proportion was about 90% in the raw fine sawdust. After eight months of operation, it was 54% in F1, 63% in F2 and 61% in F3, but 77% in F4 (Table 4-3). This data shows a 30% VS reduction in the fully sawdust vermifilter which is similar to 37% VS reduction during vermicomposting of green waste (Frederickson *et al*., 1997).

Table 4-3. The change in water content and volatile solid in the vermifiltration process at the end of the experiment

Parameters	Unit	Fine sawdust	VF1	VF2	VF3	Control
Dry weight (dried at 105°C for 24h)	gram	7.00	5.00	4.00	6.00	5.50
Fixed solids (left after burning at 550°C)	gram	0.68	2.25	1.43	2.32	1.19
Water content	%	72	80	84	76	78
Total solids	%	28	20	16	24	22
Volatile solids	%	90	55	64	61	78
Fixed solids	%	10	45	36	39	22

4.3.4 Occurrence of Clogging

Frequent clogging was observed in the control unit which stopped working after four months of operation. However, F1, F2 and F3 became clogged after 8, 9 and 10 months (end of the experiment) respectively. Besides supporting the removal of pollutants and pathogens, the earthworms thus helped to extend the lifespan of the filters especially in the sawdust vermifilters.

In F4, clogging started on the top layer. The solids accumulated at the top with high density and were also found at lower layers with lower density (Figure 4-6 (a)). This observation was similar to the findings of Rodgers *et al.* (2004). In F3, accumulation and clogging took place in a depth of 40 cm (Figure 4-6 (b)).

(a) **(b)** **(c)**

Figure 4-6. The top layer of F4 (a) the bottom of bedding material (b) and bedding material (c) of F3 after 8 months of operation

It was found that clogging in soils occurred due to solid accumulation, biomat formation, and chemical precipitation in the pores (Platzer *et al.*, 1997). In this research, the vermifilters and the control unit accumulated organic and inorganic solids, and chemical precipitations were observed. For instance, from sample analysis, the inorganic component (FS) was 47% as the VS/TSS ratio was observed to be 53%. Some of the chemical precipitations were sulfate, carbonate, calcium and magnesium bicarbonate with average concentrations of 143, 2072, 2754 and 2482 mg/Kg respectively. Adsorption of silicate, phosphate and surfactants also occurred with an average concentration of 400, 143 and 11 mg/Kg respectively.

4.4 Conclusions

This study investigated that fine sawdust can be used as a filter medium in vermifilters as a substitute for sand. However, adding a little layer of sand to the bottom is helpful. Moreover, organic matter derived from sawdust vermifilters may be used for agricultural activities. Generally, vermifilters performed much better and for a longer period than the control unit. However, the vermifilters did no longer support the earthworms' growth after several months of operation time due to high moisture content caused by the accumulation of inorganic and slowly degrading organic solids that reduced the porosity. Therefore, more experiments are needed to determine how to increase the performance and to expand lifespan of the vermifilters.

4.5 References

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Chapter 5

The Role of Vermifilter Media Layer in Pollutant Removal from Greywater

Chapter 5: The Role of Vermifilter Media Layer in Pollutant Removal from Greywater

Abstract

The contribution of each filter medium layer in removal of pollutants from concentrated greywater by vermifiltration was studied for six months. The two filters were made with cylindrical DN200-PVC pipes and were filled with 10 cm gravel, 20 cm sand and 30 cm fine sawdust from bottom to top. Two hundred *Eudrilus eugeniae* earthworms were inoculated to one of the filters and a second filter was used as a control unit. The filters were supplied with a hydraulic loading rate of 31 $L.m^{-2}.d^{-1}$ at batch basis three times a day at 8:00 am, 12:00 am, and 2:00 pm. In addition to the bottom outlet (sampling port three), two sampling ports were constructed, one at the bottom of the sawdust (sampling port one) and the other at bottom of sand layer (sampling port two). A sample of 100 ml was first collected at the bottom outlet after the first supply, and then it was closed as there were no effluents from the other ports. On the second supply, it was possible to collect sample effluent from port two, and after collecting 100 ml it was closed. During the third supply it was possible to collect 100 ml from the third port. The samples were analyzed for chemical oxygen demand (COD), total suspended solids (TSS), dissolved oxygen (DO), pH, temperature, ammonium (NH_4^+), nitrate (NO_3^-), nitrite (NO_2^-) and orthophosphate (PO_4^{3-}) concentrations. The results showed that major removal was achieved by the sawdust layer and there were significant differences ($p < 0.05$) for removal efficiencies of all parameters among the different layers of the vermifilter and the control unit. However, for concentrations, there were significant differences for COD, TSS, PO_4^{3-}, and DO among the layers but not for the other parameters. When the performances of the respective layers of the vermifilter and control unit were compared, there was no significant differences ($p > 0.05$) except for COD and DO concentrations but with a slightly less average effluent concentration of nitrate and orthophosphate in the control unit.

Keywords: Concentrated greywater; *Eudrilus eugeniae*; Filter materials; Removal mechanisms; Vermifiltration

Résumé

La contribution des couches des supports filtrant au traitement des eaux grises concentrées par vermifiltration a été étudiée pendant six mois. Les deux filtres ont été faits avec des tubes cylindriques DN200-PVC et ont été remplis avec 10 cm de gravier, 20 cm de sable et 30 cm de sciure fine de bas en haut. 200 lombrics *Eudrilus eugeniae*, ont été inoculés dans le vermifiltre et l'autre a été utilisé comme contrôle. Les filtres été approvisionnées un taux de charge hydraulique de 31 $L.m^{-2}.j^{-1}$ à base batch quatre fois par jour à 08h00, 11h00, 14h00 et 17h00. En plus de la sortie de fond (échantillonnage de port trois), deux orifices d'échantillonnage ont été construits, l'un en bas de la sciure de bois (orifice d'échantillonnage une) et l'autre au fond de la couche de sable (échantillonnage de port deux). Après la première approvisionné, à 100 ml d'échantillon ont été recueillies pour la première à la sortie en bas, puis il a été fermé car il n'y avait pas d'effluents provenant des autres ports. Sur la seconde approvisionnée, il était possible de prélever l'échantillon d'effluent à partir du port de deux, et après la collecte de 100 ml, il a été fermé. Au cours de la troisième approvisionné il a été possible de recueillir 100 ml du troisième port. L'analyse a été faite pour l'ammonium, nitrates, nitrites, orthophosphates, la DCO (demande chimique en oxygène), les MES (Matières en suspension), la OD (oxygène dissous), le pH et la température. Les résultats ont montré qu'il y avait des différences significatives ($p < 0,05$) sur l'efficacité d'élimination de tous les paramètres entre les différentes couches du la vermifiltre et l'unité de commande. Cependant, pour les concentrations, il y avait des différences significatives seulement pour la DCO, MES, PO_4^{3-} et ne concentrations entre les couches de chaque filtre. Lorsque les performances des couches respectives de l'unité de vermifiltre et de l'unité de contrôle ont été comparées, il n'y avait pas de différences significatives ($p > 0,05$), sauf pour les concentrations de DCO et d'OD, mais avec une concentration de l'effluent de nitrates et d'orthophosphates légèrement plus faible dans l'unité de commande. Pour conclure, la plus importante élimination de l'ammonium, nitrites, orthophosphates, DCO et MES a eu lieu à la couche de sciure.

Mots-clés: Eaux grises concentré; *Eugeniae de Eudrilus*; Filtrer milieu stratifie; Mécanisme de retrait ; Traitement des eaux usées à faible coût; Vermifiltration.

5.1 Introduction

In the vermifiltration process, the pollutants were removed by bedding materials, filter media, earthworms and microbial communities (Taylor *et al.,* 2003; Li *et al.,* 2009; Zhao *et al.,* 2010; Wang *et al.,* 2014).

Previous research has been done on filter media depth effect in the removal of pollutants from domestic wastewater treatment by vermifiltration. For instance, Taylor *et al.* (2003) studied the removal of selected parameters along the filter depth with 10 cm interval using organic solid waste as a medium and concluded that the filter bed depth is important for further removal some nutrients and additional oxygen demand. Wang *et al.* (2014) also reported that VF height had a significant effect on COD and total phosphorous removal rates, earthworm population, and actinomycetes number but did not affect ammonia and total nitrogen removal rates, bacteria and fungi number. Moreover, Zhao *et al*. (2009) reported that pollutant removal efficiency was highest when the vermifiltration height is between 30 and 70 cm.

In chapter four, it is reported about the effect of filter materials composition (sawdust and sand), on vermifilter performance and concluded that the sawdust can substitute for sand as a filter medium because there was no significant difference among the vermifilters performance. However, the contributions by each filter medium need to be studied further.

Therefore, the aim of this study was on quantification of contributions from the fine sawdust layer, sand layer and the gravel layer of the vermifilter and the control unit in the removal of selected physico-chemical parameters and nutrients while treating the concentrated greywater by vermifiltration.

5.2 Materials and Methods

5.2.1 Experimental Set up

The two filters were filled with 10 cm gravel, 20 cm sand and 30 cm fine sawdust from bottom to top respectively and one of the filters was inoculated with 200 *Eudrilus Eugeniae* (Figure 5-1). Sampling ports were installed immediately at the bottom of the filter medium layer to collect out samples using the extended ports passing the 200 mm diameter PVC wall.

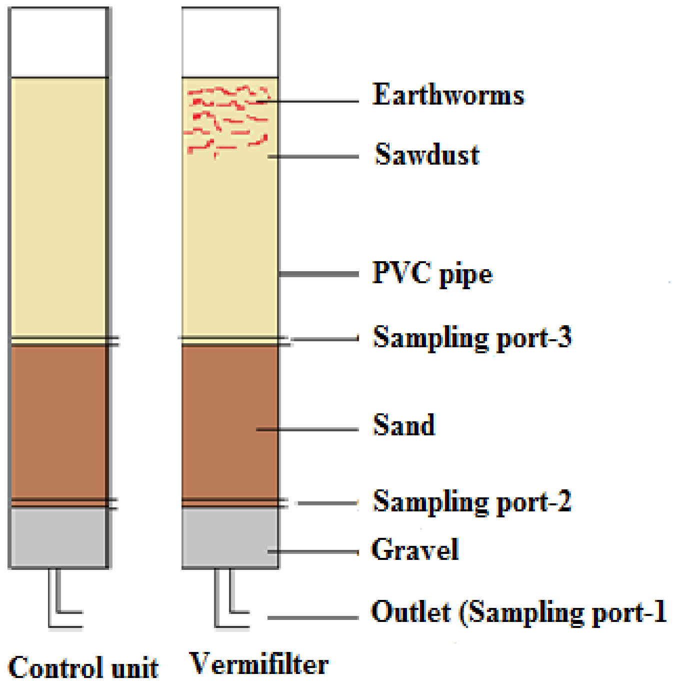

Figure 5-1. The cross-sectional view of the vermifilter and the control unit

The vermifilter and the control unit were filled with 10 cm of gravel at the bottom which was composed of a layer of medium size gravel (5 cm thickness, aggregate size 20-40 mm) at the bottom and a layer of coarse gravel (5 cm thickness, aggregate size 10-20 mm) at the top. The sand has a uniformity coefficient of 1.36, effective size of 0.118 mm and density of 1517.6 kg/m^3. The fine sawdust was composed of *Khaya Ivorensis, Mansonia altissima, Milicia excelsa* tree species and collected from a nearby woodwork shop with an average pH and density of 6.47 and 96 kg/m^3 respectively. The filter media and bedding material were washed with tap water to remove dust and other impurities.

After homogenizing the concentrated greywater collected from a poor urban household of Ouagadougou, it was supplied to the two filters three times per day at 8:00 am, 12:00 am and 4:00 pm from Monday to Friday at HLR of 95 $L.m^{-2}.d^{-1}$ (1 L/batch*3 batch/day).

5.2.2 Physico-Chemical Characteristics of Greywater

Table 5-1 presents the average concentrations of the greywater with standard deviation (SD). As shown in Table 5-1, the concentrated greywater is not only rich with organic pollutants and pathogens, but also with nutrients. The greywater was composed of high concentration of NH_4^+, NO_3^-, NO_2^-, and PO_4^{-3}. The main causes for being concentrated are (1) shower water was drained out with the drainage line constructed by the householder and (2) the other sources, kitchen and laundry wastewater, were used again and again due to water supply shortage.

Table 5-1. The concentration of the greywater

Parameters	Minimum	Maximum	Average	SD	NS
TSS (mg/L)	1270	3014	2079	605	12
COD (mg/L)	1910	4700	3062	623	5
PO_4^{3-} (mg/L)	2.55	87	34	30	14
NH_4^+ (mg/L)	3	95	25	25	14
NO_3^- (mg/L)	4	113	28	29	14
NO_2^- (mg/L)	0.12	100	37	28	14
pH	4.37	8.34	6.81	1.26	14
Temperature (°C)	26.20	29.9	30.04	1.21	14
Dissolved oxygen (mg/L)	1.7	6.03	4.69	1.34	14

NS = Number of samples

5.2.3 Water Quality, Earthworm and Bacterial Analyses

The raw greywater and effluents from different sampling ports were analyzed for physico-chemical parameters with procedures mentioned in chapter 3 and 4. 100 ml of sample was first collected at the bottom outlet, then it was closed as there were no effluents from the other ports. On the second supply, it was possible to collect sample effluent from port two, and after collecting 100 ml it was closed. During the third supply it was possible to collect 100 ml from the third port. Usually, the samples were analyzed within the same day of sample collection. When same-day was not possible, the samples were stored at 4°C for less than 24h before analyses.

COD and TSS concentrations were determined in accordance with Standard Methods (APHA, 1998) by potassium dichromate method and gravimetric methods of analyses, using HACH DR/2000 Direct reading spectrophotometer and an oven (Memmert 854. Schwabach, Germany), respectively. The pH, temperature and DO concentration were measured in situ with an integrated portable pH-T-DO meter (WTW 340i/SET). NH_4^+, NO_3^-, NO_2^-, and PO_4^{3-} were analyzed using HACH DR/2000 direct reading spectrophotometer with the absorption wavelengths of 425 nm, 500 nm, 585 nm and 880 nm after adding Nessler, Nitra Ver, Niter Ver and Phos Ver reagents in the samples, respectively (HACH Procedure, 1998). The samples were filtered using a GF/C 0.45μm filter and diluted depending on the readability by the spectrophotometer.

Two hundred adult *Eudrilus eugeniae* were inoculated to one of the filter and the other was used as a control unit. To understand the earthworm dynamics, the earthworms and cocoons were counted after sorting by hand at the end of the experiment. The earthworms were also weighed after washing with distilled water and were dried with paper towels.

Quantification of bacterial population from the filter bed material (fine sawdust) was determined by spread plate method using nutritive agar medium after 10 g of sample was collected on the top layer (10 cm thickness) from each filter using sterilized glass bottles. A gram of sample was taken from the already collected sample and diluted with 9 ml sterile water and mixed using a vortex, then diluted upto 15 dilutions. A sample of 100 µl was taken from each dilution and spread on the autoclaved petri-dish to be incubated at 37°C for 18-24h.

5.2.4 Sawdust Components and Biosolids Analyses

The degradation of the sawdust was analyzed by quantifying ash, extractives and lignin after collecting sample from 0-10 cm depth of the top layer. The ash was determined using standard methods (APHA, 1998) by gravimetric methods of analysis using Carbolite Muffle Furnace, made in UK. The extractives were determined after boiling with acetone and distilled water for 6 and 2h respectively and by drying the samples at 105°C. The lignin was determined by mixing the extracted sample with 72% sulfuric acid, which was kept in the refrigerator at 10°C for 2h before it was mixed with 300 ml distilled water and boiled for 1h. After cooling, it was diluted with 150 ml distilled water three times while being filtered. From the mass balance, it was possible to determine the helocellulose concentration. Moreover, the fine sawdust with the adsorbed solids from the greywater was analyzed for VS using standard methods (APHA, 1998). Porosity was determined by volumetric method and the bedding material depth variation was measured by ruler.

5.2.5 Statistical Analyses

Microsoft Excel 2013 was used to carry out statistical analyses and develop figures. The results were expressed as mean ± standard deviation and one way analyses of variance (ANOVA) was performed to determine significant difference ($p < 0.05$) between the vermifilter and the control unit layers and among layers in the same filter.

5.3 Results and Discussion

5.3.1 Performance Evaluation for the Vermifilter and Control unit

Both the vermifilter and the control unit were able to remove pollutants mainly at the top (top) layer where microbial communities and earthworms dominate. There were significant differences ($p < 0.05$) for all removal efficiencies among different layers of the vermifilter and the control unit for all parameters (Table 5-4). However, for concentrations among layers of the filters, there were significant differences only for COD, TSS, PO_4^{3-} and DO. Comparing the performances of the two filters at each layer, there was no significant differences ($p > 0.05$) except for COD and DO concentrations. However, effluent concentrations of NO_3^- and PO_4^{3-} were less in the control unit (Table 5-5).

5.3.1.1 Physico-chemical parameters

Table 5-2 and Figure 5-2 present TSS and COD removal efficiencies, and average effluent concentrations of TSS, COD, DO, pH and temperature respectively. The top layer removed more than 90% of TSS and 75% of COD both in the vermifilter and the control unit (Figure 5-2). However, there was less difference for TSS and COD removal efficiencies between the vermifilter and the control unit of this experiment compared to previous two experiments (Adugna *et al.*, 2014, 2015). It might be due to biosolid sample collection from top layer of both filters for analyzing the bacterial community. This allowed the control unit to continue performing rather than clogging. The concentration of pH and DO increased along the depth while temperature decreased for both filters (Table 5-2). In the vermifilter, the effluent from the active (top) layer and the bottom (out-let) had a pH of 7.6 while in the control unit, the top layer had a pH of 7.6 and at the bottom layer had a pH of 7.9 showing slight increase. The pH increment might be due to the accumulated (precipitated) carbonates, bicarbonates and chemicals in the filter materials. Low concentrations of DO was on the top layer and increased along the depth but the vermifilter had more DO compared to the control as aerobic conditions were created by the existence of earthworms and the resting period due to the batch supply system.

