RESOURCE RECOVERY & REUSE SERIES 1

1

On-farm Treatment Options for Wastewater, Greywater and Fecal Sludge with Special Reference to West Africa

Bernard Keraita, Pay Drechsel, Amah Klutse and Olufunke O. Cofie

About the Resource Recovery and Reuse Series

Resource Recovery and Reuse (RRR) is a sub-program of the **CGIAR Research Program on Water, Land and Ecosystems (WLE)** dedicated to applied research on the safe recovery of water, nutrients and energy from domestic and agro-industrial waste streams. This SRP aims to create impact through different lines of action research, including (i) developing and testing scalable RRR business models, (ii) assessing and mitigating risks from RRR for public health and the environment, (iii) supporting public and private entities with innovative approaches for the safe reuse of wastewater and organic waste, and (iv) improving rural-urban linkages and resource allocations while minimizing the negative urban footprint on the peri-urban environment. This sub-program works closely with the World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), United Nations University (UNU), and many national and international partners across the globe. The RRR series of documents present summaries and reviews of the sub-program's research and resulting application guidelines, targeting development experts and others in the research for development continuum.

CGIAR Research Program on Water, Land and Ecosystems

Led by: IWMI International Water Management Institute

WLE Partners:

RESOURCE RECOVERY & REUSE SERIES 1

On-farm Treatment Options for Wastewater, Greywater and Fecal Sludge with Special Reference to West Africa

Bernard Keraita, Pay Drechsel, Amah Klutse and Olufunke O. Cofie

The authors

Dr. Bernard Keraita is an International Researcher at the Department of International Health, Immunology and Microbiology, University of Copenhagen, Denmark. He formerly worked as an Irrigation and Water Engineer, International Water Management Institute (IWMI), Regional Office for Africa, Accra, Ghana).

Dr. Pay Drechsel is a Principal Researcher and Theme Leader - Water Quality, Health and Environment. He was based in Ghana for 11 years and is now working at the headquarters of IWMI in Colombo, Sri Lanka.

Dr. Amah Klutse is Chief of Water, Sanitation and Hygiene at the United Nations Children's Fund (UNICEF), based in Burundi. He formerly worked as Head of Research and Demonstration Projects with the Centre Régional pour l'Eau Potable et l'Assainissement à faible coût (CREPA), Ouagadougou, Burkina Faso.

Dr. Olufunke O. Cofie is a Senior Researcher specialized in fecal sludge treatment and reuse, and Head of IWMI's West Africa Office in Accra, Ghana.

Keraita, B.; Drechsel, P.; Klutse, A.; Cofie, O. 2014. *On-farm treatment options for wastewater, greywater and fecal sludge with special reference to West Africa*. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 32p. (Resource Recovery and Reuse Series 1). doi: 10.5337/2014.203

ISSN 2478-0510
e-ISSN 2478-0529
ISBN 978-92-9090-785-5

/ on-farm research / wastewater treatment / water quality / water storage / irrigation water / faecal coliforms / sewage sludge / contamination / reservoirs / filtration / weirs / ponds / wells / wetlands / health hazards / farmers / sedimentation / helminths / moringa / West Africa / Ghana /

Front cover photograph: Farmers in Lomé, Togo, using intermediate storage ponds (*credit*: Eveline Klinkenberg/ IWMI).

Editor: Mahen Chandrasoma
Illustrator: Randy Chriz Perera
Designer: Michael Dougherty

Acknowledgements

This report is based on various research projects in support of the GlobE - UrbanFoodPlus project, an African-German partnership to enhance resource use efficiency and improve food security in urban and peri-urban agriculture of West African cities.

Projects

'Safeguarding public health concerns, livelihoods and productivity in wastewater irrigated urban and peri-urban vegetable farming' project (PN 38) of the CGIAR Challenge Program on Water and Food (CPWF).

GlobE - UrbanFoodPlus

Donors

The authors would like to acknowledge the support of the CGIAR Challenge Program on Water and Food (CPWF) for funding the 'Safeguarding public health concerns, livelihoods and productivity in wastewater irrigated urban and peri-urban vegetable farming' project (PN 38). In particular, for this review for the GlobE - UrbanFoodPlus project, the authors also acknowledge the financial support provided by Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) (Federal Ministry for Economic Cooperation and Development), Germany, and Bundesministerium für Bildung und Forschung (BMBF) (Federal Ministry of Education and Research), Germany.

Funding for the research carried out in this report was provided by the following organizations, among others, through the CGIAR Challenge Program on Water and Food (CPWF).

UK Department for International Development (DFID)

European Commission

International Fund for Agricultural Development (IFAD)

Swiss Agency for Development and Cooperation (SDC)

Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) (Federal Ministry for Economic Cooperation and Development), Germany

Bundesministerium für Bildung und Forschung (BMBF) (Federal Ministry of Education and Research), Germany

The views expressed herein do not necessarily reflect the official opinion of DFID, European Commission, IFAD, SDC BMBF and BMZ.

CONTENTS

SUMMARY

Where conventional wastewater treatment is lacking, and water in streams and rivers used for crop irrigation is heavily polluted, alternative or additional options for health risk reduction are needed. The 2006 edition of the World Health Organization (WHO) guidelines for the safe use of wastewater, excreta and greywater in agriculture support such a multiple-barrier approach. On-farm treatment constitutes one of these barriers, and although it can hardly replace conventional treatment, it can contribute to risk reduction, especially if combined with other barriers such as safe irrigation practices and post-harvest crop washing.

On-farm treatment options are based on the same processes as those used in conventional wastewater treatment, such as sedimentation, flocculation, filtration and natural die-off. This paper illustrates a selection of options for safer wastewater and greywater irrigation as well as excreta use, with particular reference to studies in West Africa.

The paper shows that 'small-scale' and 'low cost' are not necessarily roadblocks for setting up effective farm-based treatment systems. A larger challenge is to understand how best to facilitate any required behavior change by farmers to adjust their farming practices. Participatory on-farm research will be needed to study risk perceptions and awareness, as well as production factors influencing the adoption of treatment options, such as tenure security and additional cost, and land or labor requirements. Interventions which can build on farmers' current practices, such as on-farm storage ponds or river bank filtration, will probably have the highest potential of acceptance.

Source: IWMI.

INTRODUCTION

Fecal contamination of urban and peri-urban water bodies is a major health issue in most low- and middle-income countries, where population growth exceeds the rate of development of wastewater or fecal sludge collection and treatment infrastructure. Estimates show that 80-90% of all wastewater generated in developing countries is discharged without appropriate treatment into surface water bodies (Corcoran et al. 2010), thereby causing, for example, 75% of the known water pollution in India (NUSP 2008). As these highly polluted waters are used for irrigation in and around four of five cities across low-income countries, the likelihood of the transmission of excreta-related diseases to farmers and, for example, vegetable consumers is very high (Raschid-Sally and Jayakody 2008). The same applies to West Africa, where high levels of fecal contamination of water sources and vegetables in urban farming sites have been reported across the region (Amoah et al. 2011; Okafo et al. 2003; Niang 1999).

To address these risks, the expansion of sewer systems and treatment capacity remain a high priority for municipal authorities. However, major progress in sanitation investments continues to be outpaced by population growth, and the average level of wastewater collection and treatment remains below 10% in most African countries (WHO-UNICEF 2010; USEPA 2012). Complementary options for safeguarding public health are needed until better alternatives are available. These options can range from safer irrigation practices to crop restrictions or post-harvest handling, and should ideally be combined to form multiple barriers for cumulative risk reduction (Amoah et al. 2011; Bos et al. 2010). Where industrial development and chemical contamination remain localized, these barriers should focus on reducing pathogen loads in irrigation water and on crops eaten raw[1]. In particular, treatment should aim at reducing levels of intestinal nematodes, especially *Ascaris lumbricoides,* and viral and bacterial loads, which pose the most significant health risks to farmers, consumers and those living close to wastewater-irrigated farming sites (WHO 2006a).

This report reflects on on-farm treatment as one of the possible barriers. It presents an overview of some low-cost wastewater treatment technologies for pathogen removal, which can be adapted for use in urban and peri-urban areas in low-income countries. It also highlights some practical experiences in using these technologies in real farm situations, and from pilot research being conducted in West Africa and other regions.

With a few exceptions (which target backyard gardens or similar controlled environments where black water and greywater remain separate), the report does not differentiate between wastewater and greywater. This is because, in the context of most low-income countries, greywater gets contaminated with fecal matter (by open defecation or 'flying toilets') on its way through storm water gutters, canals and streams before being used on open spaces by urban or peri-urban farmers. In this context, there is no clear boundary between raw wastewater, diluted wastewater and polluted stream water. So, treatment options should be robust enough to cope with a broad range of water quality characteristics.

Although this report has a technical focus, we would like to stress the importance of the biophysical, socioeconomic and cultural environment under which we are operating. The conditions which influence farmers to eventually adopt any on-farm treatment option have to be carefully analyzed before any technical trials are commenced. These conditions vary from one farming site to another (even within the same city), can differ greatly in terms of irrigation water source, water quality, tenure security, plot size, vegetables grown, irrigation method, soils, etc., and maybe, most importantly, risk awareness and perception of farmers. All these conditions have to be analyzed carefully to ensure that suggested technologies for on-farm treatment are appropriate for a specific site and target group of farmers.

[1] Options to address heavy metal contamination on farm are generally limited (Simmons et al. 2010). Therefore, all efforts are needed to implement source treatment in instances where, for example, tanneries release chemically contaminated effluent as is the case in West Africa, for example, from Kano and Ouagadougou.

LEARNING FROM CONVENTIONAL WASTEWATER TREATMENT

Where conventional wastewater treatment is not possible before irrigation, or its effectiveness questionable, understanding how treatment works, especially the mechanisms for pathogen removal, is helpful in developing appropriate technologies which can be applied on farm to improve the quality of irrigation water. Most low-cost treatment systems take advantage of natural processes that occur when water, soils, plants, microorganisms and the environment interact (Parr et al. 2002; Metcalf and Eddy, Inc 1995), such as sedimentation and flocculation, filtration and natural die-off.

Conventional wastewater treatment is carried out to remove as much of the pollutants and pathogens in wastewater as possible to minimize public health risks and negative environmental impacts. The processes involve screening to protect pumps from large materials and grit removal (preliminary treatment), and sedimentation of suspended solids to reduce the organic load (primary treatment). Secondary treatment entails the biological decomposition of organic material and pathogens to produce a clear effluent and solid biomass for removal. This can be achieved aerobically, for example, through trickling filters or suspended growth (activated sludge), or anaerobically in waste stabilization ponds. For pathogen removal, which is the main concern in West Africa, low-cost process technologies such as aerated lagoons and waste stabilization ponds are well suited and easy to maintain, although they demand more land than compact treatment systems (Scheierling et al. 2010; see also Table 1). Tertiary treatment targets nutrients, toxic compounds and further pathogen destruction through different processes, such as membrane filtration, flocculation and disinfection (Metcalf and Eddy, Inc. 1995). Most treatment systems in Africa only have two levels (primary and secondary treatment), but are often in poor state and operate far below the design capacity (Murray and Drechsel 2011). Although pathogen reduction rates will be smaller in farm-based systems than in professional treatment plants, the cost effectiveness of on-farm treatment can be very high (Drechsel and Seidu 2011).

The following sections will describe the systems applicable to the on-farm treatment of wastewater, in part, even on very small farm plots. The processes used for pathogen reduction are largely the same as those used in conventional wastewater treatment.

ON-FARM POND TREATMENT SYSTEMS

Wastewater treatment ponds are one of the best-known treatment systems which are especially suitable for low-income countries due to their low costs, low energy and maintenance needs, and high performance based on 'natural' processes (Arthur 1983; Mara 2004).

Ponds improve water quality by allowing settlement of particles and pathogens (sedimentation process), and also exposing pathogens to the environment. Settlement times of particles and pathogens differ depending on their sizes and densities (Sengupta et al. 2012; Peterson 2001). For example, while some larger and denser types of helminth eggs may take a few hours to settle, the comparatively lighter and smaller viruses may take hundreds of years to settle in water. Therefore, wastewater sedimentation ponds are better at removing helminth eggs and protozoans than bacteria and viruses (Mara 2004). Nevertheless, bacteria and viruses can also be removed through sedimentation, when mainly adsorbed on large particles (Karim et al. 2004).

TABLE 1. RATINGS FOR PATHOGEN REMOVAL AND SET UP CRITERIA OF VARIOUS WASTEWATER TREATMENT SYSTEMS.

	PACKAGE PLANT	ACTIVATED SLUDGE PLANT	TRICKLING FILTER	EXTENDED AERATION ACTIVATED SLUDGE	OXIDATION DITCH	AERATED LAGOON	WASTE STABILIZATION POND
Fecal coliforms	Poor	Poor	Poor	Fair	Fair	Good	Good
Helminths	Poor	Fair	Poor	Poor	Fair	Fair	Good
Viruses	Poor	Fair	Poor	Fair	Fair	Good	Good
Simple operations	No	No	Fair	No	Fair	No	Yes
Land demand	Low	Low	Low	Low	Low	Fair	High

Source: Adapted from Arthur 1983.

Shallow ponds exposed to sunshine reveal bacteria and viruses to unfavorable environmental conditions, such as high temperatures, changes in pH or long exposures to ultraviolet (UV) radiation, all of which enhance natural die-off (Marais 1974; Silverman et al. forthcoming). In addition, there is also high competition for survival from already adapted microorganisms which are supporting die-off. According to Feachem et al. (1983), in warm climates, most bacteria only survive up to 30 days in water, and less than 20 and 15 days in soils and on crops, respectively, while Helminth eggs can survive many months.

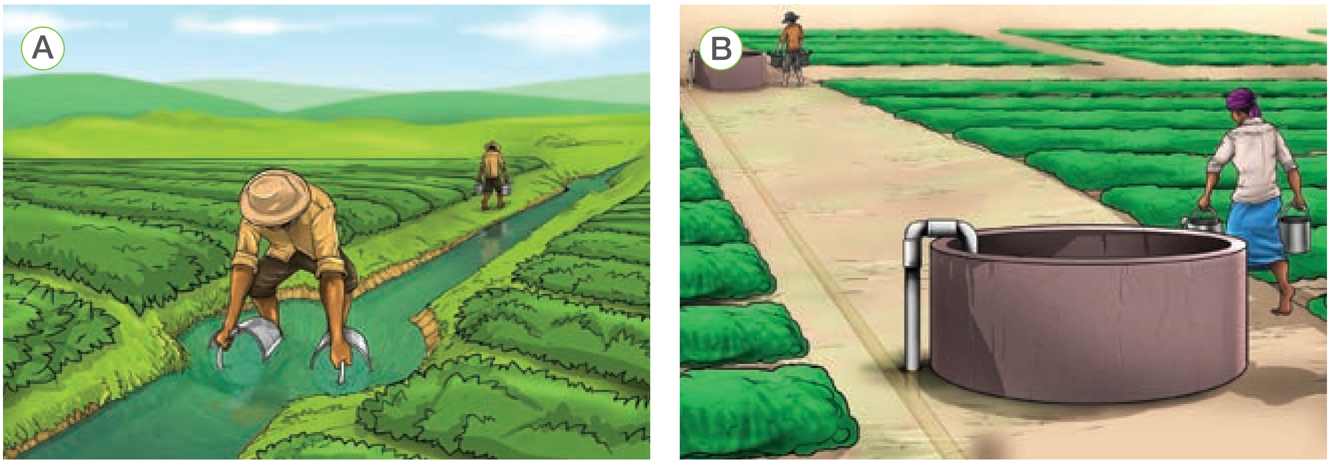
Common On-farm Ponds Used in West Africa

In many West African countries, smallholder farmers in urban and peri-urban areas use pond systems, such as shallow ponds, dugouts, drums or concrete tanks, for water storage. Dugouts and ponds might collect surface flow or subsurface flow near streams, function as storage reservoirs for pumped drain or stream water, or simply reduce walking distances to water sources where watering cans are the means of irrigation. Where the slope allows, farmers might link their ponds or reservoirs via narrow trenches or pipes in a network, which can further reduce manual water transport (Figure 1).