Table 5-2. The effluent concentration of COD, TSS, DO, pH and Temperature

Parameters		**Concentration of effluents at the sampling ports**					
		Vermifilter			**Control unit**		
		60 cm	**50 cm**	**30 cm**	**60 cm**	**50 cm**	**30 cm**
COD (mg/L)	Average	**425**	**470**	**802**	**524**	**570**	**798**
	SD	42	57	209	42	29	144
	Maximum	614	686	1221	4942	4476	5700
	Minimum	414	492	593	454	492	593
TSS (mg/L)	Average	**49**	**64**	**105**	**80**	**106**	**146**
	SD	21	23	56	49	61	95
	Maximum	79	106	220	157	188	389
	Minimum	7	32	46	17	32	42
DO (mg/L)	Average	**4.7**	**3.4**	**2.1**	**3.6**	**2.7**	**2.1**
	SD	1.3	1.3	1.4	2.3	2.0	1.7
	Maximum	6.2	5.4	5.1	6.1	5.7	5.3
	Minimum	2.5	1.8	0.4	0.5	0.7	0.3
Temperature (^{o}C)	Average	**29**	**29**	**29**	**29**	**30**	**30**
	SD	2	3	3	2	3	3
	Maximum	33	34	35	33	34	34
	Minimum	26	26	26	26	26	25
pH	Average	**7.6**	**7.6**	**7.6**	**7.9**	**7.6**	**7.6**
	SD	0.5	0.4	0.8	0.5	0.5	0.5
	Maximum	8.5	8.3	8.5	8.8	8.7	8.4
	Minimum	6.9	7.0	5.4	7.0	6.9	6.9

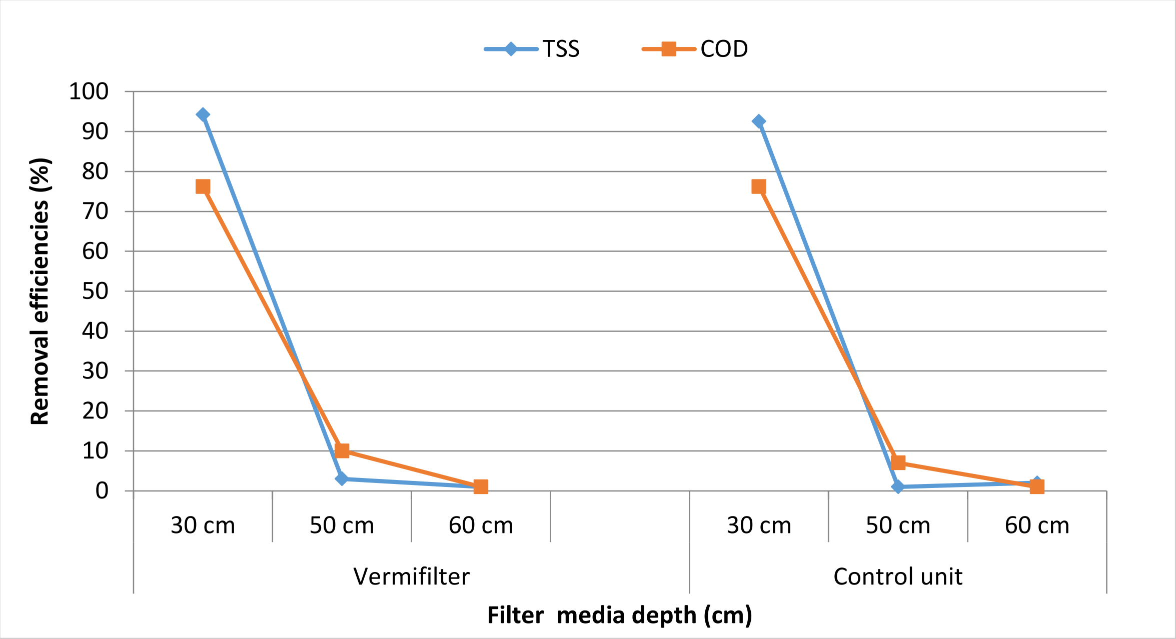

Figure 5-2. TSS and COD removal efficiencies at different layers

Generally, more removal was achieved above 30 cm (fine sawdust) for most parameters, corresponding with the findings of Zhao *et al*. (2009) that pollutant removal efficiency was highest when the VF height was between 30 and 70 cm.

5.3.1.2 Nutrients

Table 5-3 and Figure 5-3 present the removal efficiencies and the average effluent concentrations of the nutrients respectively. The top layer of the vermifilter and the control unit removed 45% and 39% of ammonium concentration respectively (Figure 5-3). This high removal of ammonium might be due to the aerobic condition created by earthworms. Taylor *et al*. (2003) found that earthworm cast production oxygenated the influent and facilitate ammonia nitrification by microbes. Due to ammonium nitrification, additional nitrate was produced which might hinder improved removal of nitrate. The good removal at the top might be due to adsorption by the sawdust and utilization by microbes and earthworms as reported by Wang *et al*. (2011) and Wang *et al*. (2013). Dalahmeh *et al.* (2011) also reported that organic matter degradation and nitrification occurred mainly in the top 20 cm of a bark filter.

As shown in the Figure 5-3, the total removal of nitrite and orthophosphate was higher in the control unit than the vermifilter. However nitrite removal was better on top layer for the vermifilter which might be due to the contribution of microbial communities and earthworms, in addition to the adsorption by the sawdust. Fang *et al.* (2010) found that fixation, adsorption and co-precipitation in earthworm packing beds, was the main mechanism for P removal. The activities of the microbial communities and earthworms may have increased the conversion of the particulate phosphorus into soluble (orthophosphate). For instance, Parthasarathi *et al.* (2007) identified the phosphate solubilizing and nitrifying bacteria in the guts and casts of the earthworms.

Table 5-3. The effluent concentration of nutrients

Parameters (mg/L)		**Concentration of effluents at the sampling ports**					
		Vermifilter			**Control unit**		
		60 cm	**50 cm**	**30 cm**	**60 cm**	**50 cm**	**30 cm**
NH_4^+	Average	**8**	**8**	**13**	**14**	**17**	**18**
	SD	14	12	11	16	18	19
	Maximum	57	47	36	43	51	57
	Minimum	0.5	0.5	1.3	0.7	0.9	1
NO_3^-	Average	**11**	**10**	**9**	**10**	**10**	**8**
	SD	10	9	8	12	11	6
	Maximum	40	36	24	48	42	18
	Minimum	1.5	0.5	0	0	0.5	0
NO_2^-	Average	**11**	**12**	**17**	**12**	**14**	**20**
	SD	7	11	26	15	13	26
	Maximum	25	35	100	60	40	100
	Minimum	0.1	0.5	0.8	0.1	0.4	0.1
PO_4^{3-}	Average	**22**	**25**	**26**	**16**	**18**	**25**
	SD	32	36	42	22	22	38
	Maximum	116	130	166	86	86	150
	Minimum	1.0	1.3	3.1	0.6	0.8	0.8

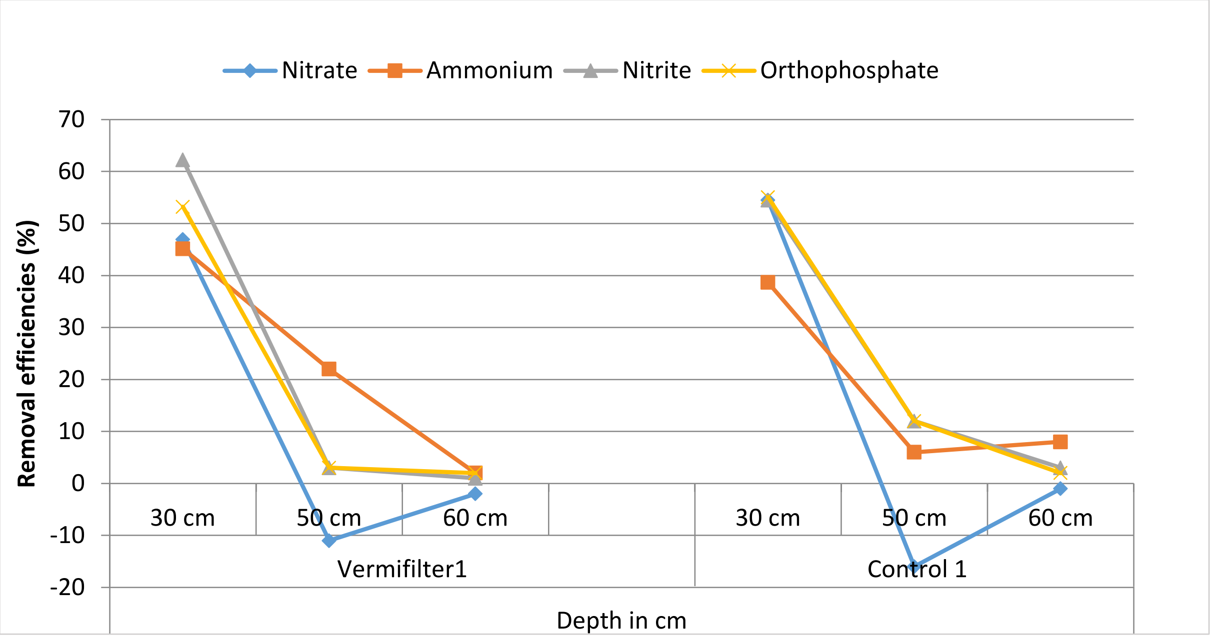

Figure 5-3. Ammonium, Nitrate, Nitrite and Orthophosphate removal efficiencies at different layers

Table 5-4. P-values for removal efficiencies among the layers in the vermifilter, control unit, and between respective layers of the vermifilter and control unit

Parameters	**Among layers in the filter**		**Between vermifilter and control unit**		
	Vermifilter	**Control unit**	**Sawdust layer X Sawdust layer**	**Sand layer X Sand layer**	**Gravel layer X Gravel layer**
COD	4.85E-23(*)	4.55E-22(*)	0.9278	0.82296	0.445087
TSS	0.0027(*)	0.0116(*)	0.08095	0.06730	0.402565
NH_4^+	0.01815(*)	0.02431(*)	0.5239	0.17441	0.443151
NO_3^-	0.0011(*)	0.02586(*)	0.9676	0.88248	0.870136
NO_2^-	6.0E-06(*)	3.5E-05(*)	0.78566	0.78566	0.540613
PO_4^{3-}	529E-07(*)	3.1E-06(*)	0.52778	0.29013	0.876944

(*) p-values ≤ 0.05: sample medians are significantly different

Table 5-5. P-values for concentrations among the layers in the vermifilter, control unit, and between respective layers of the vermifilter and control unit

Constituent	**Among layers in the filter**		**Between vermifilter and control unit**		
	Vermifilter	**Control unit**	**Sawdust layer X Sawdust layer**	**Sand layer X Sand layer**	**Gravel layer X Gravel layer**
COD	1.1E-06(*)	0.0001(*)	0.00059(*)	0.00138(*)	0.33395
TSS	2.5E-39(*)	3.7E-32(*)	0.659468	0.96799	0.40257
NH_4^+	0.4239	0.9228	0.157416	0.146443	0.44315
NO_3^-	0.8101	0.7829	0.744523	0.932557	0.6144
NO_2^-	0.5971	0.7864	0.785659	0.785659	0.54061
PO_4^{3-}	5.3E-07(*)	3.1E-06(*)	0.527783	0.290125	0.87694
DO	0.0029(*)	0.0241(*)	0.234(*)	0.04872(*)	0.036(*)
pH	0.97878	0.49478	0.22566	0.989439	0.89645

(*) p-values ≤ 0.05: sample medians are significantly different

5.3.2 Earthworm Analysis

Eudrilus eugeniae showed significant growth and reproduction performance after acclimating to the new environment. The change in earthworm weight, growth rate, number of cocoons and reproduction rate at the end of the experimental period are shown in Table 5-6. The conditions in the vermifilter favor the increase of earthworm population which is important for better removal of pollutants. Bajsa *et al.* (2003) found that earthworm population plays an important role in the adsorption and stabilization of dissolved and suspended organic matter and nutrients through complex biodegradation processes.

Table 5-6. The earthworm development in the vermifiltration process

	Earthworms	(After 6 months)		
		Mature	Immature	Cocoons
Number	200	278	535	350
Total wt. (gram)	120.3	158.2	37	-

5.3.3 Bacterial Community

As shown in Figure 5-4, more bacterial community were observed in the vermifilter than the control. The influent concentration and the hot temperature might have contributed to this result in addition to the earthworms' activities which favors growth of some microbial communities as found by (Canellas *et al*., 2002).

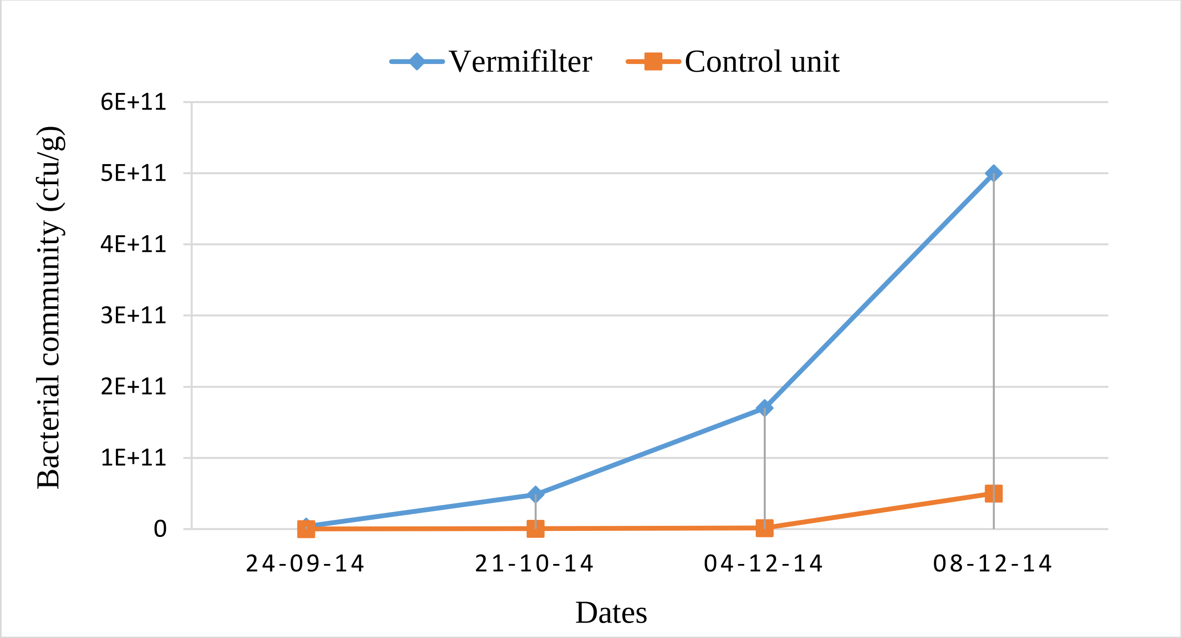

Figure 5-4. Bacterial community enumeration in the filters

5.3.4 Effect on Bedding Materials and Filter Media

5.3.4.1 Volatile solids change in the filters

Volatile solids are indicator for organic carbon. As shown in Figure 5-5, after six months, the volatile solids decreased from 92% to 73% for the vermifilter and 84% for the control unit. The figure shows that earthworms' availability promoted the degradation of the volatile solids. Similarly, Li *et al*. (2013) reported that earthworms promote degradation in biofilms.

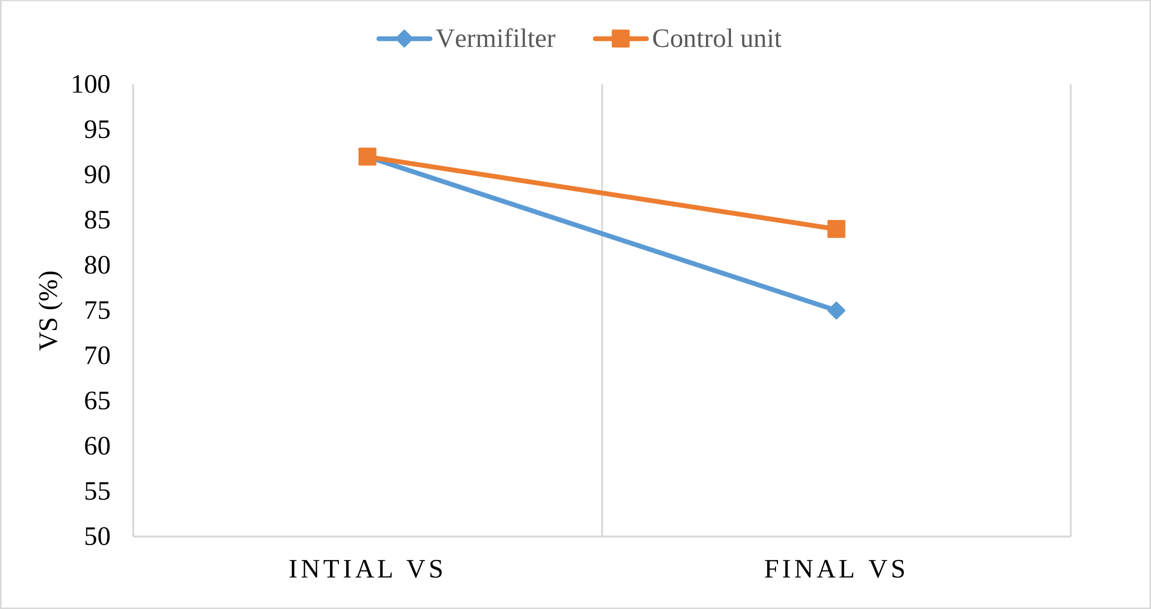

Figure 5-5. The amount of volatile solids reduction at the end of the experiment

5.3.4.2 Depth of the bedding material shrinkage

The shrinkage of bedding materials after six months is presented in Figure 5-6. The vermifilter decreased by 12 cm while the control unit increased by 1 cm. Hence there was 40% reduction in the vermifilter and about 1.5% increment in the control unit. The decrease in the vermifilter is due to the earthworm and microbial activity and the increase in the control unit might be from the accumulation of inorganic and slowly degradable organic solids from the greywater.

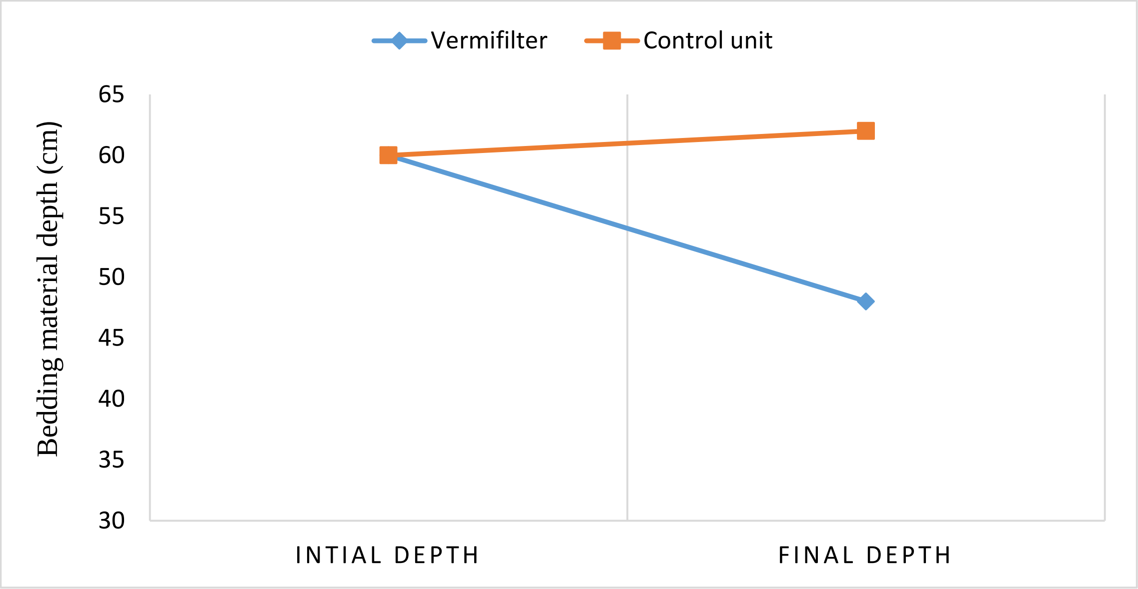

Figure 5-6. The depth of the bedding material (sawdust) at the end of the experiment

5.3.4.3 Fine sawdust component degradation

There was a significant reduction of cellulose from the bedding material in the vermifilter than the control unit. After six months, 57% of the helocellulose was reduced to 31% in the vermifilter and to 47% in the control unit (Figure 5-7). There was degradation of helocellulose in the control unit which is mainly done by microorganisms. This corresponds to Morgan and Burrows (1982) who found that earthworms and microbes act symbiotically and synergistically to accelerate decomposition of organic matter and the microorganisms break down the cellulose.

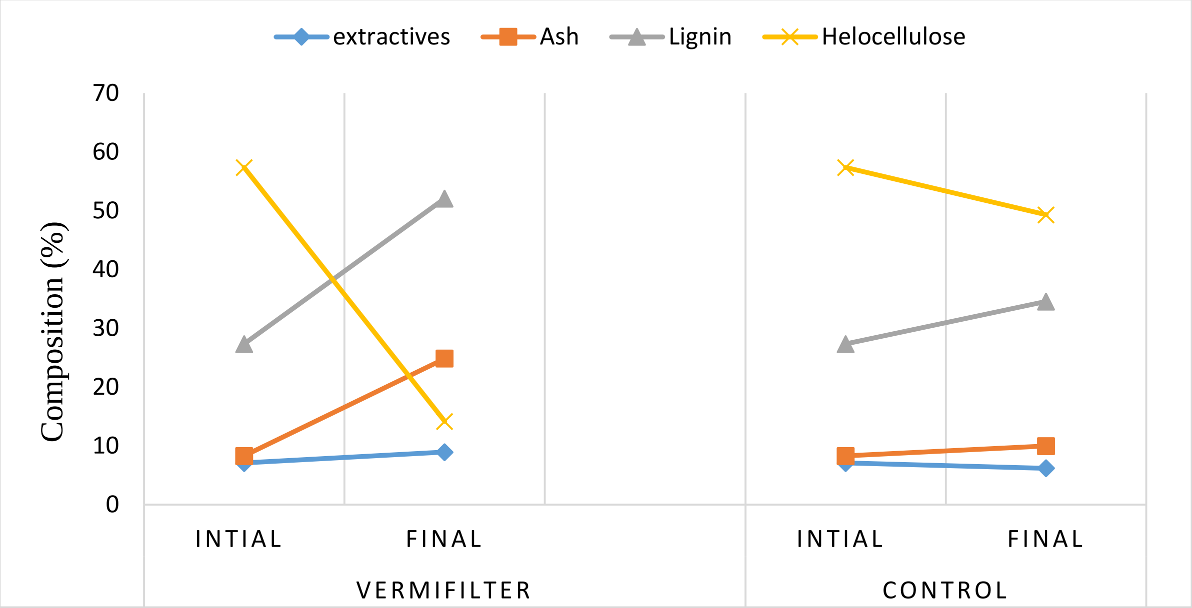

Figure 5-7. The degradation of fine sawdust in the vermifilter and control unit

5.3.4.4 Porosity of the bedding material

Porosity decreases in all filters, but at a slower rate for vermifilters than the control unit. The decrease in porosity may be due to the size reduction of the sawdust, accumulation of slowly degraded organic and inorganic solids from the greywater and the biomat formation. As shown on Figure 5-8, the porosity reduced from 85%, at the start of the experiment, to 78% for the vermifilter and 72% for the control, at the end of the experiment.

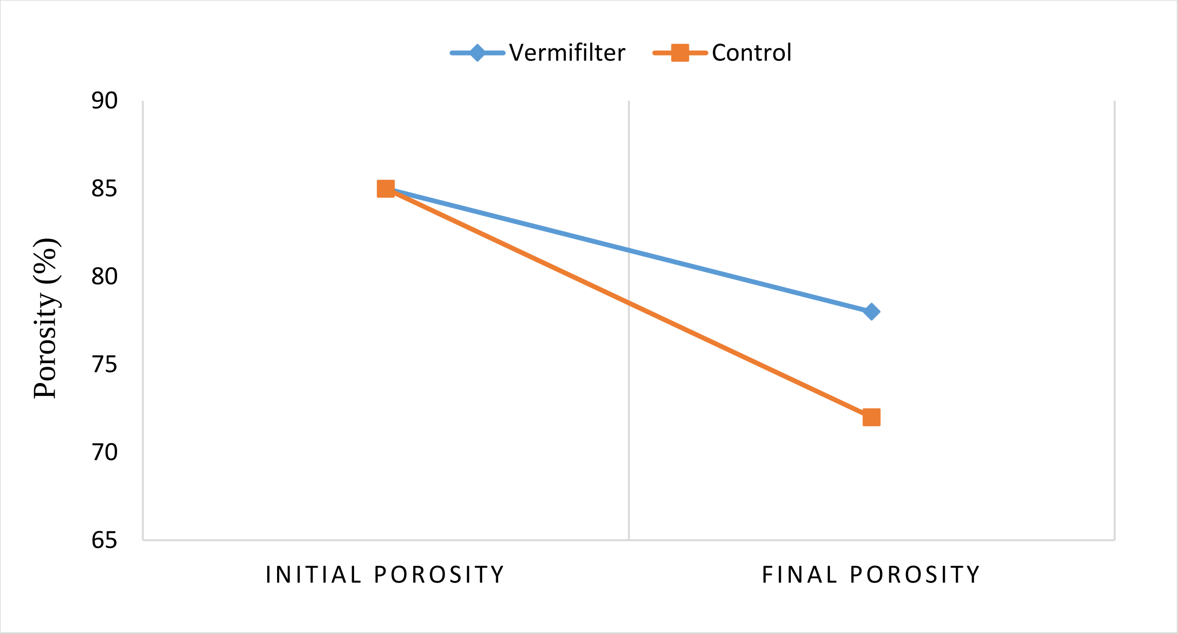

Figure 5-8. The porosity of fine sawdust in the vermifilters and controls after 6 months

5.4 Conclusion

In this study, major removal of pollutants from the concentrated greywater was achieved by the sawdust (active) layer for most parameters. This might be due to the adsorption by the sawdust, and the activities of earthworms and bacteria. For most parameters, the vermifilter was slightly better in most aspects except nitrite, orthophosphate and TSS. However, there were fluctuations from time to time for nitrate and orthophosphate. There was an increase in dissolved oxygen and average temperature along the depth, and additional depth may increase the removal of nitrate and the remaining oxygen demand.

The performance of the control unit was deteriorating but it was not possible to collect more samples from the ports. Higher numbers of bacteria were found in the vermifilter compared to the control unit which may be associated with the presence of earthworms. Moreover, the bedding material depth shrinkage in the vermifilter showed that the sawdust, mainly the carbon source, was degraded both by the earthworms and bacterial community as an energy source. The pressure effect might be minimum as the control unit didn’t show shrinkage but slight increase.

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Chapter 6

Filter Materials, Microbial Communities, and Influent and Effluent Flow Patterns in Vermifilters

Chapter 6:Filter Materials, Microbial Communities, and Influent and Effluent flow pattern in Vermifilters

Abstract

The filter materials, microbial communities, and influent and effluent flow pattern in vermifiltration process were studied for 5 months while treating the concentrated greywater. Four filters were filled with 10 cm gravel of which a layer of medium size gravel (5 cm thickness, aggregate size 20-40 mm) at the bottom and a layer of coarse gravel (5 cm thickness, aggregate size 10-20 mm) at the top, then filled with 20 cm sand (d_{60} = 0.2 mm, d_{10} = 0.118 mm). Finally, the three filters, VF1, control unit and VF2, were filled with 40 cm fine sawdust (0.05-5mm) while the other filter, VF3, was filled with 40 cm cow dung (0.05-5mm). The three filters were inoculated with 200 individuals of *Eudrilus eugeniae* except the control unit which was composed of sawdust. Five sampling ports on the wall of the filters were installed at 10 cm intervals with reference to the surface of top layer. The filters, except VF1-Sawdust supplied with drinking water, were supplied with concentrated greywater at the a hydraulic loading rate of 16 $L.m^{-2}.d^{-1}$ at batch basis four times a day at 8:00 am, 11:00 am, 2:00 pm and 5:00 pm. Every week samples from influent and effluent were collected and analyzed for selected parameters, and monthly samples of filter materials were collected from the sampling ports and analyzed for pH, MC, VS and quantity of microbial communities. Results showed that there were significant differences for BOD_5, CODt, CODd and TSS removal efficiencies between the control unit and VF2, for BOD_5 and PO_4^{3-} between the control and VF3, and for PO_4^{3-} between VF2 and VF3. There were significant differences also for pH between the control unit and VF2, BOD_5 and NO_2^- concentrations between the control and VF3, TSS and DO concentrations between VF2 and VF3. The filter materials behavior changed through time and along the depth. The pH and MC increased along the depth while high numbers of the microbial communities and earthworms were on the top layer compared to the bottom. The time needed to filtrate from the top layer and the infiltration rate at the bottom (outlet) of the control unit became higher towards the end of the experiment compared to others.

Keywords: Cow dung; *Eudrilus eugeniae;* Filter materials; Sawdust; Vermifiltration

Résumé

Le matériaux filtrants, la communauté microbienne et les caractéristiques d’écoulement de l’influent et de l’effluent ont été étudiés pendant 5 mois dans un système de vermifiltration destiné à traiter les eaux grises concentrées. Quatre filtres ont été remplis avec 10 cm de gravier, 10 cm de sable avec 40 cm de sciure de bois pour trois filtres (VF1-sciure, unité de contrôle, VF2-sciure) et 40 cm de bouse de vache pour le quatrième filtre (VF3-bouse de vache) étaient ajouter, respectivement. Les vermifiltres ont été inoculés avec 200 *Eudrilus eugeniae* de vers de terre et une du filtre de la sciure de bois a été utilisée comme contrôle. Les filtres, à l'exception de VF1-sciure qui a été approvisionnées en eau potable, été approvisionnées avec les eaux grises concentré au un taux de charges hydrauliques de 16 $L.m^{-2}.j^{-1}$ a base quatre batch fois par jour à 08h00, 11h00, 14h00 et 17h00. Tous les échantillons d'une même semaine ont été collectés et analysés pour l'ammonium, les nitrates, les nitrites, les orthophosphates, la DBO_5, la DCOt, la DCOd, les MES, li OD, le pH et la température pour l'influent et l'effluent. Des échantillons de matériaux filtrants ont également été prélevés chaque mais et analysés pour le pH, MC, VS et le nombre de la communauté microbienne. Les résultats ont montré qu'il y avait des différences significatives en efficacité d'élimination pour la DBO_5, DCOt, DCOd et MES entre le contrôle et la VF2-sciure, pour la DBO_5 et PO_4^{3-} entre la commande et VF3-bouse de vache, et pour PO_4^{3-} entre VF2-sciure et de VF3-bouse de vache. Il y avait également des différences significatives pour le pH entre le contrôle et les concentrations VF2-sciure, la DBO_5 et les NO_2^- entre le contrôle et VF3-bouse de vache, pour TSS et ne concentrations entre VF2-sciure et VF3-bouse de vache. On peut donc pour conclure pour leur performance que la VF2-sciure > VF3-bouse de vache> Unité de contrôle pour dans la plupart des paramètres. Le temps nécessaire pour filtrer une quantité d'eaux usées données à partir de la surface et le taux d'infiltration au fond (en laisse) de l'unité de contrôle devient plus élevé vers la fin de l'expérience par rapport aux autres.

Mots-clés: La bouse de vache; *Eugeniae de Eudrilus*; Matériaux de filtration; Sciure de bois; Vermifiltration

6.1 Introduction

The vermifiltration process needs filter materials for physical separation of pollutants from wastewater and to create a conducive environment for the earthworms to interact with the microbial communities. However, all filter materials will fail at some time (Kropf *et al.*, 1977). For instance, (Luth, 2011) changed the sawdust every six month in vermifiltration process for treating swine wastewater. There was also 12 cm filter bed shrinkage in the vermifiltration experiment conducted in Chapter 5. Ghatnekar *et al.* (2010) also reported that the bedding material gradually converted into humified vermicompost. In other filtration systems, Dalahmeh *et al.* (2011) found that the filters with bark and wood chips showed high durability while mixed mulch, compost and wheat straw were less durable. .

Generally, it is possible to observe physical, chemical and biological changes in the filter materials during the vermifiltration process. Physically, the sand was ground down by earthworms which increased the surface area and helped to 'adsorb' organic and inorganic pollutants from the effluent (Ghatnekar *et al.,* 2010; Sinha *et al*., 2008). Chemically, the pH was changed due to absorbed or precipitated chemicals. Biologically, the microbial communities population was increased, and selected species of bacteria were dominantly found in vermifilter. For instance, Li *et al*. (2014) reported Aeromonadaceae, Moraxellace, Enterobacteria, and Pseudomonadaceace found in the vermifilter which belong to the gamma proteobacteria.

Depending on the experimental goal, many materials have been chosen as filter material. For instance, Arora *et al.* (2014) found that riverbed material and mud balls were better for high pathogen removal and (Wang *et al*., 2010) reported that a converter slag–coal cinder filter played an important role in phosphorus removal. Xing *et al*. (2011) also reported ceramsite is better than quartz sand as medium for the vermifiltration. Moreover, domestic organic waste (Taylor *et al*., 2003; Bajsa *et al*., 2003), including gravel, sand, soil (Sinha *et al*., 2008), wood chips, bark, peat, straw (Li *et al*., 2008) were found to be good for removal of organic matter and nutrients.

The objectives of this study are (1) to understand the changes in the filter materials during the vermifiltration process while treating the concentrated greywater, (2) to identify and enumerate the microbial communities working with earthworms, (3) to study inflow and outflow pattern and (4) to compare the performance of sawdust and a degraded cow dung vermifilters, and a control unit for the removal of organic and nutrient pollutant.

6.2 Materials and Methods

6.2.1 Experimental Set up

Four filters were filled with 10 cm gravel of which a layer of medium size gravel (5 cm thickness, aggregate size 20-40 mm) at the bottom and a layer of coarse gravel (5 cm thickness, aggregate size 10-20 mm) at the top, then filled with 20 cm sand (d_{60} = 0.2 mm, d_{10} = 0.118 mm). Finally, three of them, VF1, control unit and VF2, were filled with 40 cm fine sawdust (0.05-5mm) and the fourth filter, VF3, was filled with 40 cm cow dung (0.05-5mm). The three vermifilters were inoculated with 200 *Eudrilus eugeniae* except the control unit which was filled with the sawdust (Figure 6-1). Five sampling ports on the wall of the filters were installed at 10 cm interval with reference to the surface of top layer. The filters were supplied with a hydraulic loading rate of 16 L.m^{-2}.d^{-1} at batch basis four times a day at 8:00 am, 11:00 am, 2:00 pm and 5:00 pm.

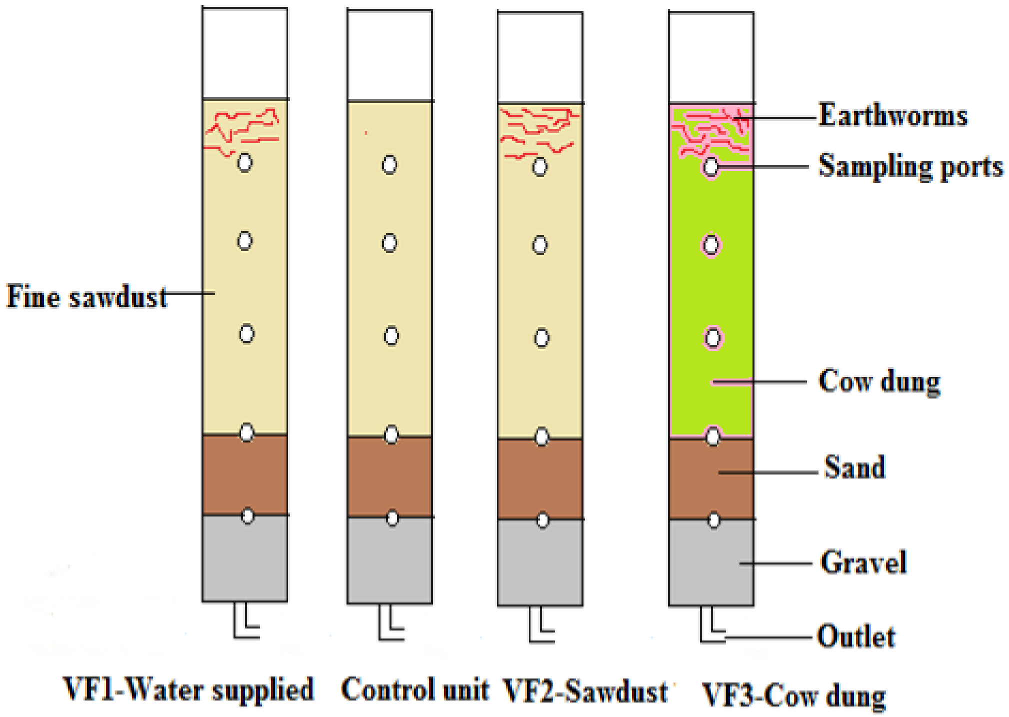


Figure 6-1. Experimental set up

Similar filter materials were used inaddition to the new bedding material, cow dung, for comparision. The filter materials were washed with tap water to remove dust and other impurities. Moreover, one of the vermifilters, composed of sawdust, was supplied with drinking water while others were supplied by concentrated greywater collected from a poor urban household after homogenizing as described in the procedure of Adugna *et al.* (2014, 2015).

6.2.2 Water Quality Analysis

Sampling influent and effluent, and analysing selected physico-chemical and nutrient parameters were done following the procedures described in Chapters 3, 4 and 5. The analysis was performed in the same-day of sampling, and when same-day analysis was not possible, the samples were stored at 4^{o}C for less than 24h before analyses.

6.2.3 Earthworm and Microbial Communities Analyses

At the beginning, two hundred adult *Eudrilus eugeniae* were inoculated to three filters except the control unit, and at the end of the experiment**,** earthworms were counted for change in number, weighed for mass gained, and counted for cocoons produced in each vermifilter after sorted by hand. The earthworms were weighed after washing with distilled water and dried with paper towels.

To identify the microbial communities working with earthworms, samples were collected on top layer surface and from five sampling ports created on the wall of filters in 10 cm interval at the beginning and towards the end of experiment. Moreover, the filter materials were analyzed for microbial communities. Each sample was averagely 5 grams and a gram of representative sample was taken and diluted with 9 ml sterile water to be mixed using a vortex. Different dilutions were made and 1ml sample was spread on the autoclaved petri-dish. It was analyzed using spread plate method with blood agar, VRBG agar, MacConkey agar, and nutritive agar media for bacteria, and Sabouraud's dextrose agar for actinomycetes and fungi. Then it was incubated for 18-24h at 37ºC for bacteria, 10-12 days at 30ºC and 37ºC for actinomycetes, and 4-7 days at 25ºC and 28ºC for fungi (Parthasarathi *et al.*, 2007). The different colony forming units (CFU) developed on the media were estimated and expressed as CFU x 10^4 g^{-1} (for fungi), CFU x 10^6 g^{-1} (for bacteria), and CFU x 10^5 g^{-1} (actinomycetes) respectively according to the method of Baron *et al*. (1994).

6.2.4 Biosolids Analysis

The bedding materials, fine sawdust/cow dung, with adsorbed solids from the greywater, were analyzed for VS as described in Chapter 5. The MC was determined by gravimetric method of analysis using an oven (Memmert 854. Schwabach, Germany). The pH change of filter materials was analyzed after diluting the solid sample with distilled water at 1:10 ratio and agitating using an Edmund Bühler GmbH SM-30 shaker at 200 rpm for 1h. The C/N ratio was determined indirectly using the volatile solids (carbon) and TKN (total nitrogen), determined by the Kjeldahl method, at the beginning and end of the experiment. The porosity of the top layer was determined by volumetric method. Moreover, the degradation of the sawdust components were analyzed by quantifying ash, extractives and lignin following the procedures described in Chapter 5.