To facilitate water collection from smaller wastewater drains or streams, farmers block the natural water flow with sandbags or other materials to create deeper pools suitable for fetching water with watering cans or to lift the water table so that the water can flow by gravity to the field. Farmers often create cascades of small dams along the fields. Although these systems are not meant for water treatment (http://youtu.be/f_EnUGa_GdM), they support sedimentation and can become part of training modules for health risk reduction (http://www.youtube.com/watch?v=Aa4u1_RblfM).

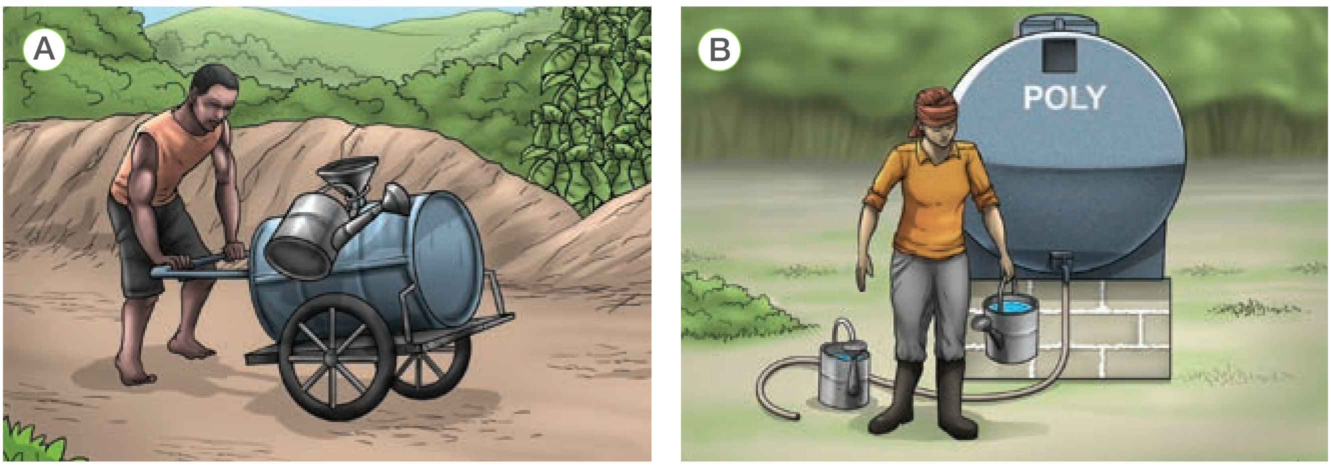
In some areas, where there are larger farms, farmers use mobile drums, poly tanks or even concrete tanks (Figure 2), which are located close to plots, to store water and use it when needed. These tanks and drums reduce water losses due to soil infiltration compared to un-lined ponds. Table 2 shows the most common forms of pond-based systems used in West Africa.

FIGURE 1. INTERCONNECTED PONDS FOR FETCHING WATER: (A) DUGOUTS CONNECTED THROUGH A TRENCH IN OUAGADOUGOU, BURKINA FASO; AND (B) CONCRETE RESERVOIRS CONNECTED THROUGH PIPES IN LOMÉ, TOGO.



Source: IWMI. *Source:* IWMI.

FIGURE 2. (A) MOBILE, AND (B) STATIONARY IRRIGATION WATER TANKS, AS SEEN IN OUAGADOUGOU, BURKINA FASO.



Source: IWMI. *Source:* IWMI.

TABLE 2. OVERVIEW OF FARM-BASED POND SYSTEMS IN SMALLHOLDER AGRICULTURE.

	ON-FARM WATER STORAGE PONDS	IN-STREAM PONDS	COMBINED POND SYSTEMS
Description	Small ponds, soil dugouts, drums or concrete tanks used for interim wastewater storage. Usually, water is fetched from these reservoirs using watering cans. They are filled with the help of small motor pumps.	To ease fetching water in wastewater drains and streams, farmers block the water flow with sandbags or other materials to create pools. Common methods are cascades of such barriers along the farming area.	Where the slope allows, farmers might link their ponds or reservoirs via narrow trenches or pipes in a network, which can further reduce manual water transport.
Area requirement and/or size of ponds	Varies from 1 to 10 m^2 surface with crop water needs (i.e., crop type and climate) and the size of the cropped farm area. Depth is usually around 1 m.	Varies widely, but is usually between 1 and 3 m^2. Depth varies between 0.5 and 1 m.	Individual ponds are usually between 0.5 and 1 m deep with a surface area of 3 to 5 m^2.
Challenges for farmers	Where soils are too sandy, concrete structures or drums are needed. Water contact where farmers step into ponds for fetching.	Sandbags commonly washed away after heavy rains. Water contact where farmers step into streams.	Structure requires maintenance during and after the rainy season. Water contact where farmers step into ponds.

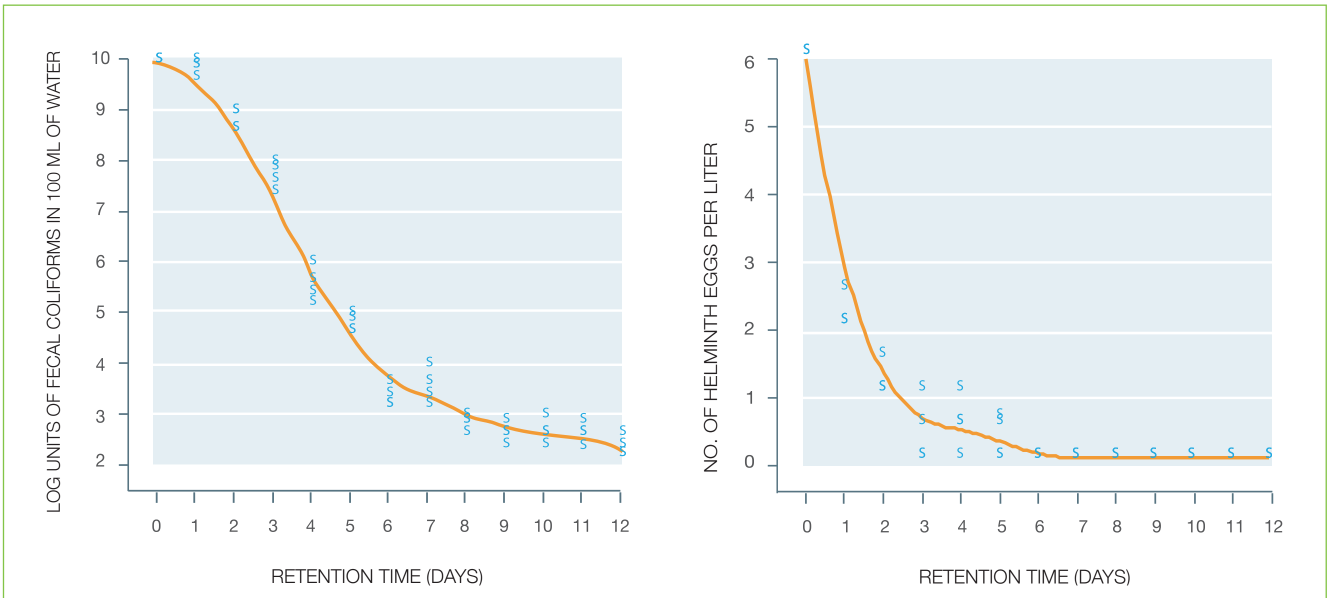
Removal of Microbial Loads

Sedimentation requires an un-disturbed retention time. The frequency of fetching water is, therefore, important. The frequency depends on crop water requirements and is closely linked to the climate. In hot climates, such as in Ghana, farmers irrigate exotic vegetables, such as lettuce, early in the morning and late in the evening, especially in the dry season, while once a day might be sufficient in the cloudier rainy season. When farmers use a single pond, particles in the pond water can thus settle for only 8 hours during the day and 13 hours overnight in the dry season. In a different climate, such as in Ethiopia, irrigation frequency can allow longer intervals of 2-3 days. These longer intervals allow for some sedimentation, especially of helminth eggs, in the ponds, and if human disturbance and re-suspension are minimized, some improvements in water quality can be achieved. Results from experimental field trials in Kumasi showed that, over a period of 2-3 days, sedimentation levels of helminth eggs found in watering cans were down to less than 1 egg per liter, accompanied by a fecal coliform removal of up to 2 log units per 100 ml (Keraita et al. 2008a; Figure 3). Fecal coliform removal was lower during the rainy season probably due to less sunshine exposure. However, in hot climates with frequent irrigation, ideal removal rates cannot be expected and additional measures are needed to minimize disturbance and enhance the retention time.

Improving Treatment Capacity of Existing On-farm Ponds

Keraita et al. (2008a, 2010) recommended a number of measures that can enhance the treatment capacity of ponds built by farmers. These include improving the design of ponds, creating additional ponds, and training farmers on how to collect water with minimal disturbance will be beneficial for their own health and also on the sedimentation process. Since adding such a 'treatment

FIGURE 3. FECAL COLIFORM AND HELMINTH EGG REMOVAL OVER TIME IN ON-FARM PONDS IN KUMASI.



Source: Keraita et al. 2008a.

objective' to ponds is likely to affect labor and space requirements (Table 3), changes have to remain modest to maintain farmers' cooperation.

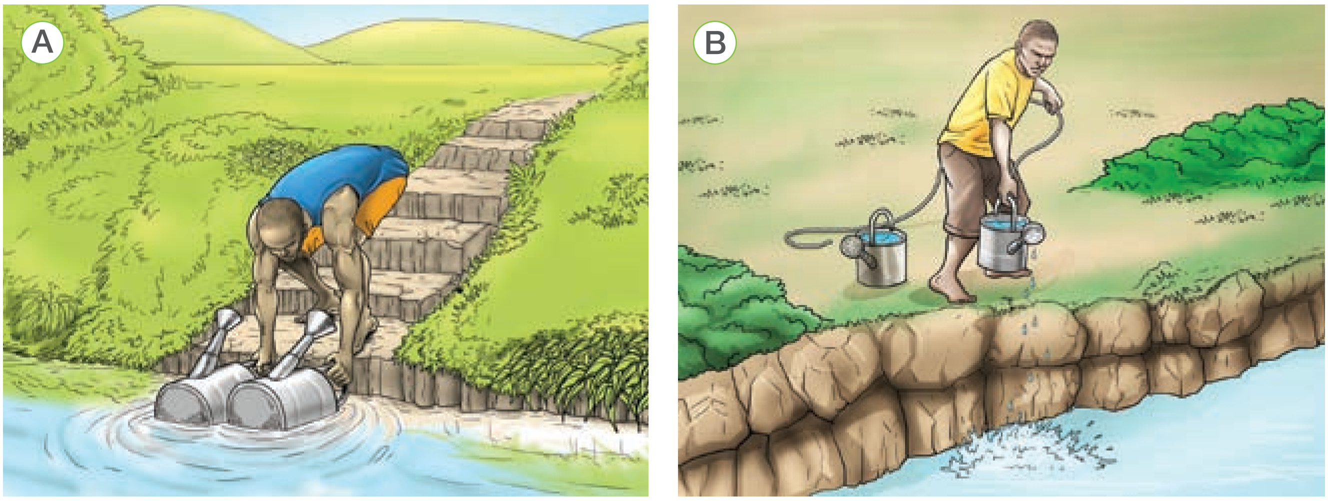
Keraita (2010) suggested additional measures that enhance sedimentation using, for example, natural flocculants such as *Moringa oleifera*[2] seed extracts, and measures that can influence pathogen die-off at farm-level, such as sunlight intensity, temperature, crop type, etc.

Frequent pond usage will undermine the accumulation of pathogenic microorganisms with the settled sediment. Where farmers step into the water, or the watering can hits the ground of a shallow pond (Figure 2), the settlement process is disturbed and helminth eggs are again floating at a shallow depth. This challenge concerns helminth eggs, in particular, but also, for example, fecal coliforms. Van Donsel and Geldreich (1971), for example, stated that 100-1,000 times more fecal coliforms were recovered from sediments than in the overlying water. To avoid this situation, different options can be applied as further illustrated by Keraita et al. (2010) and Amoah et al. (2011). These include the use of self-made stairs or a wooden log across the pond (Figure 4(a)) to prevent a farmer from stepping into the pond or touching the ground with their cans. Farmers started using watering cans connected to a rope (Figure 4(b)) to avoid bending over. The additional advantage of this is less skin contact with the water. Also, deeper pond design can prevent the watering can from touching the sediment layer when fetching water.

TABLE 3. PRODUCTION FACTORS AFFECTED BY ALSO USING ON-FARM STORAGE PONDS FOR WATER TREATMENT.

FACTORS	WATER STORAGE FUNCTION	WATER TREATMENT FUNCTION
Personal exposure	Common during fetching water, but seldom recognized as a threat	Can be minimized, as discussed in the text
Space requirements	Limiting factor as plot sizes in urban areas are usually very small	Significant constraints for recommended multi-pond systems
Labor requirements	So far, an accepted workload, but often given to laborers	Would increase due to modifications in pond depth and/or number
Capital requirements	Low	Remain low
Land tenure security	Poor; farmers occupy public or private land near streams and drains	Risk factor, as farmers will not invest in structures if the returns cannot be secured or they are not permitted to invest[3].

FIGURE 4. REDUCED WATER CONTACT AND IMPACT ON HELMINTH EGGS ALREADY SETTLED IN THE SEDIMENT. A) A FARMER STANDING ON SELF-MADE STAIRS WHILE FETCHING WATER, AND B) A FARMER USING A WATERING CAN CONNECTED TO A ROPE TO FETCH WATER (BOTH IN OUAGADOUGOU, BURKINA FASO).



Source: IWMI. *Source:* IWMI.

[2] A very fast-growing tree with multiple purposes and cultivated around the tropics. The pods (drumsticks) and leaves are among the most nutritious foods to be found in the plant kingdom (NRC 2006).

[3] In Ghana, landowners did not allow wastewater farmers to sink wells to access safer water, because structural investments could be used to claim land rights.