6.2.5 Surface Filtration and Infiltration at the outlet

The filtration from top layer surface of all filters was determined once a week by the amount of time required to fully drain the greywater supplied. The time was measured using a stopwatch which was started simultaneously with the supply, and then stopped when the greywater totally disappeared from the surface. In case of infiltration at the bottom outlet, the starting time was recorded at the start of supply at the top surface, and the final time was recorded when the accumulated effluent reached 100 ml. Moreover, the total amount of effluent collected during the first batch (8:00-11:00 am) was recorded once a week.

6.2.6 Statistical Analyses

Microsoft Excel 2013 was used to carry out statistical analyses, develop the box and whisker plots, and figures. The results were expressed as mean ± standard deviation and the significant differences among samples were analyzed using the Mann-Whitney U-test at 5% significance level.

6.3 Results and Discussion

6.3.1 Performance Evaluation for the Vermifilters and the Control Unit

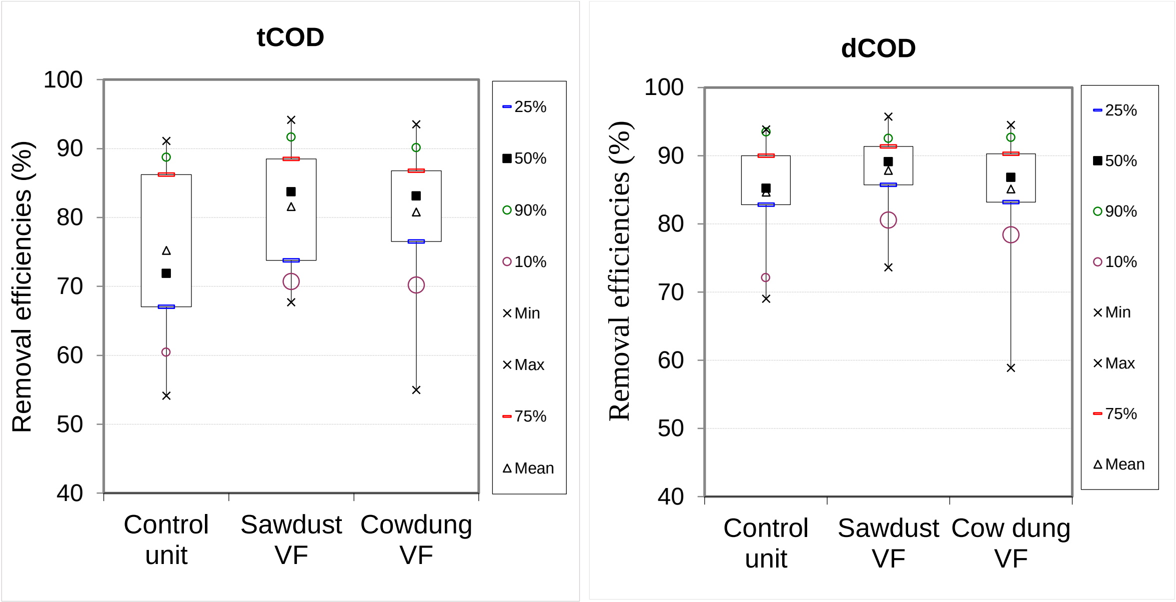
The performances of vermifilters were better than the control unit for most physico-chemical parameters (BOD_5, tCOD, dCOD and TSS) and NH_4^+. The control unit was slightly better for nutrient (NO_3^-, NO_2^- and PO_4^{3-}) removal during the study period. The results of BOD_5, tCOD, dCOD and TSS from VF1-Sawdust supplied with drinking water showed that there was leach out of pollutants from sawdust (same result was discussed in Chapter 5). Generally, there was significant differences ($p < 0.05$) for BOD_5, tCOD, dCOD and TSS removal efficiencies between the control unit and VF2-Sawdust, for BOD_5 and PO_4^{3-} removal efficiencies between the control unit and VF3, and for PO_4^{3-} removal efficiency between VF2 and VF3. Moreover, there were significant differences for pH between the control unit and VF2, BOD_5 and NO_2^- concentrations between the control unit and VF3, TSS and DO concentrations between VF2 and VF3 (Table 6-3).

6.3.1.1 Physico-chemical Parameters

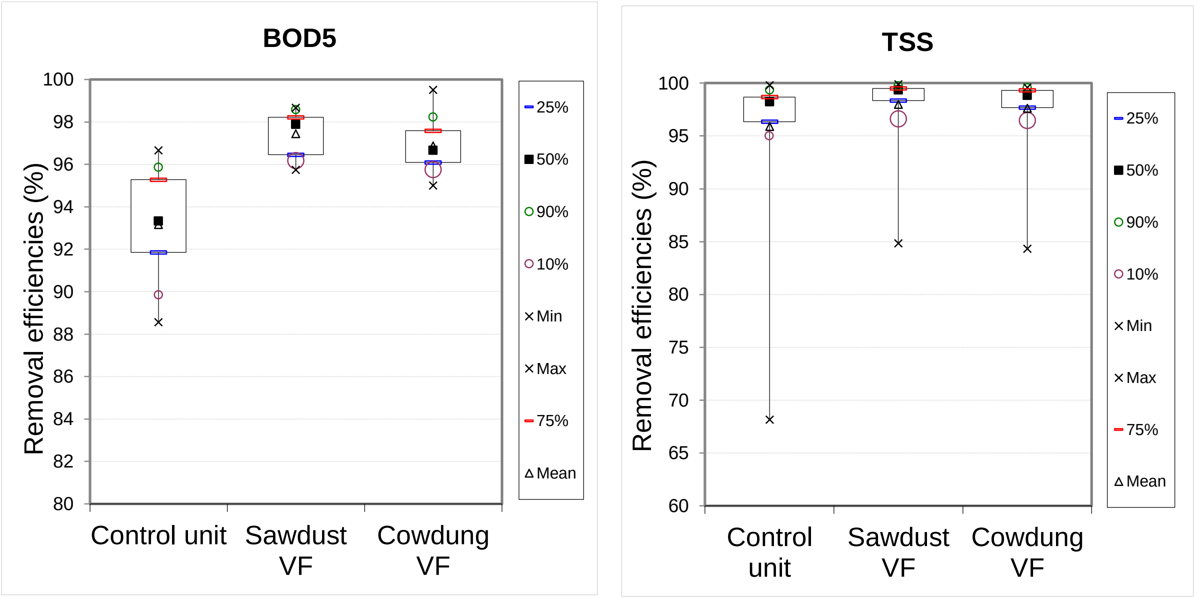
Table 6-1, Figure 6-2 and 6-3 present influent and effluent concentrations with range and standard deviation (SD) for of BOD_5, tCOD, dCOD, TSS, pH and DO, the removal efficiencies of tCOD and dCOD, and BOD_5 and TSS respectively. Additionally, Figure 6-4 presents pH of effluents for all filters. The VF2-Sawdust had slightly better performance for the physico-chemical parameters compared to others followed by VF3 (Figure 6-2 and 6-3). The pH of VF1-Sawdust effluent was always less than others since it was supplied with drinking water (Figure 6-3).

Table 6-1. Influent and effluent concentrations with ranges and standard deviation (SD) for of BOD$_5$, tCOD, dCOD, TSS, pH and DO

Parameters		**Influent**	**Effluent**			
			VF1	**Control unit**	**VF2**	**VF3**
BOD$_5$ (mg/L)	Average	**1234**	**16**	**78**	**30**	**35**
	SD	358	8	16	12	10
	Maximum	2100	25	100	60	40
	Minimum	800	0	60	20	10
tCOD (mg/L)	Average	**2195**	**146**	**518**	**383**	**386**
	SD	699	81	269	202	123
	Maximum	3520	344	906	861	549
	Minimum	1075	45	201	185	82
dCOD (mg/L)	Average	**1497**	**97**	**357**	**254**	**297**
	SD	445	39	202	135	106
	Maximum	2180	164	632	574	474
	Minimum	570	41	142	138	69
TSS (mg/L)	Average	**1120**	**3.0**	**16**	**7.0**	**12**
	SD	770	1.0	8.0	3.0	4.0
	Maximum	2960	5	38	14	16
	Minimum	352	2	5	2	4
pH	Average	**6.5**	**7.9**	**8.6**	**8.5**	**8.5**
	SD	0.5	0.2	0.2	0.2	0.2
	Maximum	7.3	8.2	8.8	8.8	8.8
	Minimum	5.8	7.6	8.3	8.2	8.2
DO (mg/L)	Average	**1.0**	**4.7**	**4.3**	**4.2**	**4.6**
	SD	0.6	1.0	1.3	0.9	1.1
	Maximum	2.2	6.8	7.7	6.2	7.1
	Minimum	0.3	3.3	2.5	2.6	3.2



(a) tCOD (b) dCOD



(c) BOD$_5$ (d) TSS

Figure 6-2. Box-plots of tCOD (a) and dCOD (b), BOD$_5$ (c) and TSS (d) removal efficiencies

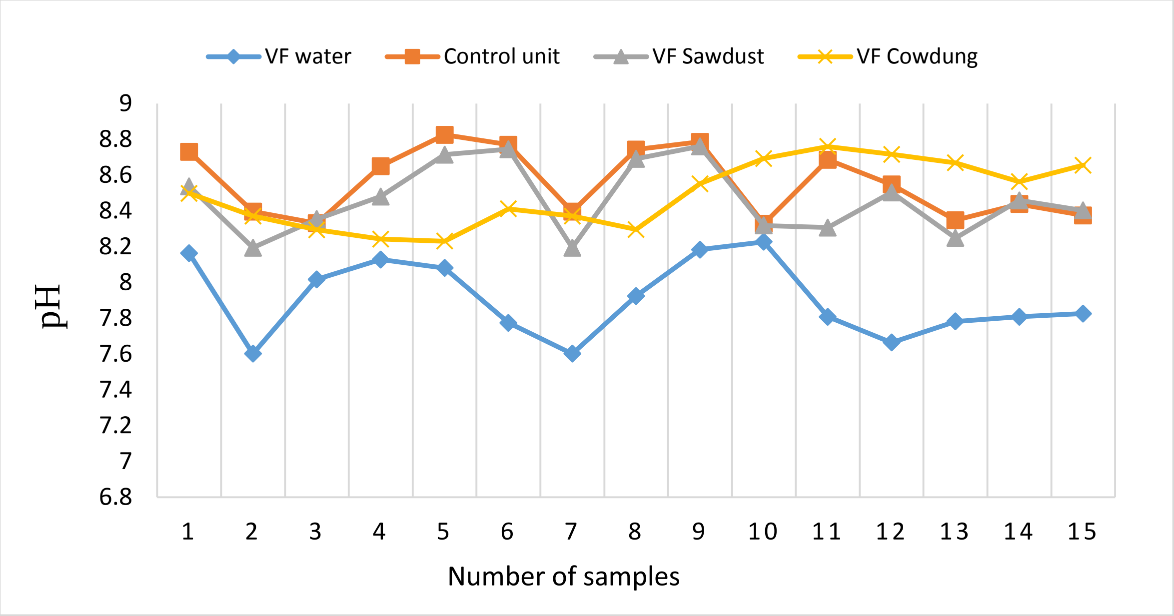


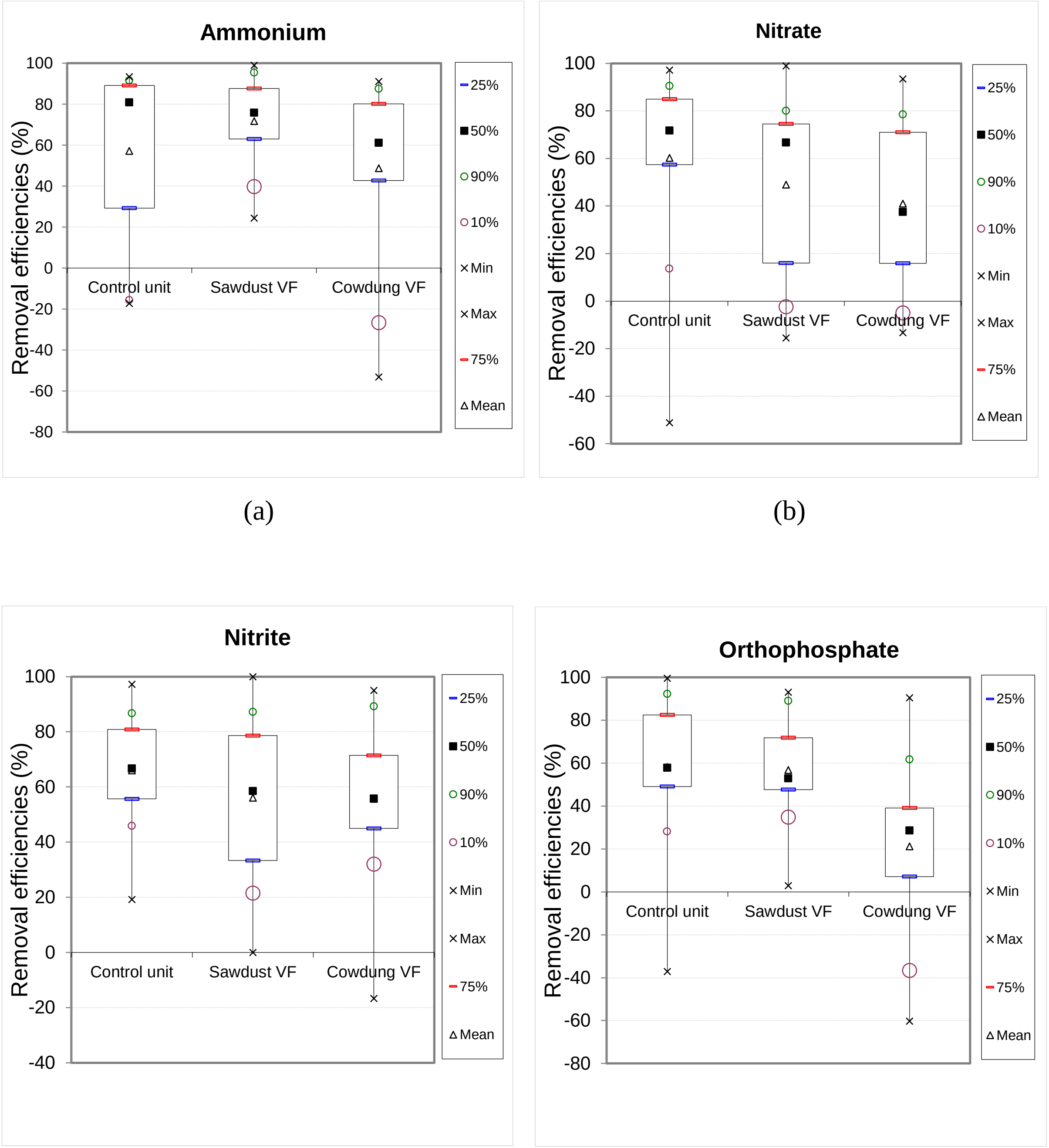
Figure 6-3. The pH of effluents for vermifilters and control unit

6.3.1.2 Nutrient Removal

Table 6-2 and Figure 6-4 present influent and effluent concentrations with ranges and standard deviations (SD) for nutrients, and removal efficiencies respectively. The control unit was slightly better in nutrient removal than VF2-Sawdust and VF3-Cow dung vermifilters except for ammonium. This may be due to more nitification in vermifilters which may affect the better nitrate removal, and the change of particulate phosphrous into soluble (orthophosphate) by the activities of earthworms and microbial communities may contribute to less efficiency in vermifilters. Moreover, adsorption capacity of sawdust might contributed for better removal. (Harmayani and Anwar, 2012) found that sawdust is a very good adsorbent to remove NH_3-N, NO_3-N and NO_2-N from aqueous solution. The earthworm casts are also known for adsorption of different chemical pollutants (Prasad Amit Kumar *et al*., 2013). Better nitrification may be achieved due to aerobic conditions created by earthworms activities in the vermifilter and the batch feeding system in the vermifilter and the control unit. Similarly, Pell and Nyberg (1989c) reported complete nitrification in the top 15 cm layer of sand filter columns. However, lower performance from cow dung might be due to the decreased porosity and the already available nutrients inside the dung (Figure 6-4). The removal of nitrate can also be due to the denitrifying bacteria in the earthworm gut (Svensson *et al*., 1986; Elliott *et al*., 1991; Matthies *et al*., 1999).

Table 6-2. Influent and effluent concentrations with ranges and standard deviation (SD) for nutrients

Parameters		**Influent**	**Effluent**			
			VF1	**Control unit**	**VF2**	**VF3**
NH_4^+ (mg/L)	Average	**12**	**2**	**3**	**3**	**3**
	SD	13	1.4	2.5	3.0	1.5
	Maximum	44	5	8	11	5
	Minimum	0.9	0.2	0.1	0.1	0.4
NO_3^- (mg/L)	Average	**37**	**6**	**13**	**14**	**20**
	SD	30	9	18	15	21
	Maximum	100	38	68	52	65
	Minimum	0.7	0.0	0.1	0.3	0.7
NO_2^- (mg/L)	Average	**61**	**10**	**15**	**19**	**22**
	SD	57	11	14	16	19
	Maximum	210	40	60	60	60
	Minimum	6.0	0.2	2.0	0.0	0.6
PO_4^{3-} (mg/L)	Average	**32**	**1.0**	**17**	**22**	**25**
	SD	53	2.0	29	41	42
	Maximum	199	6.0	91	141	144
	Minimum	0.6	0.0	0.1	0.01	0.3



(a) (b)

(c) (d)

Figure 6-4. Box-plots of Ammonium (a), Nitrate (b), Nitrite (c), and Orthophosphate (d) removal efficiencies

The vermifilter removed some of the orthophosphate, though the control is slightly better at the removal of orthophosphate than the vermifilter. Similarly Taylor *et al*. (2003) reported that the vermifilter can reduce phosphorus concentration. The phosphorus removal efficiency was 53% which is greater than reported by Luth *et al*., (2011), around 40%, and less than reported by Li *et al*. (2008), 60%.

Table 6-3. P-values for concentrations and removal efficiencies among the layers of the same filter and between layers of the vermifilter and control unit.

Constituent	Removal efficiencies			Concentrations		
	Control X VF2	Control X VF3	VF2 X VF3	Control X VF2	Control X VF3	VF2 X VF3
BOD_5	2.99E-06(*)	5.1E-06(*)	0.10497	1.96E-07(*)	3.2E-07(*)	0.32119
CODt	0.015698(*)	0.220867	0.76653	0.0078(*)	0.18513	0.97467
CODd	0.045828(*)	0.832098	0.23448	0.0271(*)	0.39698	0.29765
TSS	0.000132(*)	0.057708	0.20651	0.0003(*)	0.07290	0.016(*)
NH_4^+	0.090558	0.069806	0.06981	0.72269	0.78283	0.65469
NO_3^-	0.172944	0.139313	0.32004	0.34987	0.28028	0.32552
NO_2^-	0.130939	0.162056	0.79331	0.06231	0.038(*)	0.30327
PO_4^{3-}	0.838387	0.00055(*)	0.003(*)	0.71536	0.09048	0.11846
DO				0.40919	0.29923	0.016(*)
pH				0.0042(*)	0.25592	0.89157

(*) p-values ≤ 0.05: sample medians are significantly different

6.3.1.3 Earthworm Evolution

Table 6-4 presents the earthworms' developmental change during the five months' time. As shown in Table 6-4, the number of earthworms (adults, juveniles and cocoons) in the VF1-Sawdust was zero at the end of experiment as it was supplied with drinking water. However, in other vermifilters, there were mature and immature earthworms and cocoons. The VF2 had 202, 75 and 83 and the VF3 had 148, 35 and 20 of Adults (mature), immature and cocoons respectively. From the total death of earthworms in VF1-Sawdust, it can be concluded that greywater was the source of nutrient for earthworms in addition to the VS of sawdust/cow dung. Similarly, Ghunmi *et al.* (2011), Leal *et al.* (2011), Zeeman *et al.* (2008) and Leal *et al.* (2007) reported that greywater contained an easily available carbon and energy source.

The number of earthworms and cocoons decreased significantly due to the high temperature (24°C to 42°C) in the peak months of the year (March to May) for the site. However, the existence of juveniles and cocoons showed that earthworms are reproducing (Xing *et al.*, 2010) and they are bio indicators for ecological condition (Edwards and Bohlen, 1996; Kruum, 2005).

Table 6-4. Earthworm evolution in the vermifilters

		Initial	After 5 months		
			Mature	Immature	Cocoons
VF1 Sawdust	Number	200	0	0	0
	Total wt. (gram)	110.2	-	-	-
VF2 Sawdust	Number	200	202	75	83
	Total wt. (gram)	109.1	118.2	9.3	-
VF3 Cow dung	Number	200	148	35	20
	Total wt. (gram)	114.6	89.7	4.7	-

6.3.2 Effect on filter materials

6.3.2.1 Initial Concentrations

The initial concentrations of BOD_5, NH_4^+, NO_3^-, PO_4^{3-}, COD and pH for filter materials were analyzed and presented in Table 6-5. From the results, it can be concluded that the filter materials had already some pollutants. However, frequent washing with drinking water (see the quality on Table 6-6) before starting the experiment helped to remove majority of them.

Table 6-5. The concentrations of some parameters for filter materials

	Concentrations of parameters					
Filter materials	pH	NH_4^+ (mg/L)	PO_4^{3-} (mg/L)	NO_3^- (mg/L)	COD (mg/L)	BOD_5 (mg/L)
Sawdust	5.9	2.0	0.33	0.8	529	234
Sand	6.7	0.2	0.66	0.1	0	0
Cow dung	7.9	0.4	2.65	1.3	476	150

Table 6-6. Drinking water quality

	Drinking water quality parameters (mg/L)								(conc.)
	BOD_5	COD	TSS	NH_4^+	NO_3^-	NO_2^-	PO_4^{3-}	DO	pH
Average	0	2.2	0.2	0.1	0.3	1.0	0.1	6.1	7.4
SD	0	2.7	0.3	0.1	0.2	0.9	0.08	1.2	0.2
Maximum	0	6.0	0.5	0.4	0.5	3.0	0.2	7.6	7.6
Minimum	0	0.0	0.0	0.01	0.1	0.0	0.01	4.8	7.1
NS	3	6	3	10	10	10	10	8	8

NS = Number of samples

6.3.2.2 Average pH Trend along the Depth

Table 6-7 presents the average pH of filter materials, and Figure 6-5 presents the average pH change of filter materials along the depth. The average pH chang from the initial pH in the filter materials may be due to the supplied greywater, and activities of earthworms and microbial activities.

As shown in Figure 6-5, the values of pH slowly decreased for the fine sawdust vermifilters until 30 cm depth but VF3 showed continuous increase. However, the control unit showed both decreasing and increasing trend for the same depth. On the surface of the sand layer, the pH increased significantly which might be due to the accumulation, precipitation and transformation of bicarbonate, carbonate and hydroxide.

Table 6-7. The average pH of filter materials

	Fine Sawdust	Sand	Cow dung
pH	6.5	6.5	7.6

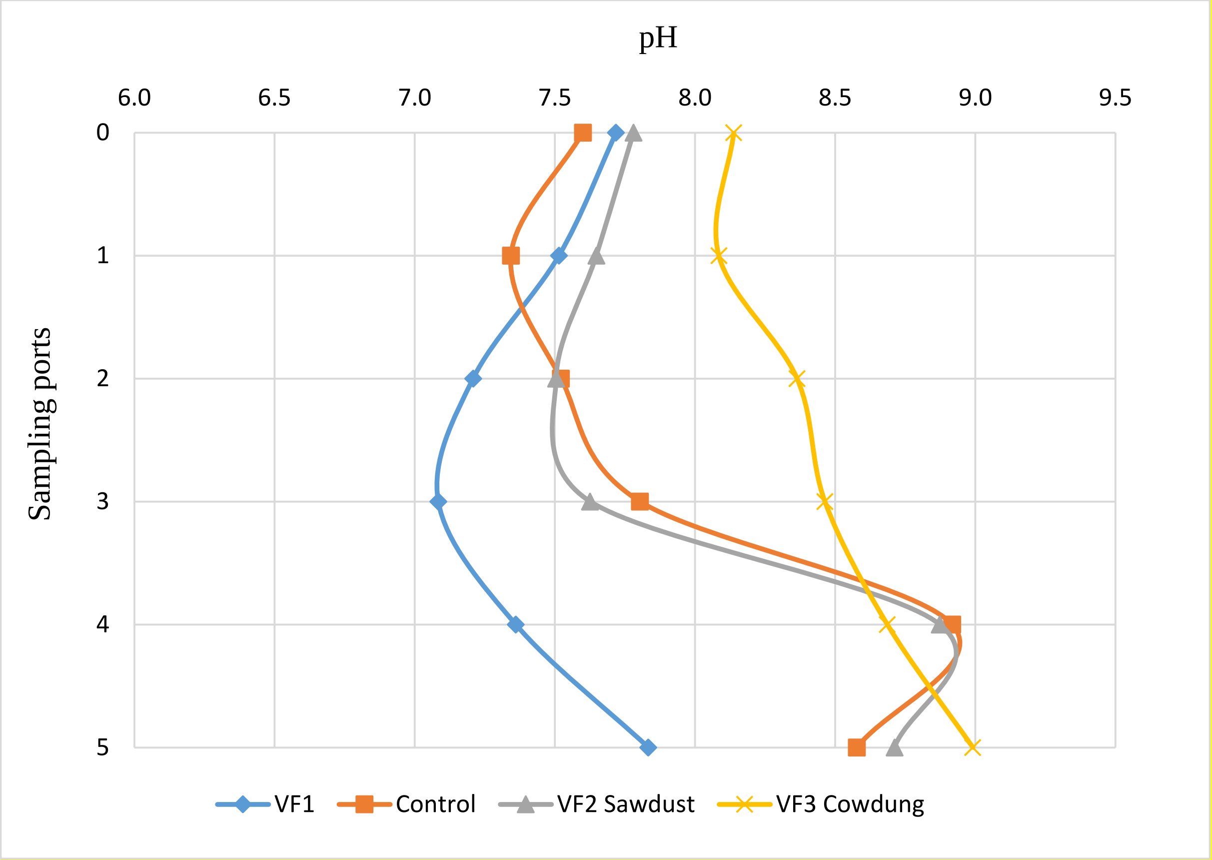


Figure 6-5. The average pH along the depth for vermifilters and control unit

In Chapter 4, the accumulated chemicals and precipitated chemicals were analyzed for selected parameters, and the bicarbonates and carbonates were the reason for the increase in pH. The accumulation of ammonia can also affect the pH at the bottom of the filters.

6.3.2.3 Porosity of the Bedding Material

Porosity decreased in all filters, but at a slower rate for vermifilters than the control unit (Figure 6-6). The decrease in porosity might be due to inorganic and slowly degraded organic solids accumulation from greywater, cast accumulation and the biomat formation. The earthworm digested the accumulated solids with the fine sawdust and reduced the size. The size reduction may also slowly reduced the porosity in vermifilters. The initial porosity of the filter system was 75% for the three sawdust filters and 56% for cow dung after calculating the initial porosities of each filter material.

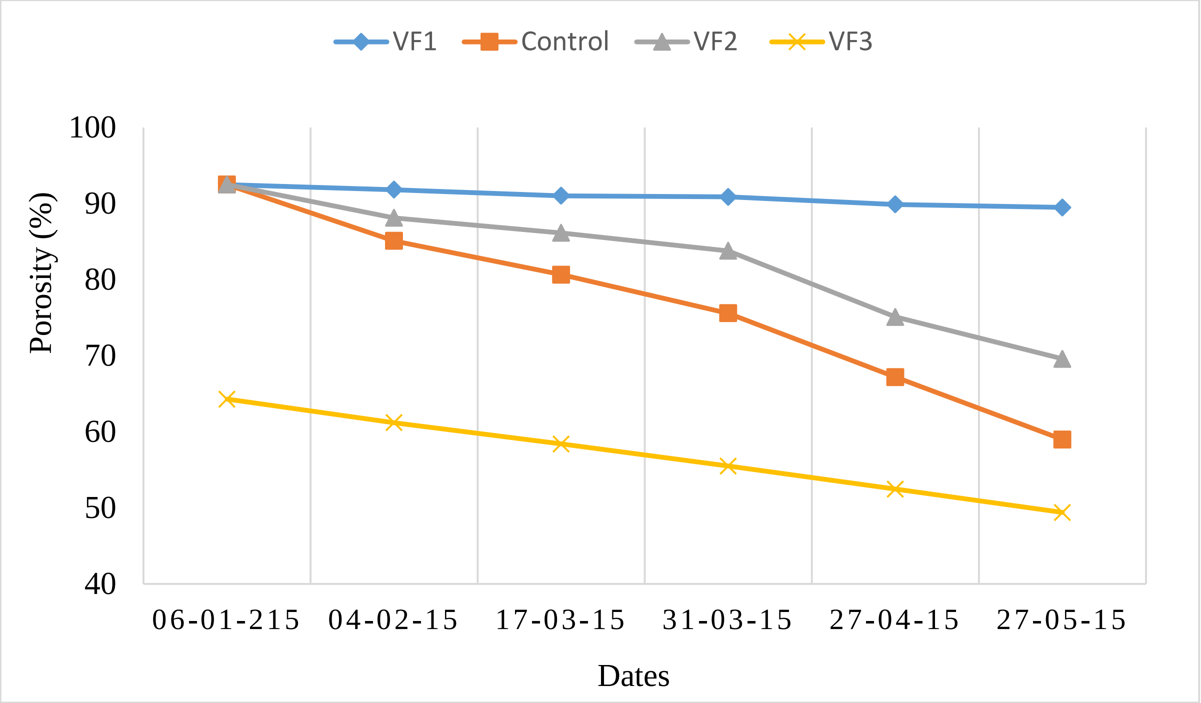


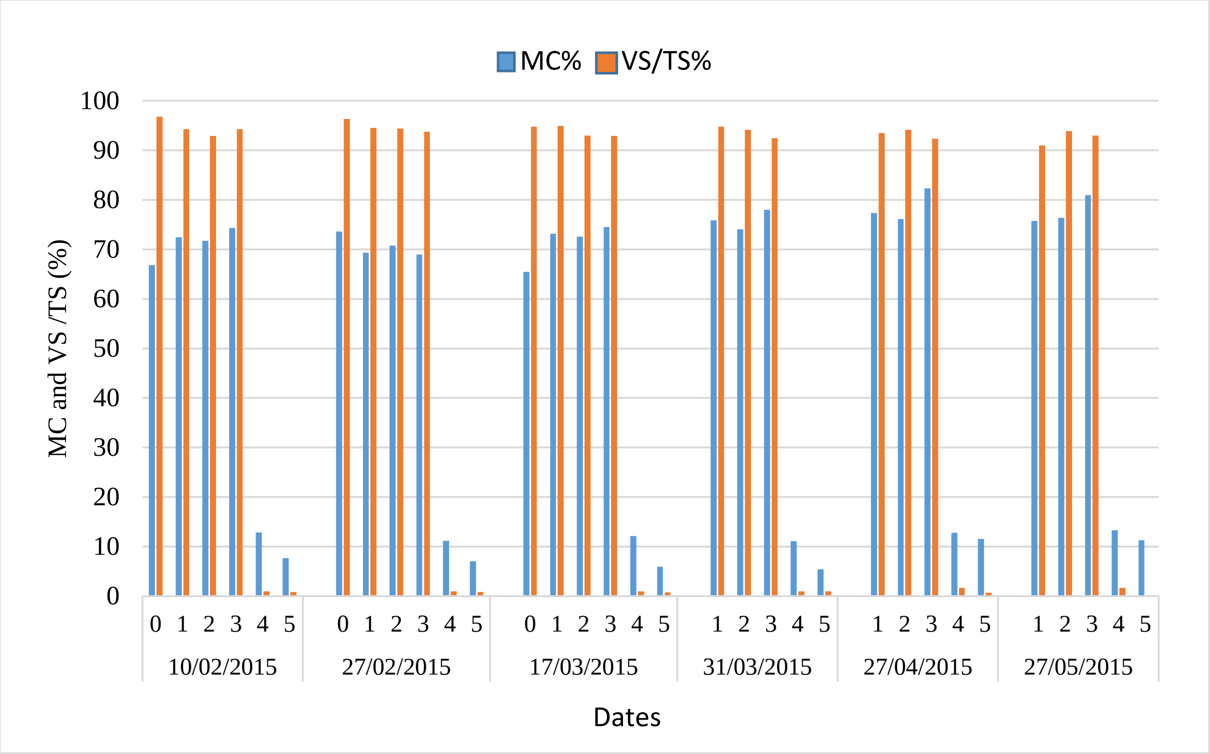
Figure 6-6. The top layer porosity change in all filters through time

The porosity of each filter was determined based on the porosity of each filter material and its volume proportion in the total filter materials (Appendix-1).

6.3.2.4 ***Volatile Solids and Moisture Content Change***

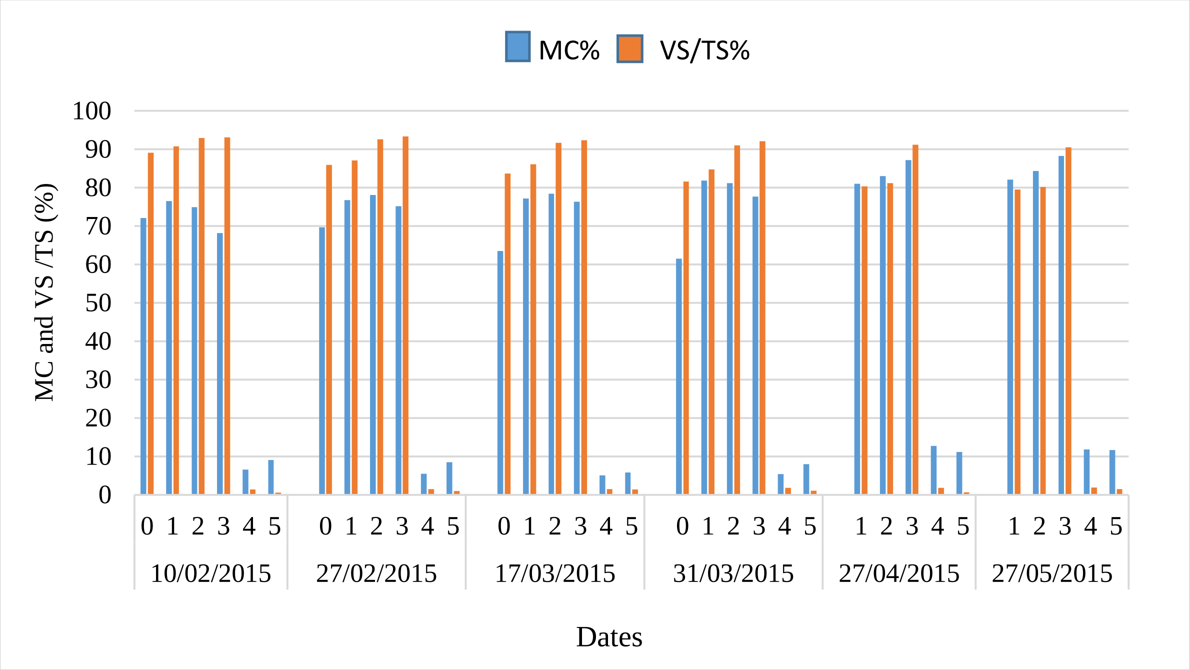
Figure 6-7 presents the VS/TS and MC percentage of the filter materials taken from the top layer surface and the five sampling ports of four filters. The VF1 showed little decrease in VS/TS through out the research period and some increment of MC through time. However, for the rest of the filters, there was more increase in VS/TS percentage on top layer, and at decreaseing rate along depth through time as more VS (carbon) was consumed where earthworms and microbes dominate. Generally, the VS/TS decreased through time for each sampling points.

Sinha *et al*., (2010) reported that the optimum moisture is in the range of (60%-70%), corresponding the results of this study for majority of the time (Figure 6-7). The bedding materials and additional solids from greywater were grinded into small particles (< 2 µm) by the earthworm gizzard which enhanced the surface area for microbial action (Singh and Sharma 2002; Aira *et al*., 2007; Suthar and Singh, 2008).



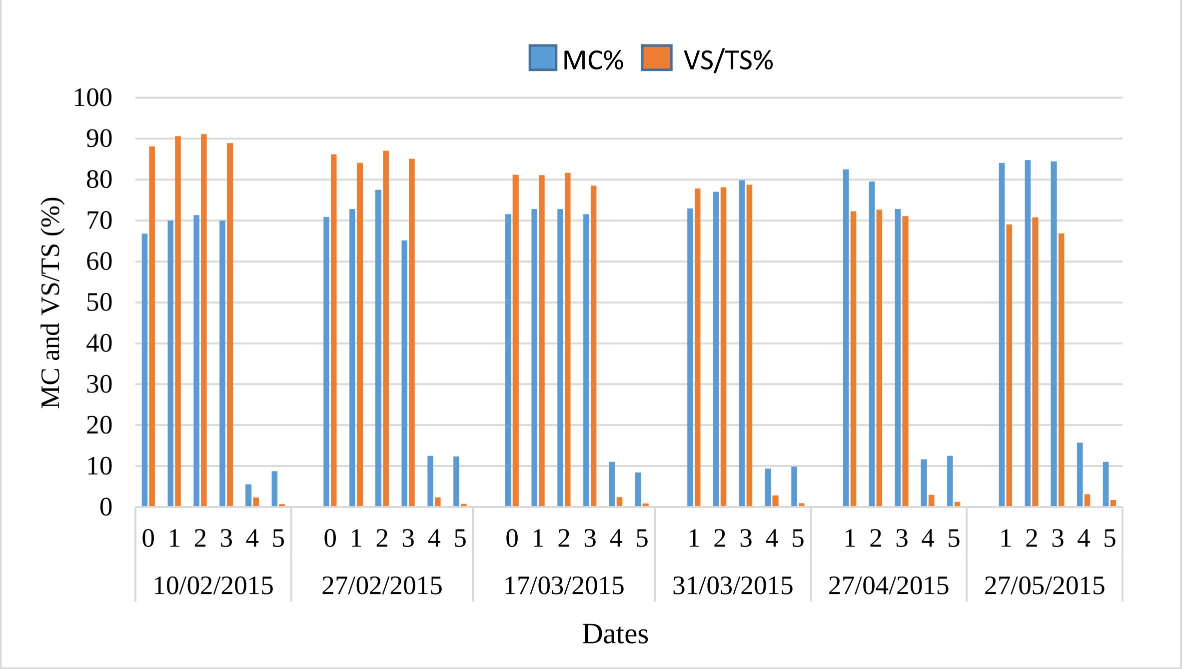
(a) VF1-Water supplied

While in the control unit (b), the top layer was degraded more through time compared to the other part which might be due to the high number of microorganisms.