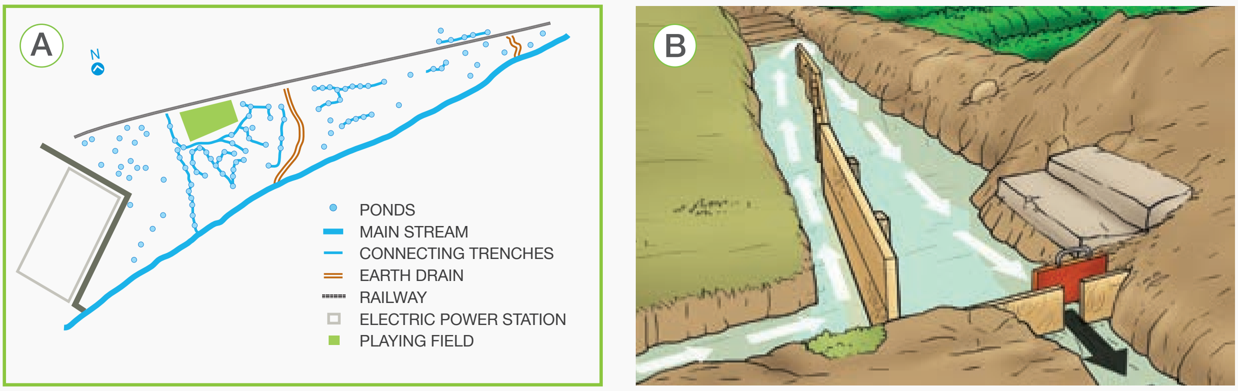
BOX 1. PARTICIPATORY ON-FARM RESEARCH TO IMPROVE POND NETWORKS IN ACCRA, GHANA.

Location: A large vegetable farming site in Accra, where water from polluted streams and drains are the common sources of irrigation water for about 100 farmers. Individual ponds and networks of interconnected ponds are common (Figure 5). Networks are managed by two to over 20 farmers depending on their size.

Technology description: The network of ponds used for fetching water allows the settling of helminth eggs and a reduction in fecal coliform counts, if water retention lasts long enough. A natural fecal coliform removal of about 2 log units from the wastewater source to the last pond of the network was used as the baseline. Design modifications were tested, which aimed at doubling the water volume, reducing rapid flow and extending overall water retention time in the systems from 1 to 2 days. Trenches were widened slightly and ponds were deepened. Some stairs were built to facilitate water fetching without the risk of touching the sediment. Simple hardwood baffles were placed in transit ponds (Figure 5) to increase the retention time of the water. Since helminths were not a problem on this site, the impact of the changes was difficult to quantify.

Required inputs: Mostly labor for construction (two man-days) and some wood used as construction materials, summing up to a maximum total of USD 50.

FIGURE 5. (A) AERIAL VIEW OF THE SITE, AND (B) HARDWOOD BAFFLES INSTALLED TO INCREASE RETENTION TIME OF THE WATER.



Source: IWMI, after Reymond et al. 2009.

Adoption and out-scaling potential: Important site-specific criteria required to maintain farmers' cooperation included available space, sufficient tenure security to allow infrastructure set-up and an adequate slope to allow flow by gravity for interconnected systems. Given the load of two 15-liter watering cans, 50 beds per farmer and 10 watering cycles per bed over the day, every reduction in transport and labor was welcomed by the farmers.

Source: Reymond et al. 2009.

Appropriate measures should consider de-silting ponds regularly to reduce the risk of re-contamination from sediment. A supporting measure would be to enhance water retention time (Box 1), and reduce water loss from the pond through infiltration.

Given the limited retention time of only one pond, a multiple pond system is recommended where space is available. For example, adapting the wastewater storage and treatment reservoirs (WSTR) technology, three batch-fed ponds can be used in sequence: on any one day, one pond is filled, one pond is resting (pathogen die-off/sedimentation) and one pond is used (Mara and Pearson 1992). This 'three-tank' system (Table 4) can enhance sedimentation and reduce re-suspension, thereby reducing pathogen levels in irrigation water (Mara et al. 1996).

The investment costs in all these cases are limited to labor (especially if a three-tank system is used) and the required behavior change of farmers during the fetching of water. Cost estimations of any required materials will be below USD 50 (Tiongco et al. 2010).

Settled microorganisms and particles can be stirred by farmers entering ponds, and even more by pumps when their suction pipe hits the sediment. Vegetable farmers across Africa are increasingly using small motorized pumps to lift water from streams, ponds and wells. Due to the large number of helminth eggs found in the sediment slight modifications on the design of suction pipes on motorized water pumps could minimize the intake of sediment (Keraita et al. 2010). An option might be U- or J-shaped suction pipe ends which reduce sediment intake (see Figure 6).

Sedimentation can be enhanced through flocculation. Table 5 shows fecal coliforms and helminth eggs settling with time after treatment with 3% weight/volume (w/v) of *Moringa oleifera* seed extract, in a field experiment conducted in Kumasi (Keraita 2010). The levels of fecal coliforms of untreated water had no significant change (8.13 to 8.04 log units) after settling for three hours. This showed that sedimentation within the period of three hours had no significant effect on the removal of fecal coliforms. However, the treated subsample showed significant changes over settling time. Levels of fecal coliforms reduced by about 4.5 log units over the three hours. The reduction showed a linear relationship, $y=-0.78x+9.06$ (where y = log units of fecal coliforms and x = time in hours). More reduction levels could have been achieved with the provision of additional time, as reduction had not reached its optimum after three hours. This shows that there is a strong influence of *Moringa oleifera* treatment on the reduction of fecal coliforms in wastewater, through its ability to flocculate and eventually settle particles to which bacteria are attached (as also shown by Ghebremichael 2004).

On the other hand, natural sedimentation for three hours reduced helminth eggs by about 24% from 14 to 10.6 eggs per liter. When treated with *Moringa oleifera,* the number of helminth eggs in irrigation water reduced exponentially, $y = 22.8e^{-0.5x}$ (where y = number of helminth eggs and x = time in hours), to less than 1 egg per liter. Optimum reduction was achieved after 2.0-2.5 hours of sedimentation, after which no significant further reduction of helminth eggs was recorded. The results show that while natural sedimentation has some influence on the removal of helminth eggs, a much faster and more significant reduction could be achieved by treating irrigation water with *Moringa oleifera* seed extracts. Depending on the level of water pollution, much lower seed extract concentrations could be tested as well as differently granulated seeds.

Moringa oleifera seed extracts have shown high coagulation and antimicrobial activities, when compared to alum (Benjamin and Odeyemi 2011). In addition, *Moringa oleifera* extract has the ability to directly act upon microorganisms and inhibit their growth (Sutherland et al. 1990; Cáceres et al. 1991). Although *Moringa oleifera* is very common, especially across Asia and Africa, it might not be as abundant as needed in the city and vicinity where water pollution is high. Carrying out tests with other, locally available plants with similar characteristics, such as okra, are encouraged (Agarwal et al. 2001; Srinivasan and Mishra 2008).

Use of Weirs and Reservoirs

Though not designed for pathogen removal, some irrigation infrastructure, such as weirs (Figure 7) and larger storage tanks (reservoirs) in irrigation schemes, can significantly improve the microbiological quality of domestically polluted water. In the case of the Musi River, which passes through the city of Hyderabad in India, the natural remediation efficiency of the river system, aided by the construction of irrigation infrastructure, particularly weirs, was very high.

TABLE 4. OPTIONS FOR PATHOGEN REMOVAL IN FARM-BASED PONDS.

	ON-FARM TREATMENT POND	THREE-TANK SYSTEM	MULTIPLE IN-STREAM OR OFF-STREAM PONDS
Main processes	Sedimentation and ultraviolet (UV) exposure.	Sedimentation and UV exposure. One pond is being filled, the water in one is settling and the settled water from the third is being used for irrigation. Pond size should exceed daily water needs.	Sedimentation and UV exposure. Cascades of in-stream ponds or networks of on-farm water storage ponds increase the sedimentation potential suitable for trapping helminth eggs.
Pathogen removal	Where ponds are used every day, the sedimentation process is disturbed and the helmith egg reduction will be limited, especially when pond volume is small.	One to two days of quiescent settling removes almost all helminth eggs and a reduction of 1 to 2 log units of other pathogens can be achieved. The longer the water can 'rest' the better.	With more than one barrier, sedimentation of helminth eggs can be significant. Fecal coliform reductions of 2 log units were found in Accra. If in-stream sandbags are perforated and closely packed, they can also function as sand filters.
Challenges for risk reduction	▪ Re-suspension of settled pathogens when farmers step in or stir water (need training). ▪ Runoff of manure or contaminated water into ponds is common.	▪ Labor to dig more ponds than usually used. ▪ See comments under 'on-farm sedimentation ponds' in the second column of this Table. ▪ Malaria control (Box 2).	▪ Two or more barrier (pond) systems are preferred. ▪ Schistosomiasis control ▪ Labor requirement; see comments under 'on-farm sedimentation ponds' in the second column of this Table.
References	Keraita et al. 2008a, 2010; Reymond et al. 2009.	Mara and Pearson 1992; Mara et al. 1996.	IWMI 2008a, 2008b.

TABLE 5. REMOVAL OF FECAL COLIFORMS AND HELMINTH EGGS (N=60 SAMPLES) USING A MORINGA SEED EXTRACT.

SETTLING TIME (HOURS)	FECAL COLIFORMS (LOG OF MPN 100 ML^{-1})	HELMINTH EGGS (NUMBER OF EGGS LITER^{-1})
0†	8.13 ± 0.44	14.0 ± 1.1
0.5	7.59 ± 0.91	9.3 ±1.3
1.0	6.79 ± 0.58	5.9 ± 1.7
1.5	5.92 ± 0.42	2.7 ± 1.0
2.0	5.18 ± 0.40	1.4 ± 0.5
2.5	4.14 ± 0.48	1.0 ± 0.4
3.0	3.62 ± 0.27	0.8 ± 0.2
3.0†	8.04 ± 0.52	10.6 ± 0.9

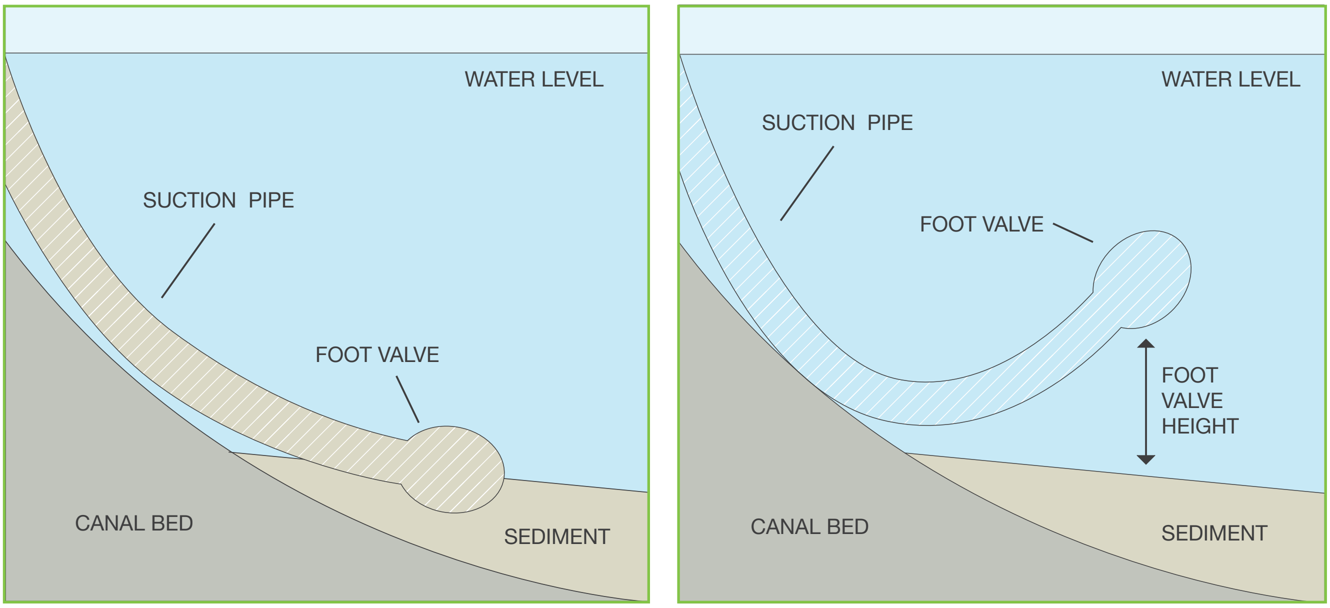
Source: Keraita 2010.

Note: † Not treated with *Moringa oleifera* extract; MPN – most probable number.

BOX 2. PONDS AS POSSIBLE BREEDING SITES FOR MOSQUITO VECTORS.

Many pond-based systems can be potential habitats for snails or mosquito vectors of diseases such as malaria, filaria and different types of encephalitis. Contrary to conventional thinking that *Anopheles gambiae* or *Anopheles stephensi* only breed in rather clean water, there are increasing indications, for example, from Pakistan, Tanzania, Nigeria and Ghana, that these malaria vectors also breed in polluted water sources (Mukhtar et al. 2003; Sattler et al. 2005). The actual occurrence, however, can vary between seasons, from region to region and on the type of wastewater (raw or diluted); therefore, program managers or extension officers should put in place vector surveillance plans with the support of the health authorities. In hyper-endemic situations, as in many parts of sub-Saharan Africa, (wastewater) ponds might not increase the general risk. However, in meso-endemic areas, as in Asia, control measures will be important. These can be natural predators, such as tadpoles, which are often present even in smaller ponds. Small ponds could also be covered with netting while larger systems may need other methods of biological control, e.g., larvivorous fish such as Tilapia (Homski et al. 1994). Precautions for schistosomiasis include, for example, attaching a filter to the pumps used for filling the ponds.

FIGURE 6. LIFTING INFLOW VALVES OF PUMPS OUT OF THE SEDIMENT (DIAGRAM ON THE RIGHT).



Source: Keraita et al. 2010

Corresponding with an estimated retention time of 2 days, a helminth egg reduction level of 80% was measured behind the first weir downstream of Hyderabad, and another 80% after the second weir. As in treatment ponds, sedimentation is also an important process here, resulting in large numbers of helminth eggs deposited just upstream of the weirs (Hofstedt 2005). Changes in fecal coliform and biochemical oxygen demand (BOD) levels were more gradual, but were comparable over the stretch of about 30-40 km with the treatment efficiency of a well-designed waste stabilization pond system (Table 6). Besides sedimentation, other natural treatment processes, including the diversion of river water over larger areas of paddy, contributed to pathogen reduction in this case (Ensink et al. 2010).

FILTRATION SYSTEMS

Similar to pond systems, filtering polluted water is also a low-cost option taking advantage of natural processes for pathogen elimination. Compared to pond systems it has the additional advantage of working even at the smallest scale, such as for household water filtration. In this section, selected systems for filtering water for direct use on the farm are explained. Options for soil filter systems for wastewater treatment without reuse, are, for example, described by Wyss and Züst (2000).