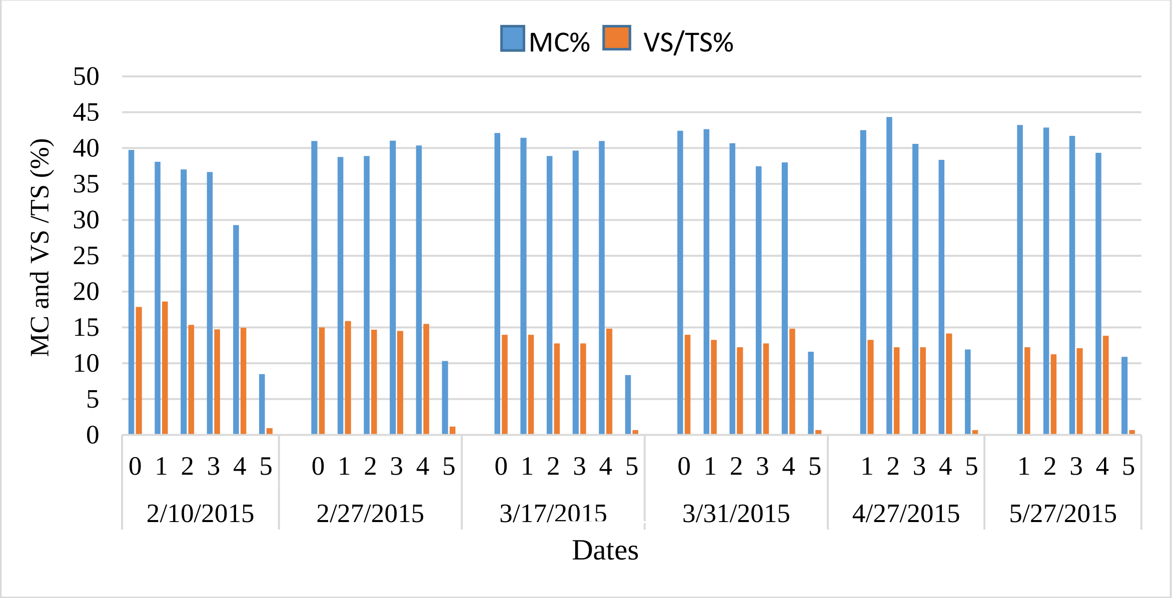
(b) Control unit

The VF2-fine sawdust (c) showed the degradation of the sawdust increasingly through time.



(c) VF2-Sawdust

Similarly, there was a decrease in VT/TS in VF3-Cow dung (a) though the cow dung had less VS initially,



(d) VF3-Cow dung

Figure 6-7. The volatile solids and moisture content along the depth of VF1-Sawdust (a), CF (b), VF2-Sawdust (c) and VF3-Cow dung (d) for different dates.

6.3.2.5 C/N ratio and Fine Sawdust Component Degradation

There was a significant reduction of cellulose from the bedding material (fine sawdust) in the vermifilters than the control unit (Figure 6-8 and Table 6-8). The lower level of cellulose degradation in the control unit showed that bacteria are responsible for the degradation. Similar finding was reported by Morgan and Burrows (1982).

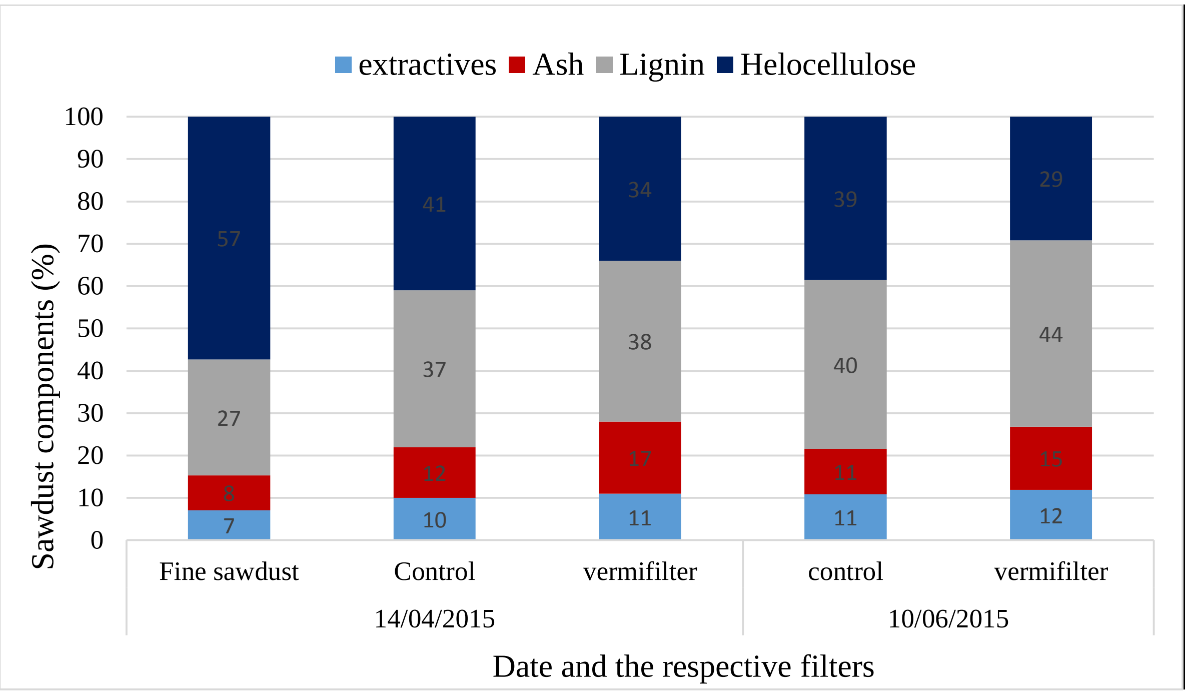


Figure 6-8. The degradation of fine sawdust in the vermifilters and controls

Table 6-8. Initial sawdust composition and composition after degradation

		14/04/2015		10/06/2015	
	Fine sawdust	Control unit	Vermifilter	Control unit	Vermifilter
Extractives (%)	7	10	11	11	12
Ash (%)	8	12	17	11	15
Lignin (%)	27	37	38	40	44
Helocellulose (%)	57	41	34	39	29

The C/N ratio of the bedding material (fine sawdust) changed by the activities of earthworm and the microbial communities in the vermifilter, and only by the microbial communities in the control unit. As a result, the C/N ratio changed from 247 to 70, 84 to 14, 79 to 25 and 17 to 11 for VF1, Control unit, VF2 and VF3 respectively (Table 6-9). Therefore, the lower C/N ratio in the control unit might be due to the adsorbed and less utilized nitrogen components compared to VF2-Sawdust as the earthworm utilized additional nitrogen components besides the less utilized VS in the control unit. However, the cow dung had more nitrogen components from the beginning which decreased the C/N ratio further. The samples were taken from the top layer within 10 cm depth. Similarly, Dominguez *et al*. (2004) reported the earthworms reduced size of the bedding material, gradually reducing of C/N ratio and increased surface area exposed to the microorganisms that facilitated the degradation.

Table 6-9. C/N ratio, TKN and Volatile solids at the initial and end of experiment

		The vermifilters and control unit			
		VF1	Control	VF2	VF3
VS (mg/kg)	Initial (20/01/2015)	968	891	881	162
	Final (02/06/2015)	935	795	691	153
TKN (mg/L)	Initial (20/01/2015)	4	11	11	10
	Final (02/06/2015)	13	55	27	13
C/N ratio	Initial (20/01/2015)	247	84	79	17
	Final (02/06/2015)	70	14	25	11

6.3.3. Microbial Communities Identification and Enumeration

Table 6-10 presents the number of identified microbial communities (bacteria, actinomycetes and fungi). The distribution of the microbial population varies in the vermifilters and the control unit along the depth at different rates. There was greater bacterial population variation along the depth in the vermifilters compared to the control unit variations. Similarly Arora *et al*. (2014) reported the same trend for bacterial population change in the vermifilter but not for the control unit. The VF2 had 10 times more population of bacteria than the control which may be due to the adequate aeration, oxygen availability, due to the activities of the earthworms.

Studies on vermicomposting and vermifiltration concluded that the dominantly available bacteria phylum is *Proteobacteria* (Danon *et al*., 2008; Fracchia *et al*., 2006; Vivas *et al*., 2009; Zhao *et al*., 2010). There were more fungi in the vermifilters as there were more aeration which enhanced their development. Parthasarathi *et al.* (2007) also found the diversity of fungi, bacteria, yeast, actinomycetes and protozoa in the gut and casts of *Eudrilus eugeniae*.

Table 6-10. Microbial communities enumeration along the depth

Sampling ports	Bacterial community (10^{11} CFU/g^{-1}), Actinomycetes (10^{7} CFU/g^{-1}) and Fungi (10^{6} CFU/g^{-1})											
	VF1 Sawdust (drinking water)			Control unit			VF2 Sawdust			VF3 Cow dung		
	Bacteria	Actimacytes	Fungi	Bacteria	Actimacytes	Fungi	Bacteria	Actimacytes	Fungi	Bacteria	Actimacytes	Fungi
1	4.6	8.8	31.3	45.2	14.5	38.3				27.0	15.0	15.0
2	3.5	11.3	12.5	42.8	18.8	34.4	205.0	27.8	37.2	38.3	23.8	23.8
3	3.4	10.0	11.3	27.1	16.4	33.6	154.2	19.7	34.2	36.6	31.3	31.3
4	1.1	6.0	6.0	13.0	5.0	5.0	42.6	6.7	32.6	23.7	12.9	12.9
5	1.6	3.5	4.1	10.4	6.7	6.7	5.3	5.7	5.3	5.7	6.9	7.7

(a) At the end of the experiment

Initial bacterial community (10^{9} CFU/g^{-1})			
VF1	**Control**	**VF2**	**VF3**
0.1	840	14	1.5
0.4	40	10	8.2
0.9	32	4.3	7.9
0.2	53	3.6	2.4
0.3	8.8	0.41	1.7
0.1	3.1	0.4	0.6

Bacterial community (10^{6} CFU/g^{-1}), Actinomycetes (10^{5} CFU/g^{-1}) and Fungi (10^{4} CFU/g^{-1})			
	Bacteria	**Actimacytes**	**Fungi**
Sawdust	5100	80	120
Sand	1200	100	140
Cow dung	5300	245	10

(b) At the beginning of the experiment and for the filter materials

6.3.4. Influent and effluent flow pattern

At the beginning of the experiment, the filtration from the top layer surface and infiltration at the bottom (outlet) were almost the same for the vermifilters and the control unit. However, through time there were changes from both direction. The change was at different rate except for the VF1 which was supplied with drinking water. As shown in Figure 6-9, the surface filtration took from 3 to 5 seconds for VF1-Sawdust which is almost constant throughout the experiment, 5 to 2100 seconds for control unit, 3 to 25 seconds for VF2, and 48 to 445 seconds for VF3. This showed that the control unit took longer time as it became clogged earlier followed by the VF3-Cow dung.

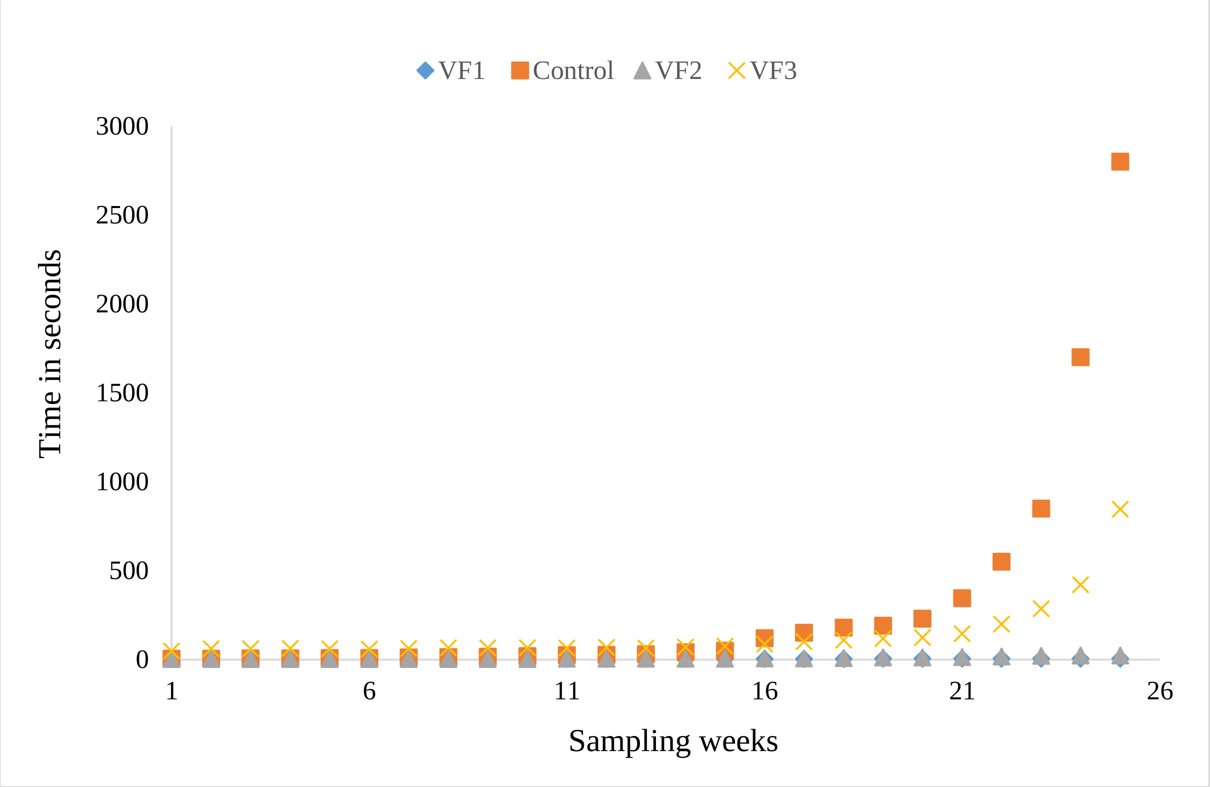


Figure 6-9. The time to filtrate supplied greywater from the surface of filters

The time needed to collect 100 ml effluent after the supply of the first batch greywater was recorded once a week throughout the experiment and is presented in Figure 6-10 below. The VF1-Sawdust drained100 ml in the range of 17 to 30 minutes, the control unit drained in the range of 120 to 180 minutes, VF2-Sawdust drained in the range of 104 to 89 minutes and VF3 drained in the range of 110 to 105 minutes. Hence, the control unit took relatively longer time towards the end of the experiment followed by VF3-Cow dung.

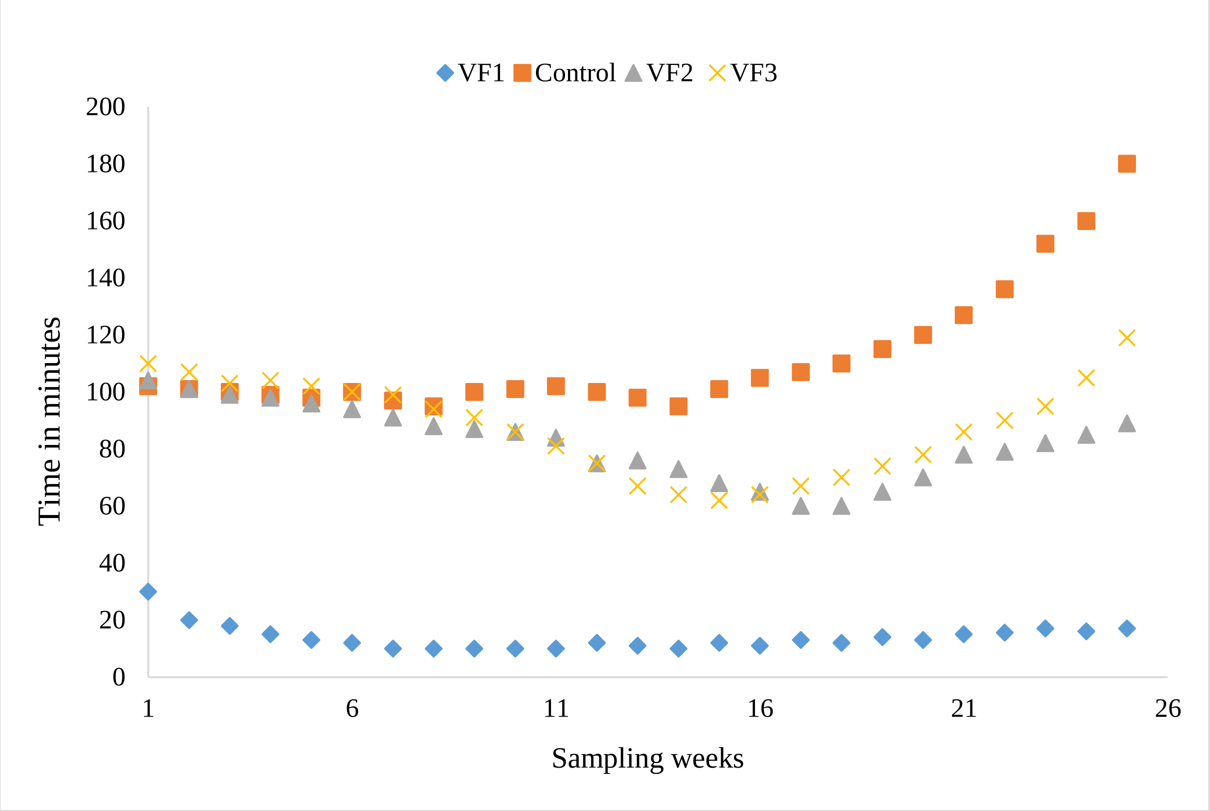


Figure 6-10. The time for collection of 100 ml effluent after the first batch of greywater was supplied

The amount of outflow, after the first batch was supplied, presented in Figure 6-11. The amount of outflow from VF1-Sawdust was almost constant through out the experiment while the amount of outflow from the control unit was decreased significantly towards the end of the experiment followed by VF3-Cow dung and the VF2-Sawdust. However, VF2-Sawdust showed a potential to work for longer period compared to the control unit and VF3-Cow dung.