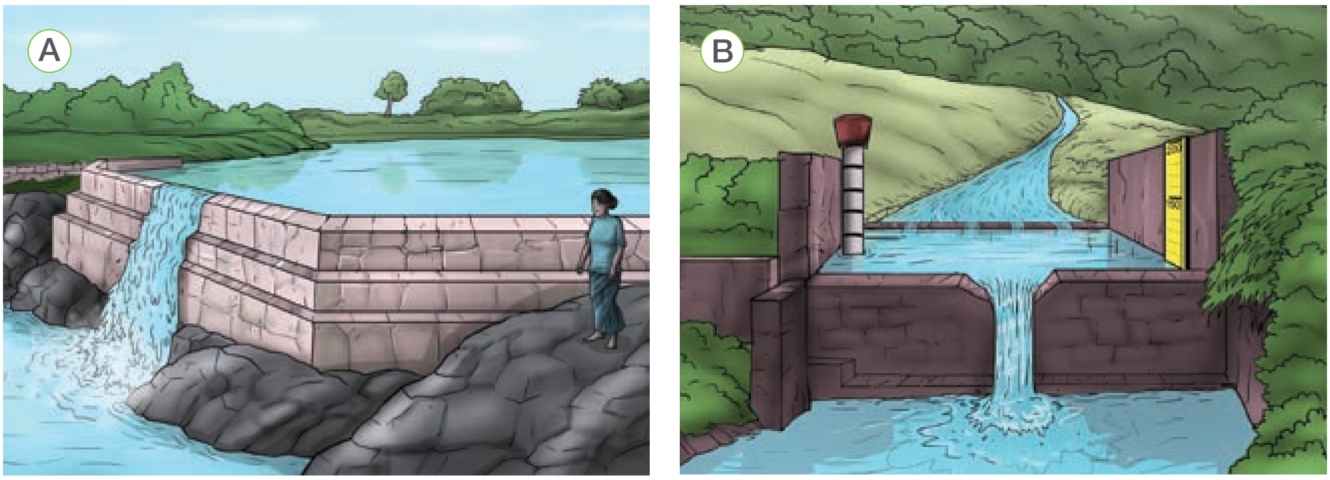
Pathogen Removal Mechanisms in Sand or Granular Filters

Pathogen removal in filtration systems undergoes two stages, i.e., retention in the media and then elimination. During retention, pathogens are immobilized in the filter by straining and adsorption.

Retention by Straining

Straining involves the physical blocking of movement through pores smaller than the pathogens. Figure 8 shows the kind of filter required, including different soil textures, to strain different kinds of pathogens (USEPA 2001). Straining can be improved by enhancing coagulation and flocculation, which can be done at a low cost in West Africa by using extracts from plant materials such as the seeds of *Moringa Oleifera* (see above).

FIGURE 7. RESERVOIR AND WEIR SYSTEMS IN (A) HYDERABAD, INDIA; AND (B) NORTHERN LAOS.



Source: (a) IWMI, and (b) IWMI, after photo from Institut de recherche pour le développement (IRD).

TABLE 6. USE OF IRRIGATION INFRASTRUCTURE FOR PATHOGEN REDUCTION.

	WEIRS AND TANKS
Description	Water reservoirs and weirs in irrigation canals can facilitate pathogen removal. ▪ In irrigation schemes in Hyderabad, India, weirs, which are used for regulating irrigation water, act as efficient traps for helminth eggs. ▪ The same principle can apply to dams constructed by smallholders (see Table 2).
Pathogen removal	The study along the Musi River showed that over a 30 km stretch of the river: ▪ helminth eggs had reduced from a range between 130 and 170 to less than one egg; and ▪ *E. coli* levels showed a reduction by 3 log units from 7.8 to 4.7 log units per 100 ml over 30 km, and by 4 log units over 40 km.
Challenges	The positive impact of natural processes for pathogen elimination and options to enhance them via standard irrigation infrastructure should be considered before investing in conventional wastewater treatment. The design and maintenance of irrigation infrastructure could benefit from consideration of its possible positive impact on pathogen levels (e.g., via sedimentation and sediment management).
References	Ensink et al. 2010; Hofstedt 2005.

Retention by Adsorption

Figure 8 shows that the pores of a sand filter are not fine enough to strain pathogens that are smaller than helminth eggs. However, the second dominant mechanism for retention is adsorption, where pathogens attach themselves to media. In this way, sand filters can also remove bacteria. Factors that may influence the adsorption of bacterial cells to porous media can be categorized into three groups: physical, chemical and microbiological. Physical factors include the porous media, presence of organic matter and biofilm, temperature and water flow velocity. Chemical factors include ionic strength and species, and pH values. Microbiological factors include hydrophobicity, chemotaxis and electrostatic charges on the cell surface, other cell surface characteristics and bacterial concentration (Stevik et al. 2004).

Elimination

After being retained in the sand media, pathogens need to be eliminated. In biological wastewater treatment systems, elimination of pathogens is controlled by many variables. These variables may be divided into abiotic and biotic factors.

- Abiotic factors: These include moisture content, pH, temperature and organic matter content. Pathogen survives better in moist environments, where pH ranges between 5 and 8 and organic matter content is high for nutrients, while high temperatures will accelerate pathogen die-off.
- Biotic factors: Presence of predating microorganisms, such as protozoans, will affect pathogen populations such as bacteria.

Having extremes in pH levels in sand (less than 5 and more than 8) and using sand with low organic matter (and hence nutrient) content, will enhance elimination. Moreover, elimination will be better in warm climates due to high temperatures. Dark colored sand filtration columns or barrels can be used to absorb heat, and thereby increase temperatures in the filtration media (Stevik et al. 2004).

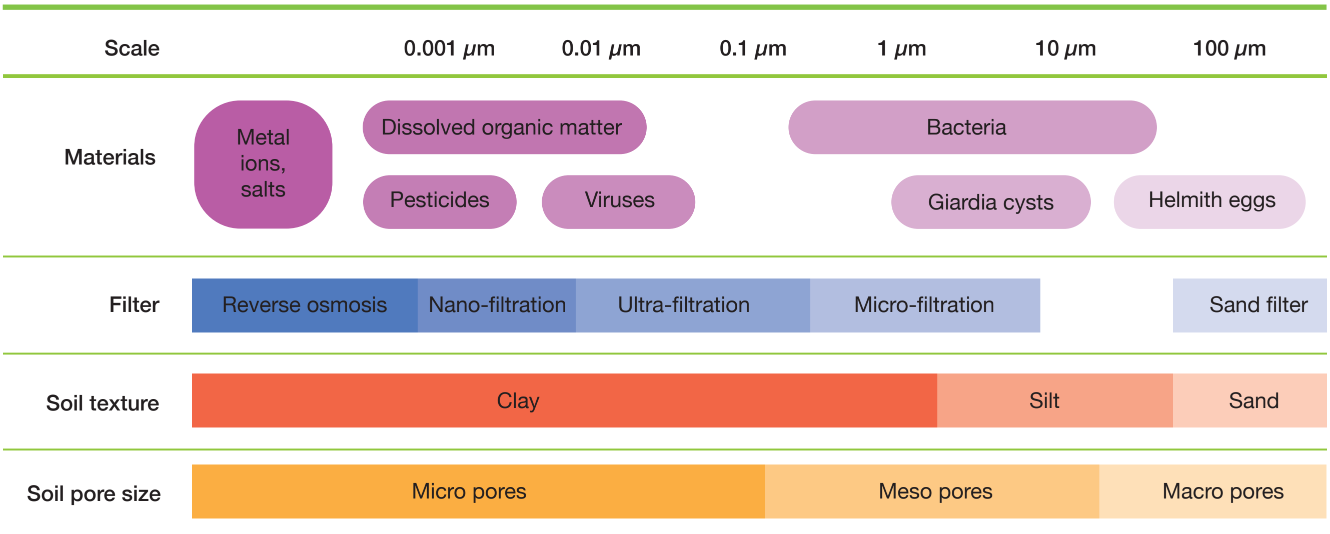
Suitable Filtration Systems for On-farm Water Treatment

Table 7 presents some common filtration systems that can be used for treatment of irrigation water at farm-level, using media such as sand, gravel or soil. For conventional water and wastewater treatment, slow and rapid sand rate filters are widely recognized (Metcalf and Eddy, Inc 1995; Morel and Diener 2006). Some of these filters can be adapted for use in treating water at farm level (Table 8).

Organic Filters

Organic filter materials can have a high potential for treating diluted wastewater or greywater to achieve irrigation quality in low-tech systems (Garzón-Zúñiga et al. 2008). Bark, peat and wood chip filters can remove organic matter better than sand and trickling filters under similar conditions, and can be expected to be resilient in dealing with variable low and high organic loads. Degradation of filter material was reported when using some mulch materials, such as bark (Dalahmeh et al. 2011). While the organic matter content and surface and hydraulic properties of bark filters resulted in high BOD5 removal rates (94-99%), the process was accompanied by the release of dissolved organic substances originating from the bark itself (Dalahmeh 2013). Garzón-Zúñiga et al. (2008), Garzón-Zúñiga and Buelna (2011), and Vigueras-Cortés et al. (2013) reported a high ability of bio-filters using, for example, wood chips and local fibers (such as agave fiber) to remove pathogens, reaching 3-4 logs of fecal coliforms and 96-100% of helminth eggs from municipal wastewater. Bark filters demonstrated 1-3 log10 removal of microorganisms (Dalahmeh 2013).

FIGURE 8. FILTER CLASSIFICATION AND MATERIAL SCALE.



Source: Modified from UNEP 2005.

The charcoal had a large specific surface area, which provided the capacity for intermediate to high levels of removal of BOD5 (83-97%), N-tot (50-98%) and P-tot (64-98%), but removal of microorganisms was poor. The sand filters demonstrated low BOD5 removal (67-91%) and high nitrification, but low nitrogen removal. Greywater treatment using bark and charcoal filters reduced their organic content to acceptable levels for irrigation.

Slow Sand Filters

Slow sand filters have a long history and are well described, especially for drinking water filtration (Huisman and Wood 1974). Sand filters with low loading rates of 2 to 5 l/min/m^2 are also a possible option for on-farm risk reduction. However, not every type and size of sand is suitable. Rounded (beach) sand grains of uniform size, when packed together, do not produce pore spaces small enough to be effective as sand filter media. Crushed rock sand grains, when packed together, could fit like puzzle pieces. Their varied sizes and jagged edges produce tiny pores small enough to filter out pathogens found in water. Gravel pits or quarries are the best place to obtain crushed rock. Sand should be of correct configuration to support straining but lessen clogging (Table 9).

As the influent passes through the sand in the filter, most of the solid particles are removed within the top 0.5-2 cm of sand. With time, this area develops a biological film called the *'schmutzdecke'* (dirt blanket). This blanket supports a substantial reduction in the number of pathogens (Huisman and Wood 1974). The *schmutzdecke*, which consists of algae, bacteria and zooplankton, has to remain wet. Therefore, the filter outlet level has to be above the level of the sand. This always ensures that the filter bed does not dry out. On the other hand, it should not become anaerobic. Typical pathogen removal range, reported by WHO and based on a review of several studies for slow sand filters, is 0-3 log units for bacteria and 1-3 log units for helminths (WHO 2006a). Combinations of flocculation with *Moringa oleifera* and sand filters to increase straining have been described by Benjamin and Odeyemi (2011).

Farmers in Ghana were mostly concerned that any technology change might negatively affect the efficiency of their work. In this regard, filters have the natural disadvantage of slowing down water flow. From the experimental filters tested in Kumasi (Box 3), an average of 3 m/day of filtrate could be obtained from each 0.17-m diameter filter, resulting in 0.068 m^3/day. Assuming that the filter works for 300 days in a year (65 days for maintenance), it could provide approximately 20 m^3 of water in a year. Irrigation water requirements in Kumasi for similar farming practices were calculated to be 362 m^3/yr for a 0.1 ha plot (Keraita 2002). As the plot sizes on urban vegetable farms range between 0.02 and 0.1 ha

TABLE 7. TYPES AND CHARACTERISTICS OF FILTERS USED IN HOUSEHOLD WATER TREATMENT.

TYPE OF FILTRATION	MEDIA	AVAILABILITY	EASE OF USE	EFFECTIVENESS (COMMENTS)	COST
Rapid rate granular media depth filter	Sand, gravel, diatomaceous earth, coal, other minerals	High	Easy to moderate	Moderate* (depends on microbe size and pre-treatment)	Low to moderate
Slow sand filter	Sand	High	Easy to moderate (community use)	High**, in principle, but often low, in practice	Low to moderate
Vegetable and animal-derived depth filters	Coal, sponge, charcoal, cotton, etc.	Medium to high	Moderate to difficult	Moderate*	Low to moderate
Fabric, paper, membrane, canvas, etc., filter	Cloth, other woven fabric, synthetic polymers, wick siphons	Varies: Low to high	Easy to moderate	Varies from high to low (with pore size and composition)	Varies: Low for natural media; high for synthetics
Ceramic and other porous cast filters	Clay, other minerals	Varies: High to low	Moderate	Varies from high to low (with pore size and ceramic filter quality)	Moderate to high
Septum and body feed filters	Diatomaceous earth, other fine media	Varies	Moderate to difficult; dry media is a respiratory hazard	Moderate	Varies

Source: Adapted from Sobsey 2002.

Notes: * 'Moderate' typically means 90-99% reduction of larger pathogens (helminth ova and larger protozoans) and solids-associated pathogens, but low (< 90%) reduction of viruses and free bacteria, assuming no pre-treatment has taken place. With pre-treatment (typically coagulation), pathogen reductions are typically > 99% (high). ** High pathogen reduction means > 99%.

TABLE 8. OVERVIEW OF ON-FARM FILTRATION SYSTEMS.

	SLOW SAND FILTERS	GRAVEL AND SAND FILTERS	ORGANIC FILTERS	RIVER BANK FILTRATION	STRAINERS
Description	Used, for example, in water containers feeding *drip irrigation systems,* where unfiltered wastewater tends to clog the drip outlets. Sand should be of correct configuration, i.e., effective size of 0.15-0.40 mm and uniformity coefficient of 1.5-3.6.	Used in confined soil trenches, e.g., to treat greywater from small streams or households before irrigating crops and flowers.	Wood chips, bark, peat, wheat straw and, for example, corncob are used as 'mulch filters' for treating wastewater and greywater. A down-flow-mode vertical filter is a common setup.	Wells are dug 1 to 5 meters away from wastewater streams or canals, with the aim of collecting shallow groundwater as observed in Burkina Faso, Mali and Ghana. Canal water passes through the soil to the well following a hydraulic gradient and is filtered in the process.	In Togo, Ghana and Senegal, farmers use various materials such as mosquito netting to prevent particles, such as algae, waste and organic debris, from entering the watering cans while fetching water. Filtration materials are also attached to pumps.
Pathogen removal	0-3 log units for bacteria and 1-3 log units for helminth eggs (WHO 2006a). In Ghana, 0.5-1 m deep column sand filters removed about 2 log units of bacteria and 71-96% of helminth eggs.	Gravel under anaerobic conditions facilitates biological treatment with retention times of 2-3 days. Pathogens and total suspended solids (TSS) were reduced to 50%.	Depending on material used, 1-4 logs for coliforms (e.g., by predatory activity of amoebas) and > 96% for helminth eggs.	Pathogen removal depends on soil properties (texture) and subsurface flow distance. Most effective for larger pathogens, such as protozoans and helminths, but less effective for removal of bacteria and viruses.	Positive side-effect is that pathogens adsorbed on to the sieved organic matter are removed. Depending on the kind of matter and pathogen load, removal levels of up to 1 log unit for bacteria and 12-62% for helminths were observed with normal nylon cloth.
Challenges	Clogging of the filtration medium (sand) makes frequent cleaning or replacement necessary.	Depending on location, cleaning to prevent odors and clogging of the gravel media that occurs with time.	Degradation and disintegration of the filter can lead to decreasing service lifetime of the filter.	Cracks in soil structure or termite tunnels can allow pathogens to pass through without being filtered.	The finer the cloth the better the egg removal, but the water flow is slower, affecting farmers' work efficiency. Continuous removal of filtered residues.
References	Keraita et al. 2008c; Metcalf and Eddy, Inc 1995; WHO 2006a	Bino et al. 2008; WQSD 2009	Dalahmeh et al. 2011; Dalahmeh 2013; Garzón-Zúñiga et al. 2008	Cornish and Lawrence 2001	Keraita et al. 2008c, 2010.

TABLE 9. TYPICAL DESIGN CRITERIA FOR SAND AND GRAVEL FILTERS.

DESIGN CRITERION	SLOW SAND FILTERS	RAPID SAND FILTERS
Filtration rate	2.5-6.0 m/day	100-300 m/day
Sand media		
Depth	0.5-1.5 m	Same
Effective size	0.15-0.4 mm	1.3-1.7 mm
Uniformity coefficient	1.5-3.6	1.2-1.7
Gravel media		
Depth	0.2-1 m	Same
Graded	Fine to coarse (top to bottom)	Same

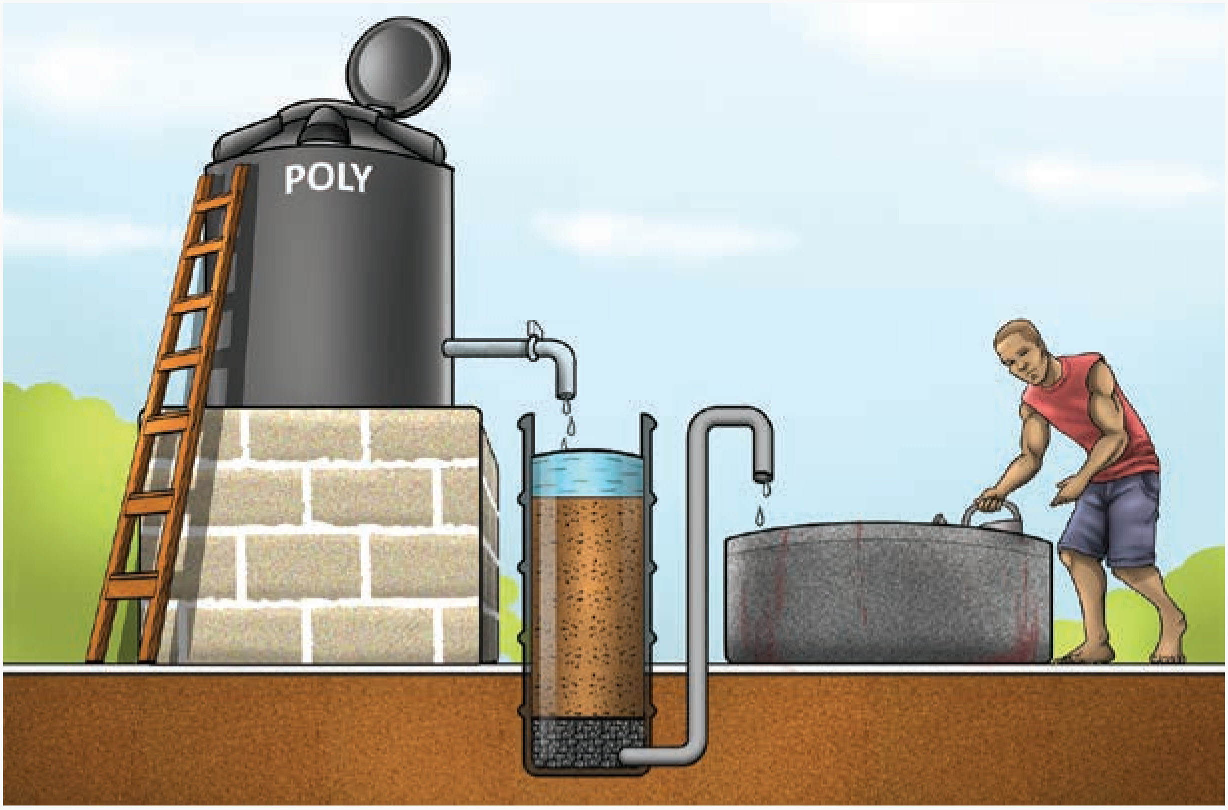
Sources: Letterman 1991; Cleasby and Logsdon 1999; UNEP 1997.

BOX 3. TESTING SAND FILTERS FOR PATHOGEN REMOVAL.

In Kumasi, Ghana, IWMI tested slow sand filters on farms to improve water quality for farmers using irrigation water with high levels of fecal contamination (Keraita et al. 2008c). They were monitored for 5 weeks and assessed for the removal of helminths and fecal coliform bacteria. Common sand used for house construction was washed and used as filtration media.

Flow rates averaged 3 m/day, though there was a steady decrease with filtration time, decreasing to 1 m/day from the 4th week. The filter with the shortest sand column of 0.5 m clogged in the 2^{nd} week while the operational filters (0.75 - 1.0 m sand depth) removed up to 3.5 log units of fecal coliforms. Sand depths had no influence on the removal, but the higher the pathogen levels in the irrigation water, the higher the rate of removal. For helminth eggs, from the 2^{nd} week, weekly removal averages of more than 80% were recorded for filters that did not clog over the 5 weeks (Keraita et al. 2008c). Proper selection of sand and better washing is likely to reduce clogging rates. Figure 9 shows a possible set-up on farm which could also be combined with drip kits.

FIGURE 9. POSSIBLE ON-FARM SET-UP FOR SLOW SAND FILTERS.



Source: IWMI.

per farmer, a filtration system of 0.15 to 0.75 m in diameter with some simple storage tank can suffice. This system will cost about USD 50-100. Assuming a system life span of 5 years, and based on the calculated net revenue of between USD 400-800 annually (Danso et al. 2002), the system cost will be less than 5% of the total revenue. For larger irrigation water volumes, the filter size could be increased.

River Bank Filtration

A common system across West Africa is wells that are dug 20-60 m away from a canal, stream or river carrying highly polluted water (Figure 10). The resulting soil-based (river bank) filtration (Singh et al. 2010; Dash et al. 2010) is, however, only a side effect for farmers who are more interested in reducing the walking distance, time and labor needed for water collection. Wastewater from the stream infiltrates the surrounding soil, and gets filtered on its way towards the well. Depending on distance and soil texture (sand, silt, clay), pathogen removal for viruses and bacteria differs strongly but should be at least 1-2 log units. The system is probably most effective in removing helminths and reducing turbidity in irrigation water. The distance between the well and the wastewater canal varies; the further the distance, less water might reach the well, although there will be an improvement in water quality. These wells can be very simple and have typical diameters ranging from 0.5 m to about 1.5 m. Their depth will have to consider the water table of the stream.

A number of water-lifting devices are used in such wells. In relatively high water tables, farmers manually draw irrigation water with a bucket and rope system (Figure 11). This is a very simple, cheap and traditional method. An improvement to this is the use of the treadle pump system, which involves manual peddling and water can be lifted from a depth of up to 7 m. Farmers with large farms and more stable incomes use diesel pumps. These pumps have a built-in filtration system for removing coarse materials. Water can be stored in simple structures before being used, used straight after lifting or concurrently if a pump is available.

Several other systems supporting water filtration have been developed by farmers in West Africa. For example, wastewater is allowed to pass through sand-filter trenches, sand embankments, or simple sandbags as farmers channel irrigation water to storage ponds. These types of filters will mostly remove larger organisms such as protozoans and helminths and could be an entry point for participatory technology development (Box 4).

FIGURE 11. SIMPLE WELL STABILIZED WITH RUBBER TIRES CLOSE TO A POLLUTED STREAM. WATER IS FETCHED WITH A BUCKET AND ROPE.

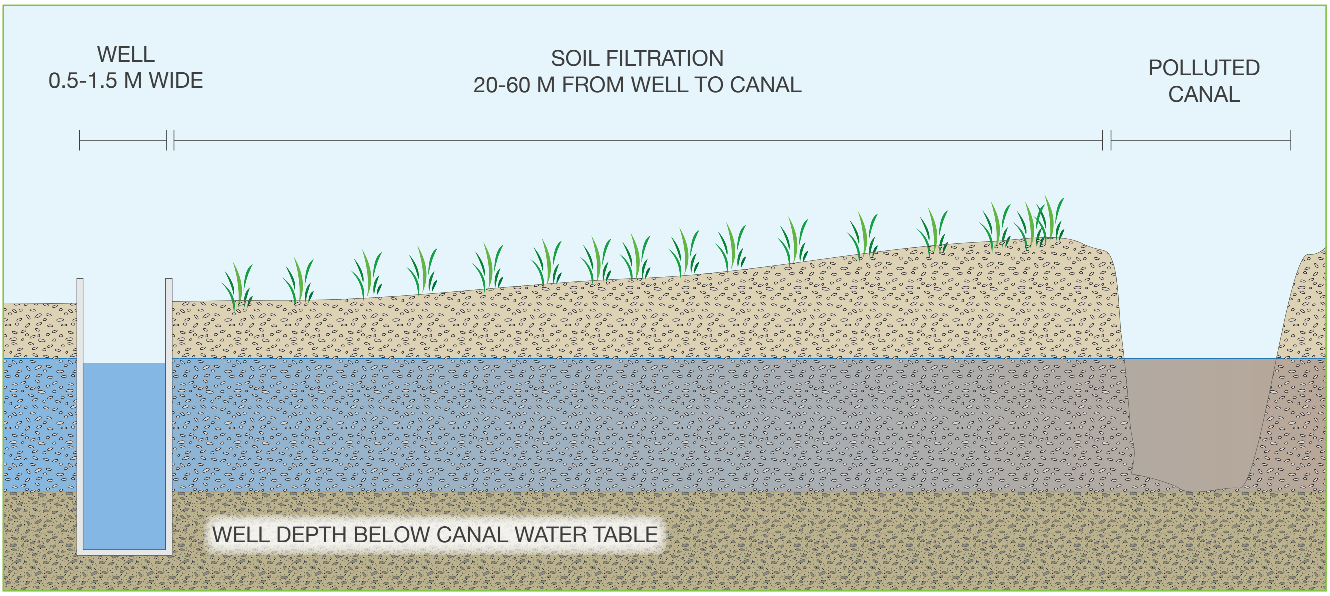
Source: IWMI.

Trench Filter Beds and Constructed Wetlands

More sophisticated, but still low-cost, filtration systems include the confined trench filter as tested, for example, across Jordan. This system has been tested successfully over several years to treat greywater to the standards needed for restricted irrigation of tree crops, such as olives, fruit trees or horticultural crops. The tested treatment media included gravel and intermittent sand filter (Bino et al. 2008), as well as volcanic tuff (Boufaroua et al. 2013). Some examples of the filtration systems tested across Jordan are given below:

- Downstream of the Jerash camp, greywater from a nearby stream is diverted through a tube to the trench. As shown in Figure 12, the water enters the trench in the back section, where the transparent plastic sheet is perforated to allow for water infiltration. From there the water moves slowly by gravity through gravel layers towards the container in front. The confined trench is lined with a dark impermeable plastic sheeting about 400 microns thick and is filled with gravel (WQSD 2009).
- In a similar confined trench system in Karak, about 3 m^3

FIGURE 10. SCHEMATIC DIAGRAM OF A WASTEWATER INFILTRATION WELL SYSTEM AS SEEN IN BURKINA FASO.

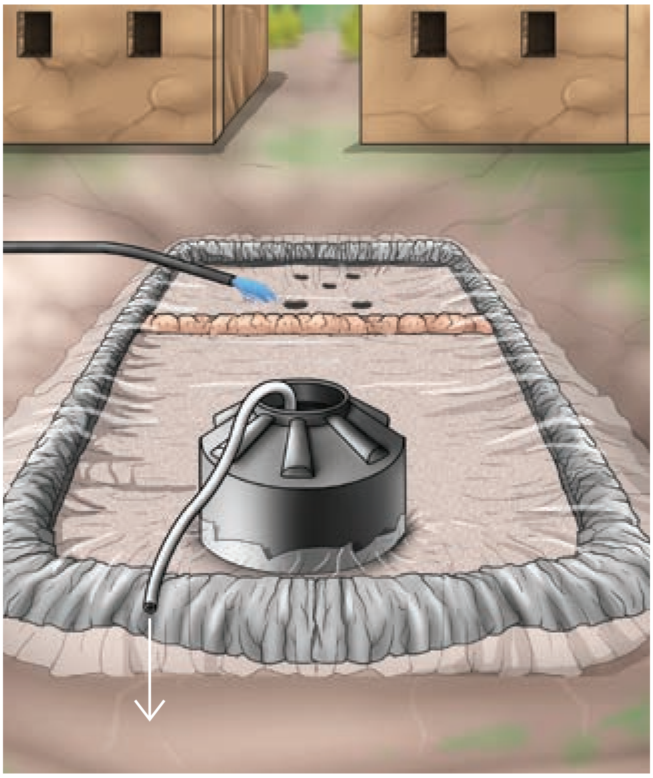


Source: M. Dougherty.

are filled with gravel as the filtration medium (Figure 13). The designed retention time is 2-3 days, after which the filtered water enters the outlet barrel through a perforated lower part. From here, the water is pumped into a larger tank supporting an olive irrigation system. One such unit can treat up to 240-300 liters a day, which is sufficient to irrigate about 20 olive trees throughout the year. Fecal coliform counts remained within allowable limits for restricted irrigation (Bino et al. 2008).

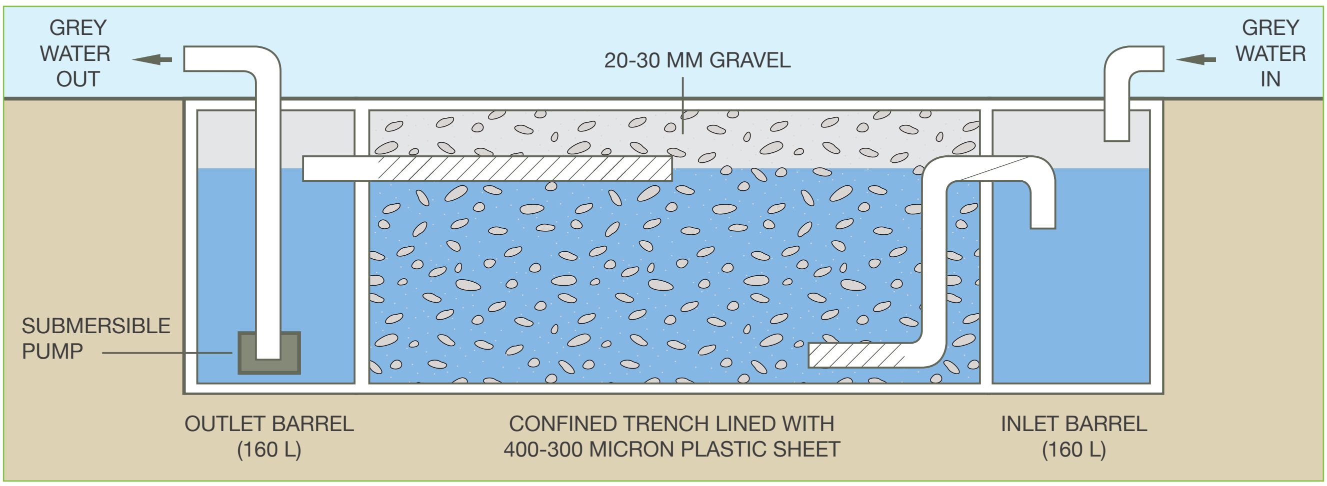
- A related system to treat an average flow of 150 liters/day of greywater effluent from a single household in the Badia area, combined a 1 m^3 septic tank and an intermittent sand filter (6 m^2, about 1 m deep). The treatment efficiency of BOD5, COD, TSS and E. coli were around 90% (Assayed et al. 2010). The quality of treated greywater complied with the Jordanian standards for reclaimed wastewater reuse for restricted irrigation. A smaller treatment bed of 4 x 1 m was used in the Madaba area by Boufaroua et al. (2013), who added a grease filter in front of the inlet barrel.
- Where space is limited, a sand filter-based filtration unit could also be set up vertically (Figure 14) as tested by the International Center for Agricultural Research in the Dry Areas (ICARDA) and the National Center for Agricultural Research and Extension (NCARE) in Jordan, as part of their project on "Community-based interventions for productive use of grey water in home farming." The vertical systems facilitate oxygen distribution, overcome the saturation problem (which occurs in traditional sand filters) and, most of all, reduce the space requirements of the treatment system, which make it suitable for rooftop farming. Significant reduction of BOD5 and TSS were noticed between the first drawer and the second drawer only, while 2 log units of fecal coliforms were removed across all 4 drawers (Assayed 2012). Research to optimize the system continues. In Karak, the cost of one unit was estimated at USD 120 for site preparation, gravel, plastic sheets and PVC pipes. The additional installation of an electric pump, electric wiring and drip irrigation would result in a total cost of about USD 300. The average annual operation and maintenance costs were estimated to be USD 39. The cost-benefit analysis showed a favorable ratio of 2.6-2.7, which was calculated for different interest rates over 5 and 10 years (Bino et al. 2008). A similar positive assessment was reported from trials in the Badia area, considering savings on freshwater and emptying of septic tanks (Al-Balawenah et al. 2011).
- A further low-cost sophistication is the addition of plants for wastewater treatment, in gravel beds or more common pond systems, serving smaller house communities. Given the large amount of literature

FIGURE 12. GRAVEL FILTER TRENCH.