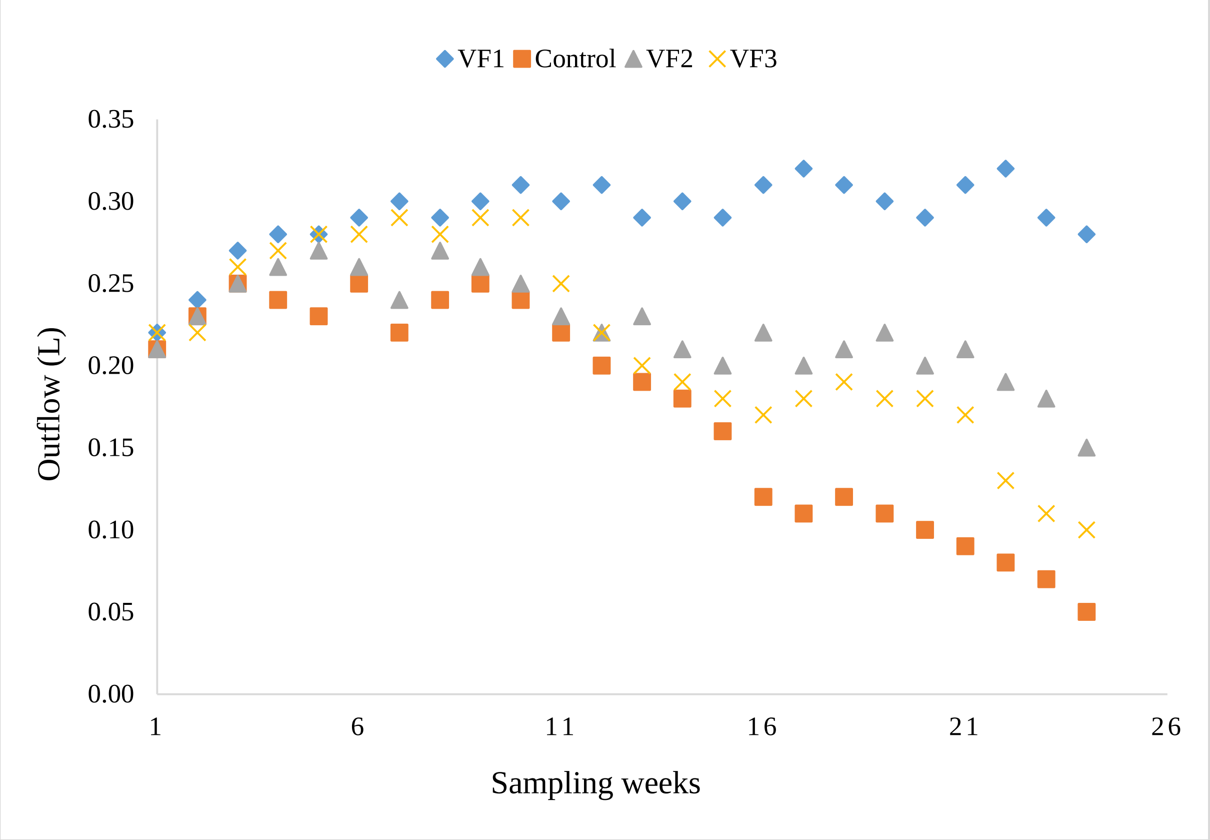


Figure 6-11. The volume of effluent collected after the first batch of greywater was supplied

To determine the amount of water lost in the process, a water balance was calculated once a week based on the effluents collected from each batch of supply. Figure 6-12 presents the daily average batch and total effluents per day from each filter. Though the supply was the same for all batches, 0.5 L, the effluents were about 0.15 to 0.3 L for the first batch, 0.41 to 0.45 L for the second batch, about 0.48 L for the third batch and 0.67 to 0.77 L for the fourth batch. Moreover, the total daily balance showed average loss of 0.2 L per day from totally supplied 2 L/day which mainly lost by evapotranspiration.

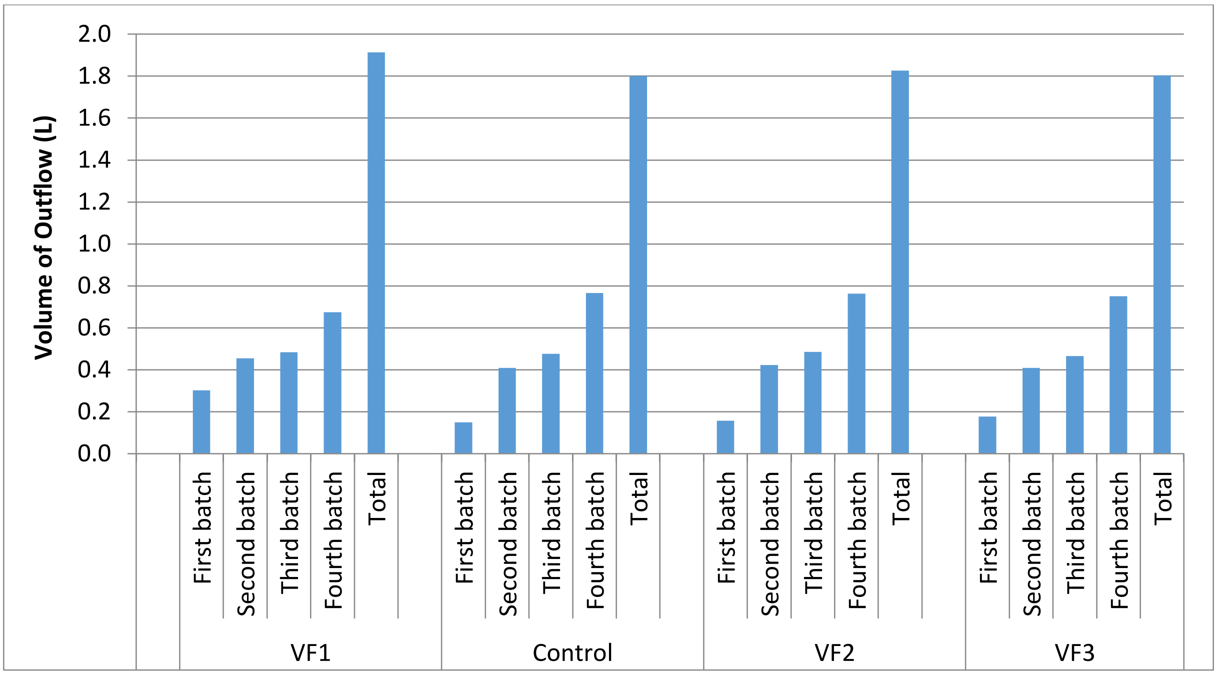


Figure 6-12. The average daily effluent (outflow) from each filter for each batch of supply

Even though it is not possible to calculate HRT for batch supplied vermifilters, the shortest residence time was estimated by the time lapse between addition of greywater to filters and the start to flow out (Dalahmeh *et al.*, 2012) and the longest residence time was estimated during clogging period. To understand the outflow patteren in the vermifilters and the control unit, measurements were done for the first batch in five minutes interval. Figure 6-13 shows the outflow distribution for each vermifilter and the control unit. The VF1-Sawdust, supplied with drinking water, drains quickly while the effluent from other filters took relatively longer time.

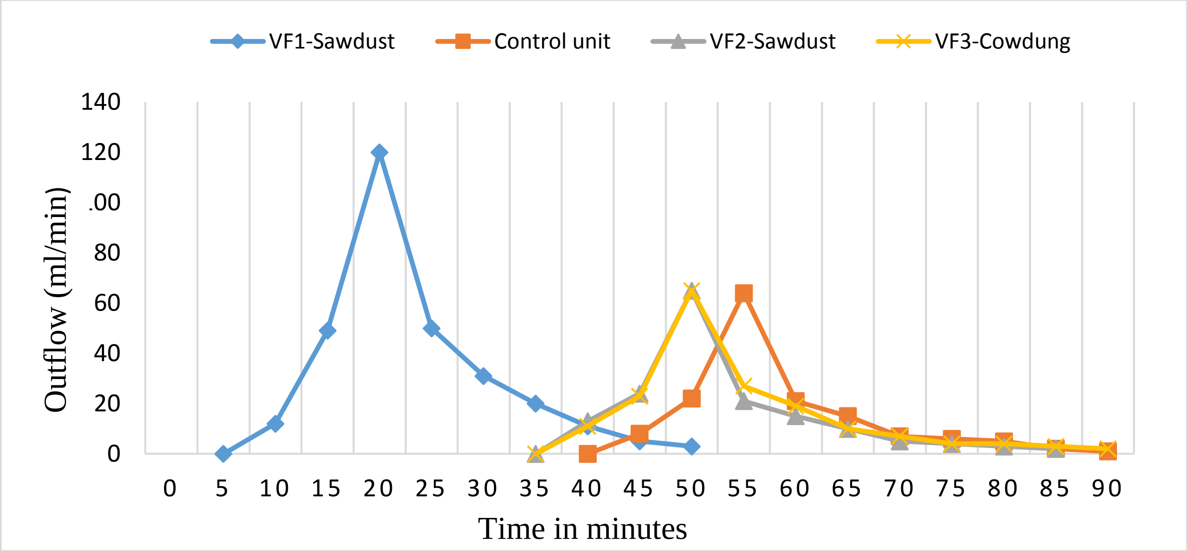


Figure 6-13. The average daily outflow distribution from each vermifilter and control unit during the first batch

As shown in Figure 6-14, the cumulative outflow of each vermifilter and the control unit is presented. The VF1-Sawdust, supplied with drinking water, drains more quickly compared to the others. The control unit took longer time to drain which might be caused by the accumulation of solids that hindered the flow.

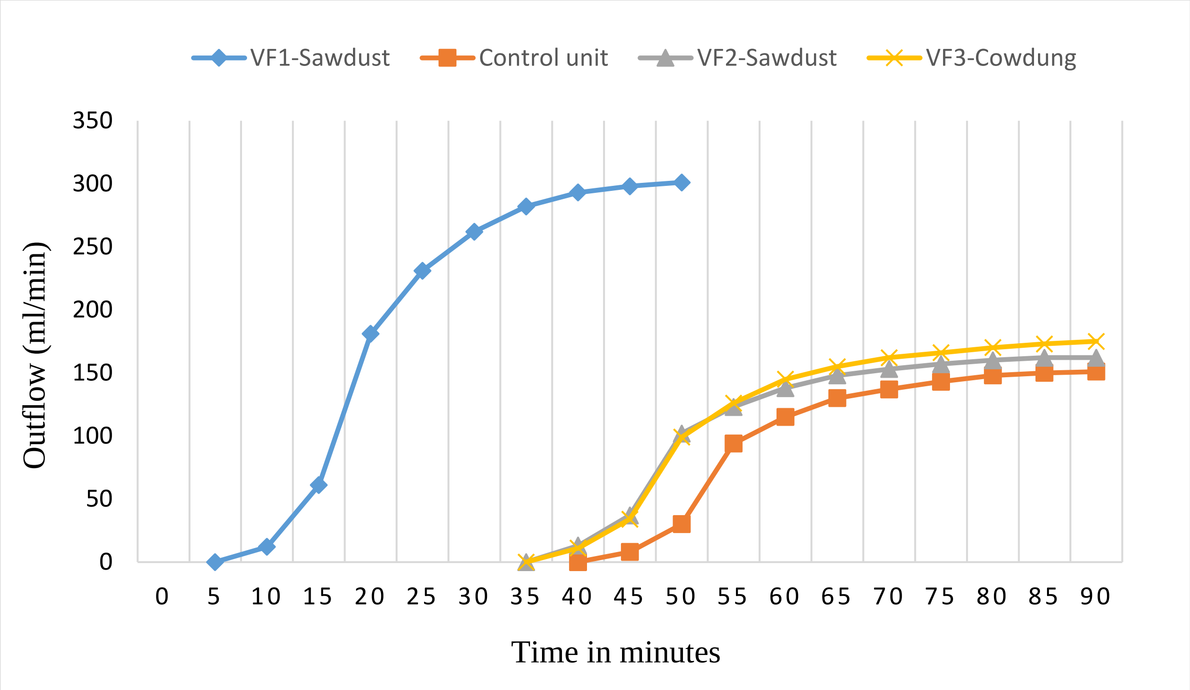


Figure 6-14. The cumulative outflow for the first batch supply

6.4 Conclusions

The VF2-Sawdust performed slightly better compared to the VF3-Cow dung. This might be due to the cow dung had a lower porosity which can be improved by mixing the dung with other porous materials suitable for filter bed. The other reason may be the availability of more pollutants in the cow dung that may drain with the effluent through time. However, VF1-Sawdust, supplied with drinking water, had leached out pollutants causing the effluent to be lower quality than the supplied drinking water. From this it is possible to conclude that contributions from the filter materials might happen especially if it is organic matter.

The most common microbial communities working with earthworms, i.e. fungi, bacteria, and actinomycetes, were identified in sample of filter materials at different depths. More bacteria were observed in the VF2-Sawdust and VF3-Cowdung compared to others. The bacterial distribution, in the vermifilters and the control unit, was higher at the top and decreased to the bottom which can be correlated to the degradation of the filter materials. Relatively, the decrease rate was higher for the vermifilters which might be caused by the earthworm dominance on the upper layer. Moreover, the total death of earthworms in the VF1-Sawdust which was supplied with drinking water may be due to the shortage of nutrients. Hence, it can be concluded that greywater was a source of nutrients for the earthworms and the microbial communities.

There were pH differences in the filter materials along depth which might be caused by the chemical accumulation or precipitation, and the earthworms and microbial activities. Relatively, the pH was lower where earthworms were prevailed.

Though each batch was supplied by same amount of greywater, 0.5 L/batch, the effluent amount was different from batch to batch. Little flow at the first and highest flow at the fourth batch, i.e the flow increased as the batch supply continued. Moreover, the daily water balance showed about 0.2 L was lost by evapotranspiration. The surface filtration and the infiltration from the outlet do not vary for VF1-Sawdust significantly throughout experiment. However, for the other filters, the time to filtrate at the surface takes longer towards the end of the experiment. The control takes more than 1h to filtrate at the end of the experiment, and the VF3-Cow dung and VF2-Sawdust increased with time at lesser rate than the control unit. Moreover, the time that took to collect 100 ml of sample of effluent varies slowly for all vermifilters. Especially the control unit and VF3-Cow dung took more time towards the end of the experiment.

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Chapter 7

General Discussion, Conclusions and Recommendations

Chapter 7: General Discussion, Conclusions and Recommendations

7.1 Introduction

The organic and inorganic solids, nutrients, pathogens and some chemicals are the main pollutants of concern in greywater of the sub-Saharan urban poor. The technology suitable to the urban poor of the developing world needs special attention. It is obvious that a series of unit processes and unit operations can treat wastewater in a better way. However, the shortage of capital, enough skilled personnel, continuous operational and maintenance will not make it feasible for the urban poor. The sub-Saharan urban poor live in congested areas and demand a technology which can be implemented in limited area at low-cost. Hence, vermifiltration is a single treatment facility that can be constructed from locally available cheap materials at the household level.

Overall, this PhD work concluded that vermifiltration can be another sanitation option for the sub-Saharan urban poor provided that the environmental conditions are kept similar or better than the experimental vermifilter model.

7.2 General Discussion

In the experiments conducted, the performances of the vermifilters were better for physico-chemical parameters such as BOD_5, dCOD, tCOD and TSS, and NH_4^+ removal efficiencies and effluent concentrations. However, there were no significant differences for nutrient like NO_3^-, NO_2^- and PO_4^{3-}, and coliforms removal efficiencies and effluent concentrations among the vermifilters and with the control unit. The overall performance of the control unit was as good as vermifilters during the first 2 to 3 months but it started to decline as clogging started earlier in the control unit.

The first experiment (Chapter 3) was conducted for 13 weeks to study the feasibility of the technology during the hottest period from March to May (24^oC to 42.5^oC). The locally available earthworms were identified as *Eudrilus eugeniae*, also known as African night crawler, which are known for waste degradation. However, there are other species of earthworms which most of them are not good for vermifiltration. Therefore, it is always necessary to properly identify and use the right type of earthworm with recommended density. It is preferred to do a pretest if there is no experience in the local environment. Not only earthworm identification but also their density affects the vermifiltration process which may vary from place to place depending on the filter materials used and the characteristics of the greywater.

The average removal efficiencies of BOD_5, COD, TSS, and coliforms (*E. coli* and TTC) at HLR of 191 $L.m^{-2}.d^{-1}$ were 71% and 59%, 62% and 56%, 91% and 85%, and (0.95 log units and 0.93 log units, and 0.98 log units and 0.90 log units) respectively, for the vermifilter and control unit. At an HLR of 64 $L.m^{-2}.d^{-1}$, the removal efficiencies of the same parameters were 96% and 93%, 74% and 66%, 97% and 94%, and (1.77 log units and 1.47 log units, and 1.54 log units and 1.22 log units) respectively for the vermifilter and the control unit. Results showed that vermifilter performance was better than the control unit in removing BOD_5, COD and TSS, but there was little difference for coliforms removal. Higher removal efficiencies were achieved with the HLR of 64 $L.m^{-2}.d^{-1}$ (16 $L.m^{-2}.d^{-1}$ per batch) compared to 191 $L.m^{-2}.d^{-1}$ (43 $L.m^{-2}.d^{-1}$ per batch) in all parameters.

The earthworms also tolerated the inside temperature of 41.5^{o}C in the vermifilter, despite their number reduction to some extent during this time. There were few numbers of juveniles and cocoons which showed temperature had influenced the earthworm reproduction. To minimize the temperature risk, the vermifilter should either be constructed under artificial shade or the combination of natural and artificial shades depending on the local environment. Besides, containers with low thermal conductivity should be used, or the container should be sealed with low thermal conductivity materials where high temperature prevailed.

The second experiment (Chapter 4) was performed for longer period of time, i.e a maximum of 10 months for the vermifilter and 6 months for the control unit which clearly showed how very important the vermifilters are. It was conducted to understand the different sawdust and sand layer thickness effect on the vermifiltration process.

In the first week of the experiment, the earthworms' exhibited weight loss, coiling, swollen clitellum region and about 3.5% deaths which may be due to the acclimatization phase of the earthworms to their new environment. However, after a few weeks, the earthworms have degraded the fine sawdust with the adsorbed solids from the greywater and made the bedding material relatively smaller and uniform in size compared to the control unit which was similar with the other three experiments (Chapter 3, 5 and 6), and Kharwade and Khedikar (2009) reported the bedding material size reduction and its uniformity due to earthworms' activity.

Following the earthworms' adaptation, the three vermifilters were better in performance than the control unit, and their life span was longer. However, there were no significant differences among the vermifilters for most parameters removal efficiencies and concentrations. Therefore, the sawdust can substitute sand as filter medium which is important in reducing the weight of the filter materials, and having more odour free potential organic matter.

Similarly, the ability of earthworms in preventing clogging was reported by Chiarawatchai *et al*. (2007); Chiarawatchai and Nuengjamnong (2009); and Spychala and Pilc (2011). Though the accurate mechanisms for clogging have not been completely clarified yet (Wang *et al*., 2010), pretreating the greywater will improve the performance and lengthen the life span of the vermifilters as there are more inorganic components in greywater used for the experiments. For instance, from sample analysis, the inorganic component (FS) was 47% and VS/TSS became 53% which indicated the slow degradation.

The depth of the bedding material (fine sawdust) had an effect on the number of earthworms and cocoons. From this experiment, the 30 cm fine sawdust layer had more earthworms and cocoons than the 10 cm layer. This may be due to the availability of more VS (carbon) which is important for their activities. The vermifilters had odour free potential organic matter and earthworms that can be harvested every 6-8 months. There was also a decrease in bedding material height in each of the three vermifilters while a little increase was observed in the control unit due to the accumulation of inorganic and poorly degraded organic solids from the greywater.

The third experiment (Chapter 5) was conducted to study the role of vermifilter media layer in pollutant removal from greywater during vermifiltration process. The majority removal of pollutants was achieved above 30 cm (fine sawdust layer) for most selected parameters. This may be due to sawdust adsorption, and utilization by bacterial and earthworm activities. Similar results were reported by Wang *et al*. (2011) and Wang *et al*. (2013). Moreover, Dalahmeh *et al*. (2011) reported that organic matter degradation and nitrification occurred mainly in the top 20 cm of a bark filter. Zhao *et al*. (2009) also reported pollutant removal efficiency was highest when the VF height was between 30 and 70 cm.

The aerobic condition created by the earthworms may favour aerobic bacteria to develop and increase the degradation process and ammonium removal. Due to ammonium nitrification, additional nitrate was produced which might hinder improved removal of nitrate. The DO concentration and temperature increased along the depth, but removal of nitrate and additional oxygen demand need additional depth. Moreover, there was more sawdust volume reduction in vermifilters while a little increment in the control unit due to the accumulation of solids from the greywater which is similarly reported in chapter 4. Towards the end of the experiment, the performance of the control unit was deteriorating but it was not possible to collect more samples from the ports. Higher numbers of bacteria were found in the vermifilter compared to the control unit which may be associated with the presence of earthworms.