Source: IWMI.

FIGURE 13. CONFINED TRENCH TREATMENT UNIT.



Source: Bino et al. 2008.

BOX 4. BUILDING ON FARMERS' PRACTICES AND INNOVATIONS.

Ponds to store water, wells supporting river bank filtration and filters attached to pumps are examples of on-farm practices, which could be starting points for participatory on-farm research on risk reduction. Another example is the use of clay pots, which have been tested in Northern Ghana, to increase both water-use efficiency and filter low-quality water (Abubakari et al. 2011). There are many more possibilities which could be food for thought for participatory technology development. In Togo, Ghana and Senegal, for example, farmers use different forms of sieves, such as mosquito nets, fitted on to the intake hole of the watering can to prevent the entry of particles such as algae, waste and organic debris. By doing so, some pathogens adsorbed to organic matter are removed. Studies on this kind of simple filter system showed a modest 1 log unit removal for bacteria and 12-62% for helminths, when a normal nylon cloth material was used (Keraita et al. 2008c). As farmers are already using these types of coarse filter systems to eliminate visible obstacles, an opportunity exists for adaptive field studies (see Keraita et al. 2008b) to determine the mesh size representing the best balance between easy water fetching/flow and maximal filtration.

Source: Keraita et al. 2010.

available on constructed wetlands, we like to refer to (a) Hoffmann et al. (2011) for the recent technology review of constructed wetlands; (b) Rose (1999) for wetland applications in urban farming; and (c) Ludwig (2009) for small-scale and household-based greywater treatment, including constructed wetlands. In West Africa, the use of pond systems with duckweed or water lettuce has been reported, for example, from Senegal, Burkina Faso, Ghana and Niger (Rose 1999; Awuah et al. 2004; Koné et al. 2002; Quayle 2012). In Kumasi, constructed wetlands as well as macrophyte-based treatment systems have been studied, for example, by Awuah et al. (2004) and Niyonzima (2007). Awuah et al. (2004) reported achieving a fecal coliform removal of 6, 4 and 3 log units for algae ponds, duckweed ponds and water lettuce, respectively. Algae ponds performed better as they offered more exposure to sunlight. Sedimentation accounted for over 99% of fecal coliform removal. A horizontal subsurface flow constructed wetland with Typha latifolia and a retention time of 15 hours achieved a 72% to 79% removal of BOD, COD, suspended solids (SS), grease and fecal coliforms, while nitrogen and phosphate removal was in the range of 34% to 53% (Niyonzima 2007).

FIGURE 14. VERTICAL DRAWER COMPACTED SAND FILTER USED FOR GREYWATER TREATMENT AS TESTED BY ICARDA AND NCARE IN JORDAN.

Source: IWMI, after photo by ICARDA/NCARE.

FARM-BASED FECAL SLUDGE TREATMENT

The application of excreta-based fertilizers has attracted much attention as a concept of ecological sanitation and due to increasing fertilizer prices. Besides its nutrient content, fecal sludge (FS) is also rich in organic matter, which can contribute positively to soil structure and water-holding capacity. Hence, FS represents an important resource for enhancing soil productivity, in general. While in the case of ecosan (ecological sanitation) and dry toilets the excreta undergo in-situ treatment (Winblad and Simpson-Hébert 2004), we will address the use of raw fecal sludge (septage) from septic tanks, which is delivered regionally by cesspit service providers to farmers (Cofie et al. 2005; Verhagen et al. 2012)[4].

In the case of Northern and Eastern Ghana, raw fecal sludge collected by vacuum trucks from on-site sanitation systems is in high demand by farmers growing maize and sorghum on poor savannah soils. Most farmers have been using fecal sludge for several years, with some using it for more than 25 years with positive effects on soil chemical and physical properties. The period of FS delivery is within the dry season

[4] The treatment options described only apply to fecal sludge derived from septic tanks (septage) and not to biosolids or sewage sludge generated by wastewater treatment plants, as the latter have an increased risk of chemical contamination (compared to septage) (Koné et al. 2010) which is not addressed in the treatment options presented in this report.

(November to April). After delivery, farmers generally employ two methods of sludge treatment, namely the 'random spot' and the 'pit' methods (Cofie et al. 2005). In the 'random spot' method, sludge is discharged at various points on the farm (Figure 15) which are accessible to the cesspit emptier. After its drying, sludge 'cakes' are scraped off the ground into heaps, before the material is eventually spread over the field or incorporated into the soil. This allows the sludge to continue drying, before the cultivation of cereals starts.

The 'pit' method is less common, as it requires digging pits on the farms and the placement of rice straw or bran at the bottom of the pit. Fecal sludge is then poured into the pit, which is large in size and can take one or more truckloads (Figure 16). Layers of bran and straw are placed in layers in between subsequent trips until the pit is full. Before the cropping season starts, the dried FS is removed from the pit and spread over the field. A more advanced system with farmer-managed drying ponds and subsequent sale of fecal sludge to other farmers has been observed in southern India (Figure 17).

The random spot and pit methods of sludge treatment take advantage of natural pathogen die-off under the hot savannah sun turning the fecal matter into an easier to handle manure, while simultaneously supporting pathogen destruction. In Ghana, relative humidity figures over the drying period are low while the solar radiation is high, resulting in the combined conditions conducive to the destruction of pathogens. By the time of the first seasonal rains (usually in April), most of the sludge is completely dry and evenly distributed on the field prior to land preparation and planting. This traditional method of soil fertility enhancement provides an effective option for mitigating occupational health risks, where drying periods are sufficiently long. However, in real life situations, drying periods can differ significantly. Drying periods that are too short will result in material which can still contain thermo-tolerant coliform bacteria and Ascaris concentrations above the WHO (2006b) monitoring guideline for fecal sludge application (Seidu 2010). Given the choice of crops (maize, sorghum), the health risks for consumers are, however, very unlikely, while the farmers are at risk of exposure as long as the sludge is fresh.

To minimize the risk to farmers, Seidu (2010) recommends the following for the temperature conditions in Northern Ghana[5]:

- For the surface spreading method (random spot method), sludge drying times of at least 30 days (ideally 60 days) is needed to meet the WHO microbial monitoring benchmark for E. coli and helminth eggs (based on less than one Ascaris egg per gram of total solids).
- The same drying time resulted in rotavirus levels below

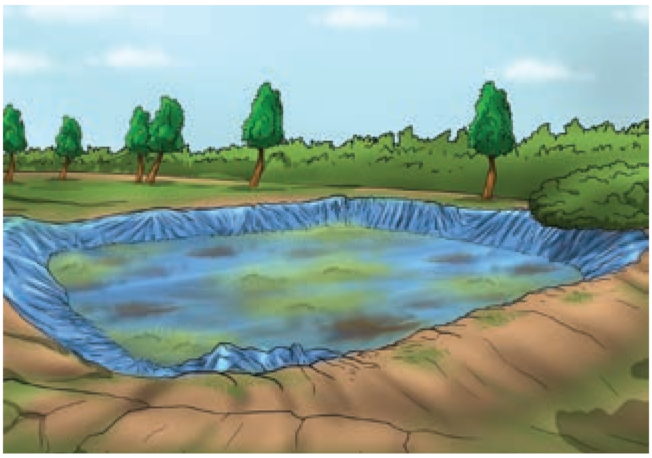
FIGURE 15. SPOTS OF FECAL SLUDGE SPREAD OVER THE SOIL SURFACE.

Source: IWMI, after photo by P. Amoah, IWMI.

FIGURE 16. PIT METHOD FOR ON-FARM PRE-TREATMENT OF SLUDGE.

Source: IWMI, after photo by P. Amoah, IWMI.

FIGURE 17. DEPOT FOR DRYING AND SALE OF FECAL SLUDGE NEAR BANGALORE, INDIA.



Source: IWMI, after photo by Lars Schoebitz, Department of Water and Sanitation in Developing Countries (Sandec), Swiss Federal Institute of Aquatic Science and Technology (Eawag).

[5] Average monthly minimum (nighttime) temperature in the dry season is 20-24 °C; average monthly maximum (daytime) temperature in the dry season is 34-37 °C with 8-10 hours of sunlight.

the WHO tolerable infection risk through accidental ingestion of small amounts of 'cake' sludge or sludge-contaminated soil.

- For the pit method, 3 months of drying time will be needed to meet the WHO microbial monitoring benchmark for E. coli, Ascaris and rotavirus infections.
- Further risk reduction could be achieved if the farmer used protective clothing. About one out of five farmers complained of itching feet after working with fecal sludge, which is normally done without wearing any protective foot covering (Cofie et al. 2005).

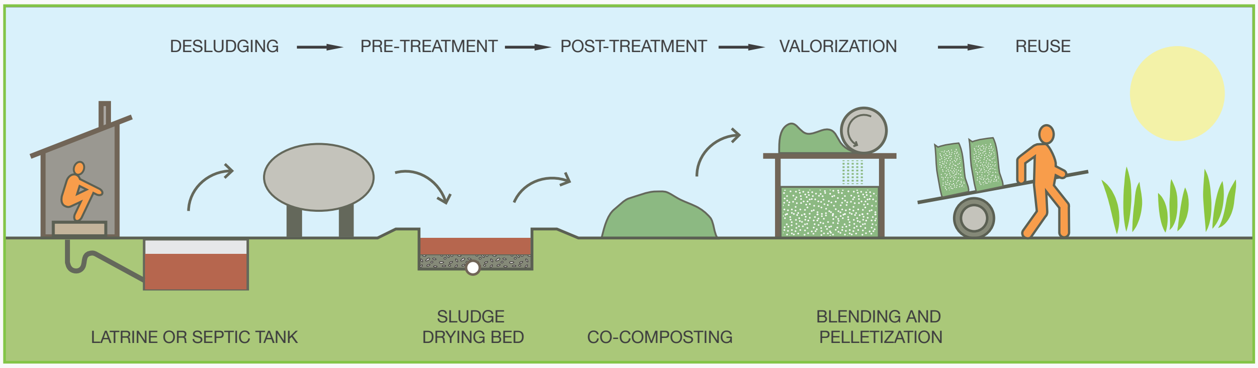
Where cropping patterns, insects, odor, legislations or the climate do not allow open drying of sludge over 1 to 3 months, the alternative options are as follows:

a. Disposal of fecal sludge into a system of parallel trenches as done in tree crop plantations in southern India (Figure 18). The trench filled can then be covered with soil. In South Africa, trenches are also used for sludge disposal, where there are no designated treatment plants. Here, lime is applied on top of the soil to control smells and flies. If lime gets mixed with excreta at a ratio of 1 to 10 and aeration is secured, a very positive impact on helminth eggs can also be expected while maintaining sufficiently high nitrogen levels (Vu-Van et al. 2013).
b. Where groundwater levels are high, or a dry product is preferred, fecal sludge can be composted or co-composted as described above (Figure 19).

FIGURE 18. TRENCH USED FOR FECAL SLUDGE FERTILIZATION ALONG A BANANA PLANTATION NEAR BANGALORE, INDIA.

Source: IWMI.

FIGURE 19. REUSE-ORIENTED SEPTAGE MANAGEMENT AS A SAFE ALTERNATIVE TO FARM-BASED TREATMENT.



Source: IWMI.

Pre-treatment: The first stage of a sludge treatment process is dewatering of the sludge in so-called sludge drying beds. Drying beds consist of a gravel-sand filter, equipped with a drainage system. The sludge is loaded on to the bed and the water is evacuated mainly by percolation through the filter and by evaporation (Cofie and Koné 2009). Depending on the climate and rainfall, this process will take between 10 and 20 days. The dewatered sludge is suitable for further treatment, which is necessary for pathogen removal or inactivation.

Post-treatment: Further treatment of the sludge may happen through co-composting with organic waste, e.g., kitchen waste or garden waste (Cofie et al. 2006, 2009). The pre-treated sludge is composted together with the organic material at a ratio of 1:2 or 1:3 over 12-13 weeks. If the composting is performed well, temperatures in the heaps of sludge reach 55-60 °C. The compost that is produced constituted a safe and valuable soil conditioner. However, to increase the competitive advantage and acceptance of the compost, it can be enriched, for example, with urine, rock-phosphate or fertilizer (Adamtey et al. 2009), and pelletized (Nikiema et al. 2012).

CONCLUSIONS

This paper presents an overview of selected, low-cost, on-farm wastewater, greywater and fecal sludge treatment technologies that can contribute to the reduction of health risks in instances where conventional treatment is insufficient or nonexistent. There is strong evidence showing that these technologies can improve crop safety, especially if multiple risk reduction approaches are combined. Used in isolation, however, many of the technologies presented here would be insufficient to fully protect farmers or consumers except in situations where water pollution levels are moderate or low, as is the case with greywater. In all other cases, the interventions should play a complementary role to any available level of wastewater treatment and/or other post-harvest measures (such as careful vegetable washing) to comprehensively reduce health risks (Bos et al. 2010).

Despite it being a common reality in many low-income countries, the development of on-farm water or sludge treatment technologies has not yet received the attention that is needed in research, perhaps due to the traditional focus on conventional wastewater treatment. In essence, the farm-based technologies presented in this paper use the principles of conventional wastewater treatment. It is, however, important to understand both the nature of contamination as well as the biophysical and socioeconomic conditions in various locations to adapt the technologies accordingly. In this sense, the technology options presented here should not be considered as a blueprint for on-farm treatment, but as suggestions for local adaptation and verification.

Interventions which can build on farmers' current practices and irrigation systems will have the highest potential of adoption (Keraita et al. 2007, 2008b). Our field experience in West Africa showed that, if farmers understand the technologies and their advantages, they will continue to modify the techniques on their own even after scientists have left the project.

A key challenge for the adoption of farm-based measures is that they require behavior change, often without obvious or direct benefits unless farmers' risk awareness is high. This requires incentive systems which can range from increased tenure security to branding and market demand for safer crops, or involve social marketing (Karg and Drechsel 2011). All innovations require that farmers (and ideally consumers) are equipped with the knowledge on the health risks involved in using contaminated water, and can rely on institutional support, for example, from the extension service for technical advice, but also monitoring of farmers' compliance with the recommended safety practices.

To achieve high adoption rates, researchers have to actively involve farmers in the development or adaptation of the technology to understand farmers' needs, ability, interest to invest and change behavior, and their awareness of the risks involved (Keraita et al. 2008b). To ensure lasting adoption, the benefits should exceed the costs. This could ideally be the provision of market incentives for growing safer crops. However, other incentives, such as increased tenure security, could also facilitate technology change. Most farm plots in urban areas have low tenure security and farmers can be easily expelled from their plots. In such situations, it is unlikely that farmers will invest in on-farm infrastructure (Obuobie et al. 2006). Increasing tenure security is thus an attractive incentive which could be offered by authorities for the adoption of safety measures. A lasting technology change should, however, be supported by regulations to institutionalize the change and related compliance monitoring by extension staff (Drechsel and Karg 2013).

REFERENCES

Abubakari, A.-H.; Husseini, R.; Addi, P.E. 2011. *Strategies for minimising health risks of wastewater for poor farmers in the urban environment.* Proc. First All African Horticultural Congress; ISHS Acta Horticulturae 911: I All Africa Horticultural Congress, p. 123-131.

Adamtey, N.; Cofie, O.; Ofosu-Budu, G.K.; Danso, S.K.A.; Forster, D. 2009. Production and storage of N-enriched co-compost. *Waste Management* 29: 2429-2436.

Agarwal, M; Srinivasan, R.; Mishra, A. 2001. Study on flocculation efficiency of okra gum in sewage waste water. *Macromolecular Materials and Engineering* 286(9): 560-563.

Al-Balawenah, A.; Al-Karadsheh, E.; Qadir, M. 2011. Community-based reuse of greywater in home farming. In: *Food security and climate change in dry areas: Proceedings of an International Conference, February 1-4, 2010, Amman, Jordan,* eds., Solh, M.; Saxena, M.C. Aleppo, Syria: International Center for Agricultural Research in the Dry Areas (ICARDA). Pp. 299-303.

Amoah, P.; Keraita, B.; Akple, M.; Drechsel, P.; Abaidoo, R.C.; Konradsen, F. 2011. *Low-cost options for reducing consumer health risks from farm to fork where crops are irrigated with polluted water in West Africa.* Colombo, Sri Lanka: International Water Management Institute (IWMI). 37p. (IWMI Research Report 141). Available at http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB141/RR141.pdf (accessed on March 20, 2013).

Arthur, J.P. 1983. *Notes in the design and operation of waste stabilization ponds in warm climates in developing countries.* World Bank Technical Paper No. 7. Washington, DC: World Bank.

Assayed, A. 2012. *Drawer Compacted Sand Filter: A new and innovative design for on-site wastewater treatment.* Paper presented at the 5th International Civil Engineering Conference is an extension of the Jordan Engineers Association, January 17-19, 2012, Landmark Hotel, Amman. Available at www.jeaconf.org/UploadedFiles/Document/a2fcc5dc-c0d5-4d16-930d-ce85c965fe7d.pdf (accessed on October 7, 2013).

Assayed, A.K.; Dalahmeh, S.S.; Suleiman, W.T. 2010. Onsite greywater treatment using septic tank followed by intermittent sand filter - A case study of Abu Al Farth Village in Jordan. *International Journal of Chemical and Environmental Engineering 1*(1): 67-71.

Awuah, E.; Oppong-Peprah, M.; Lubberding, H.J.; Gijzen, H.J. 2004. Comparative performance studies of water lettuce, duckweed, and algal-based stabilization ponds using low-strength sewage. *Journal of Toxicology and Environmental Health* 67: 1727-1739.

Benjamin, M.I.; Odeyemi, A.B.a.O. 2011. Comparative treatment of well and stream water for drinking using Moringa Oleifera seeds, alum, sand filter beds and solar radiation. *International Journal of Tropical Medicine and Public Health* 1(Supplement 1): 28-34.

Bino, M.; Al-Beiruti, S.; Ayesh, M. 2008. Greywater use in rural home gardens in Karek, Jordan. In: *Greywater use in the Middle East: Technical, social, economic and policy issues*, eds., McIlwaine, S.; Redwood, M. IDRC, Practical Action, Center for the Study of the Built Environment. Available at http://web.idrc.ca/openebooks/466-6/ (accessed on October 2, 2013).

Bos, R.; Carr, R.; Keraita, B. 2010. Assessing and mitigating wastewater-related health risks in low-income countries: An introduction. In: *Wastewater irrigation and health: Assessing and mitigating risk in low-income countries*, eds., Drechsel, P.; Scott, C.A.; Raschid-Sally, L.; Redwood, M.; Bahri, A. London, UK: Earthscan; Ottawa, Canada: International Development Research Centre (IDRC); Colombo, Sri Lanka: International Water Management Institute (IWMI). pp. 29-47.

Boufaroua, M.; Albalawneh, A.; Oweis, T. 2013. Assessing the efficiency of grey-water reuse at household level and its suitability for sustainable rural and human development. *British Journal of Applied Science & Technology* 3(4): 962-972.

Cáceres, A.; Cabrera, O.; Morales, O.; Mollinedo, P.; Mendia, P. 1991. Pharmacological properties of *Moringa oleifera*: Preliminary screening for antimicrobial activity. *Journal Ethnopharmacol* 33(3): 213-216.

Cleasby, J.L.; Logsdon, G.S. 1999. Granular bed and precoat filtration. In: *Water quality and treatment*, ed., Letterman, R.D. New York: McGraw Hill, Inc. Pp. 8.1-8.99.

Cofie, O.; Koné, D. 2009. Co-composting of fecal sludge and organic solid waste Kumasi, Ghana: Case study of sustainable sanitation projects. Sustainable Sanitation Alliance (SuSanA). Available at http://www.susana.org/lang-en/library?view=ccbktypeitem&type=2&id=113 (accessed on March 20, 2013).

Cofie O.; Koné, D.; Rothenberger, S.; Moser, D.; Zubruegg, C. 2009. Co-composting of fecal sludge and organic solid waste for agriculture: Process dynamics. *Water Research* 43: 4665-4675.

Cofie, O.O.; Agbottah, S.; Strauss, M.; Esseku, H.; Montangero, A.; Awuah, E.; Koné, D. 2006. Solid–liquid separation of fecal sludge using drying beds in Ghana: Implications for nutrient recycling in urban agriculture. *Water Research* 40(1): 75-82.

Cofie, O.O.; Kranjac-Berisavljevic, K.; Drechsel, P. 2005. The use of human waste for peri-agriculture in northern Ghana. *Renewable Agriculture and Food Systems* 20(2): 73-80.

Corcoran, E.; Nellemann, C.; Baker, E.; Bos, R.; Osborn, D.; Savelli, H. (eds). 2010. *Sick Water? The central role of wastewater management in sustainable development. A Rapid Response Assessment.* United Nations Environment Programme, UN-HABITAT, GRID-Arendal.

Cornish, G.A.; Lawrence, P. 2001. *Informal irrigation in peri-urban areas: A summary of findings and recommendations.* Report OD 144. Wallingford: H.R. Wallingford; Department for International Development. 88 p.

Dalahmeh, S. 2013. *Bark and charcoal filters for greywater treatment: Pollutant removal and recycling opportunities.* Doctoral thesis. Sveriges lantbruksuniversitet (Swedish University of Agricultural Sciences), Uppsala. Acta Universitatis Agriculturae Sueciae 2013: 51. 75 p.

Dalahmeh, S.S.; Hylander, L.D.; Vinnerås, B.; Pell, M.; Oborn, I.; Jönsson, H. 2011. Potential of organic filter materials for treating greywater to achieve irrigation quality: A review. *Water Science and Technology* 63(9): 1832-40.

Danso, G.; Drechsel, P.; Wiafe-Antwi, T.; Gyiele, L. 2002. Income of farming systems around Kumasi. *Urban Agriculture Magazine* 7: 5-6.

Dash, R.R.; Bhanu Prakash, E.V.P.; Kumar, P.; Mehrotra, I.; Sandhu, C.; Grischek, T. 2010. River bank filtration in Haridwar, India: Removal of turbidity, organics and bacteria. *Hydrogeology Journal* 18(4): 973-983.

Drechsel, P.; Karg, H. 2013. Motivating behaviour change for safe wastewater irrigation in urban and peri-urban Ghana. *Sustainable Sanitation Practice* 16: 10-20. http://www.ecosan.at/ssp/issue-16-behaviour-change/SSP-16_Jul2013_10-20.pdf/view (accessed on October 5, 2013).

Drechsel, P.; Seidu, R. 2011. Cost-effectiveness of options for reducing health risks in areas where food crops are irrigated with wastewater. *Water International* 36(4): 535-548.

Ensink, J.H.J.; Scott, C.A.; Brooker, S.; Cairncross, S. 2010. Sewage disposal in the Musi-River, India: Water quality remediation through irrigation infrastructure. *Irrigation and Drainage Systems* 2: 65-77.

Feachem, R.G.; Bradley, D.J.; Garelick, H.; Mara, D.D. 1983. *Sanitation and disease: health aspects of excreta and wastewater management.* World Bank Studies in Water Supply and Sanitation 3. Chichester, UK: John Wiley & Sons.

Garzón-Zúñiga, M.A.; Buelna, G. 2011. Treatment of wastewater from a school in a decentralized filtration system by percolation over organic packing media. *Water Science and Technology* 64(5): 1169-1177.

Garzón-Zúñiga, M.A.; Tomasini-Ortíz, A.C.; Moeller-Chavez, G.; Hornelas-Uribe, Y.; Buelna, G.; Mijaylova-Nacheva, P. 2008. Enhanced pathogen removal in on-site biofiltration systems over organic filtration materials. *Water Practice and Technology* 3(2): doi:10.2166/wpt.2008.053

Ghebremichael, K.A. 2004. *Moringa seed and pumice as alternative natural materials for drinking water treatment.* PhD thesis. Sweden: University of Stockholm.

Hoffmann, H.C.; Platzer, M.; Winker, E.; von Muench, E. 2011. *Technology review of constructed wetlands.* Eschborn, Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Hofstedt, C. 2005. *Wastewater use in agriculture in Andhra Pradesh, India: An evaluation of irrigation water quality in reference to associated health risks.* MSc thesis. IWMI, Uppsala University, SLU, Sweden. 55p.

Homski, D.; Goren, M.; Gasith, A. 1994. Comparative evaluation of the larvivorous fish *Gambusia affinis* and *Aphanius dispar* as mosquito control agents. *Hydrobiologia* 284(2): 137-146. Available at http://www.springerlink.com/content/pu56504627577586/ (accessed on March 20, 2013).

Huisman, L.; Wood, W.E. 1974. *Slow sand filtration.* Geneva: World Health Organization (WHO). Available at http://www.who.int/water_sanitation_health/publications/ssf9241540370.pdf (accessed on March 20, 2013).

IWMI (International Water Management Institute). 2008a. Good farming practices to reduce vegetable contamination. Awareness and training video for wastewater farmers. 16 min. CPWF, DVD. Available at http://www.youtube.com/watch?v=Aa4u1_RblfM (accessed on March 20, 2013) (for main video) Extra: Taking advantage of farmers' creativity (7 min).

IWMI. 2008b. Health risk reduction in a wastewater irrigation system in urban Accra, Ghana. 7 min. DVD. Available at http://youtu.be/f_EnUGa_GdM (accessed on March 20, 2013).

Karg, H.; Drechsel, P. 2011. Financial and non-financial incentives and triggers to enhance the adoption of safer irrigation and post-harvest practices in West Africa. *Water International* 36(4): 476-490.

Karim, M.R.; Manshadi, F.D.; Karpiscak, M.M.; Gerba, C.P. 2004. The persistence and removal of enteric pathogens in constructed wetlands. *Water Research* 38: 1831-1837.

Keraita, B. 2002. *Wastewater use in urban and peri-urban vegetable farming in Kumasi Ghana.* MSc thesis. Wageningen, the Netherlands: Wageningen University.

Keraita, B. 2010. Using Moringa oleifera seed extracts to reduce microbial contamination in irrigation water in urban vegetable farming in Ghana. International Foundation of Science (IFS) Report No. W/4520.

Keraita, B.; Drechsel, P.; Konradsen, F. 2007. Safer options for irrigated urban farming. *LEISA Magazine* 23.3: 26-28. Available at http://www.agriculturesnetwork.org/magazines/global/healthier-farmers-better-products/safer-options-for-irrigated-urban-farming/at_download/article_pdf (accessed on March 21, 2013).

Keraita, B.; Drechsel, P.; Konradsen, F. 2008a. Using on-farm sedimentation ponds to improve microbial quality of irrigation water in urban vegetable farming in Ghana. *Water Science & Technology* 57(4): 519-525.

Keraita, B.; Drechsel, P.; Konradsen, F. 2008b. Perceptions of farmers on health risks and risk reduction measures in wastewater-irrigated urban vegetable farming in Ghana. *Journal of Risk Research* 11(8): 1047-1061.

Keraita, B.; Drechsel, P.; Konradsen, F.; Vreugdenhil, R.C. 2008c. Potential of simple filters to improve microbial quality of irrigation water used in urban vegetable farming in Ghana. *Journal of Environmental Science and Health, Part A* 43(7): 749-755.

Keraita, B.; Konradsen, F.; Drechsel, P. 2010. Farm-based measures for reducing microbiological health risks for consumers from informal wastewater-irrigated agriculture. In: *Wastewater irrigation and health: Assessing and mitigating risk in low-income countries,* eds., Drechsel, P.; Scott, C.A.; Raschid-Sally, L.; Redwood, M.; Bahri, A. UK: Earthscan; Canada: International Development Research Centre (IDRC); Sri Lanka: International Water Management Institute (IWMI). Pp. 189-207.

Koné, D.; Cofie, O.O.; Nelson, K. 2010. Low-cost options for pathogen reduction and nutrient recovery from fecal sludge. In: *Wastewater irrigation and health: Assessing and mitigating risk in low-income countries*, eds., Drechsel, P.; Scott, C.A.; Raschid-Sally, L.; Redwood, M.; Bahri, A. UK: Earthscan; Canada: International Development Research Centre (IDRC); Sri Lanka: International Water Management Institute (IWMI). Pp. 171-188.

Koné, D.; Cissé, G.; Seignez, C.; Holliger, C. 2002. Le lagunage à laitue d'eau (Pistia stratiotes) à Ouagadougou: une alternative pour l'épuration des eaux usées destinées a l'irrigation. Cah. Etud. Rech. Francoph./*Cahiers Agricultures* 11(1): 39-43.

Letterman, R.D. 1991. Filtration strategies to meet the surface water treatment rule. Denver, CO: American Water Works Association.