The fourth experiment (Chapter 6) was conducted to study filter materials, microbial communities, and influent and effluent pattern in the vermifiltration process while treating greywater. There were physical, chemical and biological changes on the filter materials due to the activities of earthworms and microbial communities in addition to the effects due to the supplied greywater. There was VS reduction which can be related to earthworms and microbial activities, and MC increase due to porosity reduction in the filter materials through time. The C/N ratio was reduced significantly from the initial but the vermifilters had more C/N ratio compared to the control unit which might be due to the existence of earthworms in vermifilters. Similarly, Dalahmeh *et al*. (2011), Luth (2011), Ghatnekar *et al.* (2010) and Kropf *et al.* (1977) reported the degradation of filter materials.

Moreover, high helocellulose degradation was observed in the vermifilter compared to the control unit which is similar to Chapter 5 report. The degradation in the control unit showed that the microbial communities play important role. This corresponds to Morgan and Burrows (1982) who found that the earthworms and the microbes act symbiotically and synergistically to accelerate the decomposition of organic matter and the microorganisms break down the cellulose. Moreover, Wolter *et al.,* (1999) reported earthworms are rich in different types of microbial communities that can help in biodegradation of the sawdust.

Earthworms were able to multiply except in VF1-Sawdust, supplied with drinking water four times a day at 0.5 L/batch. The total death of earthworms in VF1 may be due to shortage of energy and nutrients which was possible to obtain from greywater. The easy availability of carbon and energy source in greywater was reported by Ghunmi *et al.* (2011), Leal *et al.* (2007, 2011) and Zeeman *et al.* (2008). The pH of the filter materials varied along the depth but had a higher level at the surface of the sand layer which might be due to the accumulation of carbonates and bicarbonates. A similar result was reported in Chapter 4. Furthermore, the most common microbial communities working with earthworms were identified, i.e. fungi, bacteria, actinomycetes in the samples of filter materials at different depths. More microbial communities were observed in the vermifilters than the control unit but decreased at different rate along the depth.

There was a decrease both on the top surface filtration and infiltration from the bottom in all filters towards the end of experiment but at high rate in the control unit which might be due to the accumulation of solids from the greywater inside the filter materials that reduced the porosity of the filter system. However, VF1-Sawdust, supplied with drinking water, showed a similar trend throughout the experiment with slight difference towards the end. Though the supply is the same, 0.5 L/batch, the effluents were about 0.15 to 0.3 L for the first batch, 0.41 to 0.45 L for the second batch, about 0.48 L for the third batch and 0.67 to 0.77 L for the fourth batch. Moreover, the daily water balance showed the average loss of 0.2 L from the supplied 2 L greywater which may be mainly due to evapotranspiration.

The new bedding material, cow dung, showed less performance compared to the sawdust which might be due to the less porosity and more nutrients found in the cow dung. The performances among the vermifilters and the control unit were in sequence of VF2-Sawdust > VF3-Cow dung > Control unit in most parameters. However, VF1-Sawdust supplied with drinking water leached out pollutants and made the effluent be of low quality compared to the drinking water. This showed that the filter materials may reduce the quality by leaching out through time, especially organic materials.

Generally, the physico-chemical parameters removal efficiencies reported in this research work were similar to Sinha *et al*. (2008), Kharwade and Khedikar (2011), and Kumar *et al*. (2014) report, i.e 80%-90% BOD_5, COD and TSS removal from wastewater. Though there was no significant difference for coliforms removal among the filters, more than 2 log units of removal were achieved for HLR of 16 $L.m^{-2}.d^{-1}$ per batch (Chapter 3 and 4) which is similar to Arora *et al.* (2014) findings.

Therefore, vermifiltration can be another sanitation option for the sub-Saharan urban poor. The zero cost for collection and the ability to treat pollutants physically, chemically and biologically in a single facility makes the technology cheaper and selective.

To scale up the vermifiltration technology for household use, the average daily greywater disposed to open spaces and streets should be estimated. Though there is variation from place to place, for the Ouagadougou urban poor, of the total greywater amount, averagely 10 $L.capita^{-1}.d^{-1}$ is being thrown out on the streets (Kando, 2008; Yofe, 2008). From the laboratory scale results of this research, the HLR of 16 $L.m^{-2}.d^{-1}$ per batch (0.5 L/batch) gave better removal efficiencies for the surface area of 0.03 m^2 (200 mm diameter PVC pipe). Hence, the surface area needed for a family member is about 0.16 m^2. However, depending on the space availability, the surface area can be adjusted by varying the HLR, but the quality of the effluent may be affected. For instance, the surface area needed for the HLR of 43 $L.m^{-2}.d^{-1}$ per batch (1.5 L/batch) is 1/3 times less. The depth should be similar to the laboratory scale vermifilter so that it can be operated by most family members.

The site selection should be done in consultation with the household preferably where it is not exposed directly to sun. Artificial or both artificial and natural shades can be used depending on the local environment. It can be fixed or portable type, and the shade should be greater than the dimensions of the prototype surface area for effective protection. The roof material should have less thermal conductivity to minimize the temperature effect and the side wall needed to be partially covered for proper ventilation. When the greywater is supplied, it should be uniformly distribute on the surface of the vermifilter after separating bigger solid materials. Temporary storage is important during high production time to avoid over flooding in the vermifilter. It is also important to check the supply with the surface filtration of the greywater.

Furthermore, the treated effluent either can be used for gardening with proper management or can be drained to leach/soak away pit or sewer line. The degraded odour free sawdust and earthworms can be harvested every 6-8 months to be used as fertilizer for agriculture and poultry feed respectively.

7.3 Conclusions

From this research, the following main conclusions are drawn:

Greywater generated from the sub-Sahran urban poor was found highly polluted (COD > 1910 mg/L, BOD_5 > 1039 mg/L, TSS > 1120 mg/L, *E. coli* > $18*10^3$ cfu/100mL and TTC > $535*10^3$ cfu/100mL averagely). The laboratory model vermifilter was able to remove > 90% of BOD_5 and TSS, 80%-90% of COD, 60%-70% of NH_4^+, 40%-50% of NO_3^-, 50%-60% of NO_2^- and PO_4^{3-}, and 1-4 log units of coliforms. Better performances were achieved by the vermifilter loaded with HLR of 64 $L.m^{-2}.d^{-1}$ (16 $L.m^{-2}.d^{-1}$/ batch) compared to the HLR of 191 $L.m^{-2}.d^{-1}$ (43 $L.m^{-2}.d^{-1}$/batch). The *Eudrilus euginae* tolerated a maximum inside temperature of 41.5°C. Therefore, vermifiltration can be another low-cost sanitation option for the sub-Sahran urban poor provided that the environmental conditions are either similar or better than the laboratory scaled vermifilter model.

The filter medium layer composition (sawdust and sand) had little effect on the vermifilters performance. However, the vermifilters performed better and their life span was longer than the control unit. Therefore, the sawdust can substitute sand as a filter medium, but adding a little layer of sand to the bottom is helpful. However, the vermifilters did no longer support the earthworms' growth after several months of operation due to high moisture content caused by the accumulation of inorganic and slowly degrading organic solids that reduced the porosity. The vermifilters had odour free potential organic matter and earthworms that could be harvested every 6-8 months.

The top (sawdust) layer of the vermifilter played an important role in removing most pollutants selected for analyses. This may be due to the sawdust adsorption capacity, and activities of earthworm and microbial communities. For most parameters, the vermifilter was slightly better in most aspects except nitrite, orthophosphate and TSS removal compared to the control unit. However, there were fluctuations from time to time for nitrate and orthophosphate. There was also an increase in dissolved oxygen and average temperature along the depth, and additional depth may increase the removal of nitrate and the remaining oxygen demand.

The new bedding material, cow dung, was examined and showed less performance than the sawdust. The overall performances among the vermifilters and the control unit were in sequence of VF2-Sawdust > VF3-Cow dung > Control unit for most parameters. There were physical, chemical and biological changes on the filter materials during the vermifiltration process. In addition to the size and volume reduction in the sawdust layer due to biodegradation, there were accumulation of carbonates and bicarbonates at the surface of the sand layer which might increase the pH. The most common microbial communities working with earthworms was also identified, i.e. fungi, bacteria, actinomycetes in the samples of filter materials at different depths. More bacteria was observed in the VF2-Sawdust and VF3-Cow dung compared to others. The bacterial distribution in the vermifilters and the control unit were higher at the top compared to the bottom.

7.4 Recommendations for Further Research

- The sawdust vermifilter was performing better than cow dung vermifilter. However, if there are no sawdust and cow dung in the area, different filter bed materials need to be examined individually or in mixture at different composition.
- The identification of individual microbial communities working with earthworms should be studied further detail.

- Additional characteristics of the concentrated greywater should be studied, for instance, heavy metals, salt, surfactants, oil, fat and grease which may have impact on the vermifiltration process.
- The experiments of this study were conducted with three and four times supply during the day time. Effect of different resting periods with different HLR should be studied further.
- The potential of the degraded bedding material for agricultural purpose should be experimentally examined.

7.5 References

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Appendices

Appendix- 1. The initial and final porosities of each filter was calculated after measuring the porosity of each filter material for each filter at the beginning and end of the experiment.

Appendex 1-a. Porosity for vermifilter supplied with drinking water

Dates	Filter material	Total volume (mL)	Water added (mL)	Porosity (%)	Proportion (%)	Porosity*proportion (%)
04/02/2015	gravel	100	41	41	8	3
	Coarse gravel	100	38	38	8	3
	sand	100	40	40	17	7
	Fine sawdust	100	93	93	67	62
	Total porosity					**75**
01/06/2015	gravel	100	40	40	8	3
	Coarse gravel	100	37	37	8	3
	sand	100	39	39	17	7
	Fine sawdust	100	90	90	67	60
	Total porosity					**73**

Appendex 1-b. Porosity for control unit

Dates	Filter material	Total volume (mL)	Water added (mL)	Porosity (%)	Proportion (%)	Porosity*proportion (%)
04/02/2015	Gravel	100	41	41	8	3
	Coarse gravel	100	38	38	8	3
	Sand	100	40	40	17	7
	Fine sawdust	100	93	93	67	62
	Total porosity					**75**
01/06/2015	Gravel	100	39	39	8	3.3
	Coarse gravel	100	36	36	8	3
	Sand	100	38	38	17	6.3
	Fine sawdust	100	63	63	67	42
	Total porosity					**55**

Appendex 1-c. Porosity for sawdust vermifilter

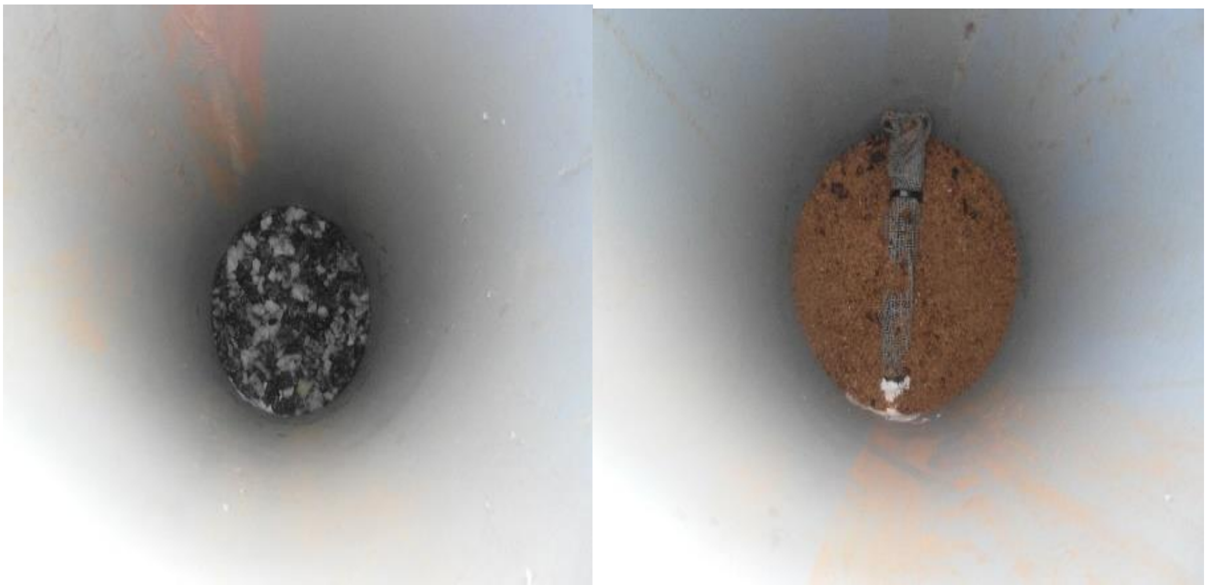
Dates	Filter material	Total volume (mL)	Water added (mL)	Porosity (%)	Proportion (%)	Porosity*proportion (%)
04/02/2015	Gravel	100	41	41	8	3
	Coarse gravel	100	38	38	8	3
	Sand	100	40	40	17	7
	Fine sawdust	100	93	93	67	62
	Total porosity					**75**
01/06/2015	Gravel	100	39	39	8	3.3
	Coarse gravel	100	36	36	8	3
	Sand	100	38	38	17	6.3
	Fine sawdust	100	74	74	67	49.3
	Total porosity					**62**

Table Appendex 1-d. Porosity for cow dung vermifilter

Dates	Filter material	Total volume (mL)	Water added (mL)	Porosity (%)	Proportion (%)	Porosity*proportion (%)
04/02/2015	Gravel	100	41	41	8	3
	Coarse gravel	100	38	38	8	3
	Sand	100	40	40	17	7
	Cow dung	100	64	64	67	43
	Total porosity					**56**
01/06/2015	Gravel	100	39	39	8	3.3
	Coarse gravel	100	36	36	8	3
	Sand	100	38	38	17	6.3
	Cow dung	100	49	49	67	33
	Total porosity					**47**

Appendix- 2. Photos during construction, earthworm counting and weighing, and comparison the degraded bed material with the raw sawdust

(a) Construction of filters



Gravel Sand

Sawdust Earthworms

(b) Filling the filter materials and earthworm inoculation

(c) Earthworm washing, drying and counting

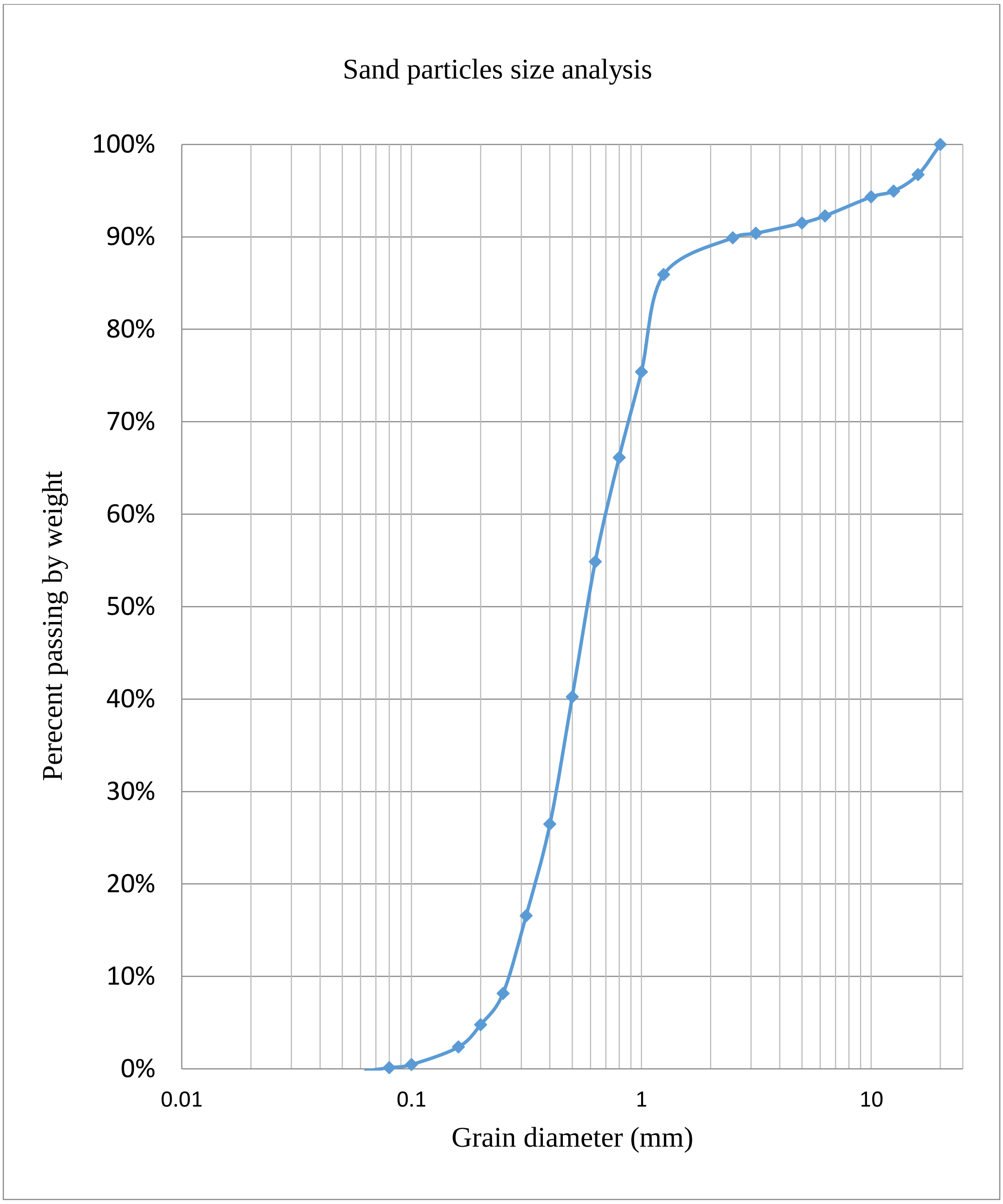
(d) Bedding material degradation and volume reduction

(e) Sawdust components and volatile solid detrmination

Appendix- 3. Sand particles distribution

Particle size analysis by screening						
			Intial dry weight (g) : 931 g			
Modules AFNOR	**mm sieve**	**particles retained**	**retained cummulative**	**% retained cummulative**	**% Passed cummulative**	**Observations**
45	25					
44	20		0 g	0.0%	100.0%	
43	16	30 g	30 g	3.3%	96.7%	
42	12.5	17 g	47 g	5.1%	94.9%	
41	10	6 g	53 g	5.7%	94.3%	
39	6.3	19 g	72 g	7.7%	92.3%	
38	5	7 g	79 g	8.5%	91.5%	
36	3.15	10 g	90 g	9.6%	90.4%	
35	2.5	4 g	94 g	10.1%	89.9%	
32	1.25	37 g	131 g	14.1%	85.9%	
31	1	98 g	229 g	24.6%	75.4%	
30	0.8	86 g	315 g	33.9%	66.1%	
29	0.63	105 g	420 g	45.1%	54.9%	
28	0.5	136 g	556 g	59.8%	40.2%	
27	0.4	128 g	684 g	73.5%	26.5%	
26	0.315	92 g	777 g	83.4%	16.6%	
25	0.25	78 g	855 g	91.8%	8.2%	
24	0.2	31 g	886 g	95.2%	4.8%	
23	0.16	23 g	909 g	97.6%	2.4%	
21	0.1	18 g	926 g	99.5%	0.5%	
20	0.08	3 g	930 g	99.9%	0.1%	
19	0.063	3 g	933 g	100.2%	-0.2%	
18	0.05					

(a) Particle size analysis by screening



(b) Graph for sand particles size analysis