Ludwig, A. 2009. *Create an oasis with greywater. Choosing, building and using greywater systems – Includes branched drains.* 5th edition. Santa Barbara, CA: Oasis Design.

Mara, D.D. 2004. *Domestic wastewater treatment in developing countries.* London, UK: Earthscan Publications.

Mara, D.D.; Pearson, H.W. 1992. Sequential batch-fed effluent storage reservoirs: A new concept of wastewater treatment prior to unrestricted crop irrigation. *Water, Science & Technology* 26(7-8): 1459-1464.

Mara, D.D.; Pearson, H.W.; Oragui, J.I.; Crawley, L.R.; de Oliveira, R.; Silva, S.A. 1996. *Wastewater storage and treatment reservoirs in Northeast Brazil.* Research Monographs in Tropical Public Health Engineering No. 12. Leeds, UK: University of Leeds, Department of Civil Engineering.

Marais, G.V.R. 1974. Fecal bacterial kinetics in stabilisation ponds. *Journal of Environmental Engineering Division* 100(1): 119-139.

Metcalf and Eddy, Inc. 1995. *Wastewater engineering: Treatment, disposal, and reuse.* New York: McGraw-Hill. 1819 pp.

Morel, A.; Diener, S. 2006. *Greywater management in low and medium income countries; A review of different treatment systems for households or neighborhoods.* Dübendorf, Switzerland: Swiss Federal Institute of Aquatic Science and Technology (EAWAG).

Mukhtar, M.; Herrel, N.; Amerasinghe, F.P.; Ensink, J.; van der Hoek, W.; Konradsen, F. 2003. Role of wastewater irrigation in mosquito breeding in south Punjab, Pakistan. *The Southeast Asian Journal of Tropical Medicine and Public Health* 34(1): 72-80. Available at http://www.ncbi.nlm.nih.gov/pubmed/12971517 (accessed on March 21, 2013).

Murray, A.; Drechsel, P. 2011. Why do some wastewater treatment facilities work when the majority fail? Case study from the sanitation sector in Ghana. *Waterlines* 30(2): 135-149. Available at http://practicalaction.metapress.com/content/b2267762560ph944/fulltext.pdf (accessed on October 21, 2013).

NRC (National Research Council). 2006. Moringa. In: Lost crops of Africa: Volume II: *Vegetables*. Washington, DC: The National Academies Press. Pp. 246-267. Available at http://books.nap.edu/openbook.php?record_id=11763&page=247 (accessed on March 21, 2013).

Niang, S. 1999. *Utilisation des eaux usées brutes dans l'agriculture urbaine au Sénégal : Bilan et perspectives*. In: Urban agriculture in West Africa: Contributing to food security and urban sanitation, ed., Smith, O.B. Ottawa, Canada: International Development Research Centre (IDRC). Pp. 104-125.

Nikiema, J.; Cofie, O.; Impraim, R.; Drechsel, P. 2012. *Fortified excreta pellets for agriculture*. Paper presented at the Second International Fecal Sludge Management Conference in Durban, South Africa, October 29-31, 2012. Available at http://susana.org/lang-en/library?view=ccbktypeitem&type=2&id=1624 (accessed on March 21, 2013).

Niyonzima, S. 2007. *Grey water treatment using constructed wetland at KNUST in Kumasi.* MSc thesis submitted to the Department of Civil Engineering, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi. Available at http://www.switchurbanwater.eu/outputs/pdfs/W5-3_GEN_PHD_D5.3.12_MSc_Niyonzima_Greywater_treatment_with_constructed_wetland.pdf (accessed on March 21, 2013).

NUSP (National Urban Sanitation Policy). 2008. Ministry of Urban Development, Government of India. New Delhi, India.

Obuobie, E.; Keraita, B.; Danso, G.; Amoah, P.; Cofie, O.O.; Raschid-Sally, L.; Drechsel, P. 2006. *Irrigated urban vegetable production in Ghana: Characteristics, benefits and risks.* IWMI-RUAF-IDRC-CPWF. Accra, Ghana: IWMI. 150p. Available at www.cityfarmer.org/GhanaIrrigateVegis.html (accessed on May 9, 2013).

Okafo, C.N.; Umoh, V.J.; Galadima, M. 2003. Occurrence of pathogens on vegetables harvested from soils irrigated with contaminated streams. *The Science of the Total Environment* 311: 49-56.

Parr, J.; Smith, M.; Shaw, R. 2002. Wastewater treatment options, Technical Brief no. 64. *Waterlines* 21(1): 15-18.

Peterson, H.G. 2001. Rural drinking water and waterborne illness. In: *Maintaining Drinking Water Quality, Lessons from the Prairies and Beyond. Proceedings of the 9th National Conference on Drinking Water, Regina, Saskatchewan, Canada, May 16-18, 2000, ed.,* Robertson, W. Ottawa, Canada: Canadian Water and Wastewater Association. Pp. 162-191

Quayle, T. 2012. *Wastewater treatment and water recycling for biomass production in Niamey, Niger.* Available at http://www.accessanitation.org/fileadmin/accessanitation/Case_studies/Sub_Saharan_Africa/ACCESS_Case_study_Niamey.pdf (accessed on March 21, 2013)

Raschid-Sally, L.; Jayakody, P. 2008. *Drivers and characteristics of wastewater agriculture in developing countries: Results from a global assessment.* Colombo, Sri Lanka: International Water Management Institute (IWMI). 29p. (IWMI Research Report 127). Available at http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB127/RR127.pdf (accessed on October 21, 2013).

Reymond, P.; Cofie, O.; Raschid, L.; Koné, D. 2009. *Design considerations and constraints in applying on-farm wastewater treatment for urban agriculture.* Paper presented at the 4th SWITCH Scientific Meeting, October 4-7, 2009, Delft, the Netherlands.

Rose, G.D. 1999. *Community-based technologies for domestic wastewater treatment and reuse: Options for urban agriculture.* Cities Feeding People Series – Report 27. Ottawa, Canada: International Development Research Centre (IDRC).

Sattler, M.A.; Mtasiwa, D.; Kiama, M.; Premji, Z.; Tanner, M.; Killeen, G.F.; Lengeler, C. 2005. Habitat characterization and spatial distribution of *Anopheles sp.* mosquito larvae in Dar es Salaam (Tanzania) during an extended dry period. *Malaria Journal* 4:4. Available at http://www.malariajournal.com/content/4/1/4 (accessed on March 21, 2013).

Scheierling, S.M.; Bartone, C.; Mara, D.D.; Drechsel, P. 2010. *Improving wastewater use in agriculture: An emerging priority.* World Bank Policy Research Working Paper No. WPS 5412. Available at http://go.worldbank.org/UC28EAWNI0 (accessed on March 21, 2013).

Seidu, R. 2010. *Disentangling the risk factors and health risks associated with fecal sludge and wastewater reuse in Ghana.* PhD thesis. Ås, Norway: Norwegian University of Life Sciences, Department of Mathematical Sciences and Technology.

Sengupta, M.E.; Keraita, B.; Olsen, A.; Boateng, O.K.; Thamsborg, S.M.; Pálsdóttir, G.R.; Dalsgaard, A. 2012. Use of *Moringa oleifera* seed extracts to reduce helminth egg numbers and turbidity in irrigation water. *Water Research* 46(11): 3646-3656.

Silverman, A.I.; Akrong, M.O.; Drechsel, P.; Nelson, K.L. Forthcoming. *On-farm treatment of wastewater used for vegetable irrigation: Bacteria and virus removal in small ponds in Accra, Ghana.* In preparation.

Simmons, R.; Qadir, M.; Drechsel, P. 2010. Farm-based measures for reducing human and environmental health risks from chemical constituents in wastewater. In: *Wastewater irrigation and health: Assessing and mitigating risk in low-income countries,* eds., Drechsel, P.; Scott, C.A.; Raschid-Sally, L.; Redwood, M.; Bahri, A. (eds.). UK: Earthscan; Canada: IDRC; Sri Lanka: IWMI. Pp. 209-238.

Singh, P.; Kumar, P.; Mehrotra, I.; Grischek, T. 2010. Impact of riverbank filtration on treatment of polluted river water. *Journal of Environmental Management* 91(5): 1055-1062.

Sobsey, M.D. 2002. *Managing water in the home: Accelerated health gains from improved water supply.* Geneva, Switzerland: Water, Sanitation and Health, Department of Protection of the Human Environment, World Health Organization.

Srinivasan, R.; Mishra, A. 2008. Okra (*Hibiscus esculentus*) and Fenugreek (*Trigonella foenum graceum*) mucilage: Characterisation and application as flocculants for textile effluent treatments. *Chinese Journal of Polymer Science* 26(6): 679-687.

Stevik, T.K.; Aa, K.; Ausland, G.; Hanssen, J.F. 2004. Retention and removal of pathogenic bacteria in wastewater percolating through porous media: A review. *Water Research* 38(6): 1355-1367.

Sutherland, J.P.; Folkard, G.K.; Grant, W.D. 1990. Natural coagulants for appropriate water treatment - a novel approach. *Waterlines* 8(4): 30-32.

Tiongco, M.M.; Narrod, C.A.; Bidwell, K. 2010. Risk analysis integrating livelihood and economic impacts of wastewater irrigation on health. In: *Wastewater irrigation and health: Assessing and mitigating risk in low-income countries,* eds., Drechsel, P.; Scott, C.A.; Raschid-Sally, L.; Redwood, M.; Bahri, A. (eds.). UK: Earthscan; Canada: International Development Research Centre (IDRC); Sri Lanka: International Water Management Institute (IWMI). Pp. 127-145.

UNEP (United Nations Environment Programme). 1997. Sourcebook of alternative technologies for freshwater augmentation in Latin America and the Caribbean. IETC Technical Publication Series, Osaka/Shiga, Japan.

UNEP. 2005. Water and wastewater reuse: *An environmentally sound approach for sustainable urban water management.* Nairobi, Kenya: United Nations Environment Programme (UNEP); Osaka, Japan: Global Environment Centre Foundation (GEC).

USEPA (United States Environmental Protection Agency). 2001. *Low-pressure membrane filtration for pathogen removal: Application, implementation, and regulatory issues.* EPA 815-C-01-001. Washington, DC: United States Environmental Protection Agency (USEPA), Office of Ground Water and Drinking Water, Standards and Risk Management Division, Technical Support Center.

USEPA. 2012. *Guidelines for water reuse.* Washington, DC: United States Environmental Protection Agency (USEPA); Washington, DC: United States Agency for International Development (USAID); Massachusetts, USA: CDM Smith. EPA/600/R-12/618.

Van Donsel, D.J.; Geldreich, E.E. 1971. Relationships of salmonella to fecal coliforms in bottom sediments. *Water Research* 5: 1079-1087.

Verhagen, J.; Kvarnström, E.; Nilsson, M.; Srikantaiah, V.; Ramachandran, S.; Singh, K. 2012. *The business of the honey-suckers in Bengaluru (India): The potentials and limitations of commercial faecal sludge recycling – an explorative case study.* Paper prepared for the South Asia Sanitation and Hygiene Workshop, January 31 - February 2, 2012, Rajendrapur, Bangladesh.

Vigueras-Cortés, J.M.; Villanueva-Fierro, I.; Garzón-Zúñiga, M.A.; de Jesús Návar-Cháidez, J.; Chaires-Hernández, I.; Hernández-Rodríguez, C. 2013. Performance of a biofilter system with agave fiber filter media for municipal wastewater treatment. *Water Science and Technology* 68(3): 599-607.

Vu-Van, T.; Pham-Duc, P.; Nguyen-Viet, H.; Zurbrügg, C.; Huu Bich, T.; Zinsstag, J. 2013. Helminth eggs die-off and nutrients: Human excreta storage experiment. *Sandec News* 14: 9.

WHO (World Health Organization). 2006a. *Guidelines for the safe use of wastewater, excreta and greywater. Volume 2: Wastewater use in Agriculture.* Geneva: World Health Organization (WHO); Food and Agriculture Organization of the United Nations (FAO); United Nations Environment Programme (UNEP).

WHO. 2006b. *Guidelines for the safe use of wastewater, excreta and greywater. Volume 4: Excreta and greywater use in agriculture.* Geneva: World Health Organization (WHO); Food and Agriculture Organization of the United Nations (FAO); United Nations Environment Programme (UNEP).

WHO-UNICEF (United Nations Children's Fund). 2010. *Progress on sanitation and drinking-water: 2010 update.* WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP). Available at http://www.unwater.org/downloads/JMP_report_2010.pdf (accessed on October 4, 2013).

Winblad, U.; Simpson-Hébert, M. 2004. *Ecological sanitation – revised and enlarged edition.* Stockholm, Sweden: Stockholm Environment Institute (SEI).

WQSD (Water Quality Study Division). 2009. WHO/FAO/IDRC project on non-treatment options for the safe use of wastewater, excreta and greywater in agriculture and aquaculture. Final Report 2009. Amman, Jordan: Environmental Research Center, Royal Scientific Society.

Wyss, P.; Züst, B. 2000. *Sustainable wastewater treatment with soil filters.* Switzerland: Centre for Applied Ecology Schattsweid; Switzerland: Swiss Resource Centre and Consultancies for Development (SKAT). London, UK: Intermediate Technology Publications.

RESEARCH PROGRAM ON Water, Land and Ecosystems

Led by: IWMI International Water Management Institute

CGIAR Research Program on Water, Land and Ecosystems

The **CGIAR Research Program on Water, Land and Ecosystems (WLE)** combines the resources of 11 CGIAR centers, the Food and Agriculture Organization of the United Nations (FAO) and numerous national, regional and international partners to provide an integrated approach to natural resource management research. WLE promotes a new approach to sustainable intensification in which a healthy functioning ecosystem is seen as a prerequisite to agricultural development, resilience of food systems and human well-being. This program is led by the International Water Management Institute (IWMI) and is supported by CGIAR, a global research partnership for a food secure future.

Resource Recovery and Reuse (RRR) is a sub-program of WLE dedicated to applied research on the safe recovery of water, nutrients and energy from domestic and agro-industrial waste streams. This SRP aims to create impact through different lines of action research, including (i) developing and testing scalable RRR business models, (ii) assessing and mitigating risks from RRR for public health and the environment, (iii) supporting public and private entities with innovative approaches for the safe reuse of wastewater and organic waste, and (iv) improving rural-urban linkages and resource allocations while minimizing the negative urban footprint on the peri-urban environment. This sub-program works closely with the World Health Organization (WHO), Food and Agriculture Organization of the United Nations (FAO), United Nations Environment Programme (UNEP), United Nations University (UNU), and many national and international partners across the globe. The RRR series of documents present summaries and reviews of the sub-program's research and resulting application guidelines, targeting development experts and others in the research for development continuum.

CGIAR Research Program on Water, Land and Ecosystems
International Water Management Institute (IWMI)
127 Sunil Mawatha, Pelawatta
Battaramulla, Sri Lanka
Email: wle@cgiar.org
Website: wle.cgiar.org
Agriculture and Ecosystems Blog: wle.cgiar.org/blogs

ISSN 2478-0510
e-ISSN 2478-0529
ISBN 978-92-9090-785-5

WLE Partners:

CGIAR Challenge Program on WATER & FOOD, CIAT, ICARDA, ICRISAT, World Agroforestry Centre, Bioversity International, CIP, IFPRI, ILRI, IITA, WorldFish, FAO